THE IMPACT OF DECLINING ROADWAY CONDITIONS ON ROAD USER COSTS AND GREENHOUSE GAS EMISSIONS

Final Report

RESEARCH

Oregon Department of Transportation

THE IMPACT OF DECLINING ROADWAY CONDITIONS ON ROAD USER COSTS AND GREENHOUSE GAS EMISSIONS

by

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16. Abstract:

In a pavement life cycle, a significant portion of the emissions are generated during the roadway's use phase rather than solely from material production and construction stages. Therefore, effective emission reduction strategies should encompass all phases of the pavement life cycle to maximize environmental impact. This component of the pavement life-cycle assessment (LCA) is essential to achieve a comprehensive cradle-to-grave approach. To support this objective, this study focused on quantifying the effects of roadway roughness on vehicle fuel consumption, tire wear, and the resulting CO_2 emissions. To achieve this, ODOT's Pavement Management Division gathered and analyzed pavement smoothness data across various route categories, differentiated by traffic volume and speed. For selected roadway sections, the OSU research team projected future pavement smoothness deterioration using roughness progression models based on historical data. With the finalized network-level dataset, the study assessed the impact of roadway roughness on CO_2 emissions and vehicle operating costs (VOC). The entire analysis was conducted in Python, with custom code developed to process Pavement Management System (PMS) data and calculate the roughness-related excess fuel consumption, tire wear, and associated CO_2 emissions. It was concluded that investing in smoother roads offers substantial long-term financial and environmental benefits. While the initial costs of achieving smoother roads are higher, the significant savings from reduced excess fuel consumption and tire wear, especially in high-traffic areas, more than compensate for these upfront expenses. Prioritizing high-traffic sections for smoother pavement maximizes cost savings and improves road durability, making it a cost-effective strategy for both vehicle operations and infrastructure maintenance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	shorttons(2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

Pavement conditions influence current and future preservation costs, the costs incurred by road users, and the levels of transportation-related greenhouse gas (GHG) emissions. This research study aimed to assess the impact of pavement smoothness across these areas and analyze various scenarios to identify opportunities for reducing financial expenditures and emissions via reductions in overall roadway roughness levels.

According to the 2020 ODOT Pavement Condition Report (Coplantz 2021), the current ODOT pavement program is significantly underfunded ($220M was needed while the expected funding for 2021-2024 STIP was less than $107M), which is expected to result in a decline in pavement conditions in Oregon within the next five years. According to the report, *"Preservation project mileage programmed in 2021-2024 provides an equivalent resurfacing cycle time of 50 years, which is roughly twice as long as pavement lasts. In the long run, Oregonians will pay more to rehabilitate failing pavement than it would have cost to maintain them in a state of good repair."* Since these funding projections did not consider the recent increases in oil prices (which directly controls asphalt paving costs) and inflation rates, it is expected that the condition of the Oregon roadway network will even get worse than the 2020 predictions within the next decade.

According to the 2022 ODOT Pavement Condition Report (Coplantz 2023), the current ODOT pavement program is still significantly underfunded ($280M is needed while the expected funding for 21-24 STIP is less than $115M, and 24-27 STIP is around $110M), It was also mentioned in the same report that *"The pavement funding levels for the 27-30 STIP may be as low as $65 million per year or even lower. This funding level is lower than it has been in decades"*. The reductions in funding in previous years have already started to show their effects, as there has been a decline in pavement network conditions for all five regions in Oregon (see Figure 9 in the 2022 ODOT Pavement Condition Report).

To combat those long-term pavement condition-related issues, timely preventive maintenance and preservation of roads are essential for minimizing the life-cycle costs of pavements. However, reduced paving activities due to insufficient funding are projected to significantly decrease the percentage of pavements in fair or better condition across Oregon within the next decade. Innovative methods and technologies can be employed to mitigate the effects of limited paving budgets on roadway conditions to lower both the cost and environmental impact of pavements. One key strategy involves reducing roadway roughness across the ODOT network, which can decrease vehicle fuel consumption and tire wear, thereby reducing road user costs and greenhouse gas (GHG) emissions.

Furthermore, smoother roadways reduce the dynamic loads exerted on pavement surfaces by minimizing the vertical axle movements of commercial trucks. This reduction in dynamic loads is expected to significantly enhance the longevity and durability of pavement structures. Table 1.1 shows the average service life increase for different pavement types across different states with a

10%, 25%, and 50% reduction in roughness (Smith et al. 1997). The data indicates that as roughness decreases, a significant increase in service life is observed across the different pavement types, with the percentage varying by state, material types, and construction methods.

Table 1-1: Average percent increase in performance life with the decrease in pavement roughness (Smith et al. 1997)

	Average Percent Increase in Performance Life		
Reduction in roughness	**10%**	**25%**	**50%**
Alabama PCC	11	28	55
Arizona PCC	7	18	36
Illinois CRC	5	11	22
Minnesota PCC	6	15	30
Illinois AC/PCC	4	9	18
Alabama AC	8	20	39
Arizona AC	3	9	18
Minnesota AC	5	11	23

Note: PCC: Portland Cement Concrete, CRC: Continuously Reinforced Concrete, AC: Asphalt Concrete.

Governor Kate Brown's Executive Order No. 20-04 directed state agencies, including ODOT, to take action to reduce and regulate GHG emissions in Oregon. The transportation sector contributes 40% of total GHG emissions in Oregon, the largest of any sector economy-wide (ODOT Climate Office 2021). In the pavement life-cycle, GHG emissions are released during the i) Material production, ii) Construction, iii) Use phase (service life), and iv) Maintenance and rehabilitation stages. In these four stages, the use phase and the associated pavement-vehicle-interaction (PVI) related GHG emissions and vehicle operating costs (VOC), including fuel consumption, tire wear, and vehicle maintenance costs, are the most significant factors controlling the sustainability of the pavement structures (Harvey et al. 2016).

Data from the NCHRP 720 report (Chatti and Zaabar 2012a) show that reducing the road roughness by maintenance and rehabilitation can create a \$0.4 to \$0.8 reduction in user costs for one truck for one lane mile with significant associated GHG savings. This data alone suggests that substantial savings for road users can be created by developing a smoother roadway network. High roadway roughness levels increase the rolling resistance for vehicles traveling on roadways, resulting in higher fuel consumption and vehicle maintenance costs (also called vehicle operating costs - VOC). The impact of roadway roughness on VOC is predicted to be around 2%-5% of overall VOC (Coleri et al. 2016; Haddadi et al. 2017). Considering the amount of fuel consumed annually in Oregon and the U.S., the impact of roadway roughness on vehicle operating costs and GHG emissions is significant (even more than the combined energy used for material production and construction stages).

In addition to considering the upfront construction and life-cycle costs of pavements (which is the current method followed for decision-making), the development of a decision-making process to reduce the environmental impact (measured in GHG emissions) of pavements by reducing road roughness-related excess fuel consumption should be explored. In the long-term, the developed process can be implemented to calculate GHG emissions for all four stages of the pavement life cycle to perform "cradle-to-grave" pavement life cycle assessment (LCA) and develop more accurate Environmental Product Declarations (EPD) for different pavement materials.

1.1 KEY OBJECTIVES OF THE STUDY

ODOT is interested in a comprehensive assessment that would relate pavement asset management practices to GHG emissions and costs. The majority of emissions stem from the roadway's use phase, not just the embodied carbon in construction materials. Therefore, reducing emissions should focus on both phases and the construction phase to achieve the greatest environmental impact. Additionally, there is a relationship between pavement conditions and cost. Most people intuitively know that spending more money on a transportation network will improve conditions but do not know how investments in the network can make using it cheaper. To help ODOT understand the relationship between emissions (from materials and users) and costs (those paid by ODOT as well as the road user costs to use the network), the following work was undertaken in this study by the OSU-Asphalt Materials and Pavement (AMaP) research group:

ODOT's Pavement Management Division evaluated and summarized pavement smoothness data on several different categories of routes, differentiated by traffic and speed. For those selected roadway sections, the OSU research team projected the decline in smoothness into the future using roughness progression models derived from historical data.

Based on this data set and the developed procedure, OSU determined and reported on the following four major outcomes:

1) How much are road user costs and user emissions projected to increase in the future on some of the routes, given the projected flat funding levels from the Transportation Asset Management Plans (TAMP)? (Note that federal standards require continued interstate investment and paving, and therefore relatively smooth pavement).
2) ODOT funding levels for pavement preservation will cause pavement conditions to decline. ODOT must decide where to spend its funding, and its decisions will determine the conditions that can be maintained on certain routes such that some will decline faster than others and experience accelerated pavement decline. OSU-AMaP assessed the impacts of declining conditions on several categories of routes and to what extent that would increase user costs and emissions.
3) The impact of *"after construction IRI level"* on user cost and CO_2 emission savings.
4) The distribution of road user cost and emission savings for different pavement (concrete and asphalt) and vehicle (car&SUV and trucks) types.

The research methodology followed in this research study involved the following components:

1) **Processing International Roughness Index (IRI) and Performance Data:** Pavement management system data from ODOT databases and the data from automated pavement

condition surveys (biennially collected in Oregon) were analyzed to develop an algorithm (a code written in Python) with performance equations to predict the roughness progression on different roadway sections (as a function of age, current condition, material properties, climate, and traffic).

2) **Oregon Roadway Network Segmentation and Performance Modeling:** ODOT Pavement Management Division evaluated the existing database to summarize average pavement smoothness data on several categories of routes, differentiated by traffic and speed. Using the provided data, the International Roughness Index (IRI) and pavement performance models were developed and evaluated separately for different segments of roadways. The impact of roadway roughness on CO_2 emissions and VOC was also determined. World Bank's Highway Development and Management Models (HDM4) calibrated for U.S. vehicles and pavement conditions (Chatti and Zaabar 2012a) were used to determine the effects of roughness reduction and increases in on-road users' vehicle operating costs and CO_2 emissions. The entire process was modeled in Python by developing a code to process the PMS data and calculate the roughness-related excess fuel consumption, tire wear, and the associated CO_2 emissions. The results of a preliminary cradle-to-gate LCA conducted by Proudfoot and Toneys (2022) were also used to compare ODOT's total annual CO_2 emissions to the CO_2 emissions that can be saved by reducing the network-level pavement roughness.

3) **Final Projections and Data Analyzes:** All developed models and their outputs were summarized to achieve the four major outcomes listed above. Results were presented in detailed figures and tables in this research report.

This study focused exclusively on the impact of pavement roughness on road user costs and the associated CO_2 emissions. The division of tasks between ODOT and OSU also facilitated ODOT working on the engineering side of this issue based on current engineering established best practices, while OSU working on the research side of this issue using trends and data relationships still not precise and in their conceptual infancy.

1.2 PROGRESS TO DATE IN OREGON TO ADDRESS ENVIRONMENTAL CHALLENGES

The Oregon Department of Transportation (ODOT), Oregon State University (OSU), and consulting firms have been making progress toward carbon reduction goals for several years. The following achievements were attained so far:

- ODOT has recently reviewed its practices with industry, academia, and a sustainability consultant to complete a GHG inventory of operational emissions. ODOT's Delivery and Operations Division and Climate Office are currently working through the recommended action items listed in the final report (Proudfoot and Toneys, 2022). One of the key actions is to develop an EPD program to better track emissions from materials used in ODOT projects.

- The Oregon Legislature passed House Bill 4139 in March 2022, requiring ODOT to establish a program to reduce GHG emissions from concrete, asphalt paving mixtures, and steel products commonly used in road construction. The legislation mandates that ODOT gather Environmental Product Declarations (EPDs), which detail the environmental impacts of specific products, much like nutritional labels on food. These EPDs will support the agency in making informed decisions to lower GHG emissions while maintaining performance standards.

- Through legislation, ODOT also recently obtained resources to begin documenting and measuring carbon reduction efforts, which it is anticipated will be conducted through EPDs. Additionally, ODOT anticipates waiting until reliable EPDs have been established, using established Product Category Rules (PCRs), before conducting cradle-to-grave LCAs. The Oregon team has been working with Athena and the FHWA's LCA Pave tools for parametric evaluations of current products and has discovered that the data set is not yet available for reliable cradle-to-grave LCAs.

- Relating to construction materials, ODOT has been working with OSU for several years on balanced mix design and increasing recycled material content for asphalt concrete mixtures with several field trials, documenting carbon benefits and detractors from the research studies (Coleri et al. 2017, 2018, 2020; Kumar et al. 2021). Also, ODOT and OSU have been working together to reduce cementitious content in paving concrete mixes, recently concluding research with a field trial that reduced total cementitious content by 16 percent (Trejo et al. 2022).

1.3 ORGANIZATION OF THE REPORT

This research study focused on: (1) quantifying the impact of roadway roughness on vehicle operating costs and the associated emissions; (2) the potential impact of future pavement funding levels on user cost savings and emissions; and (3) Strategies to reduce the network level roughness were analyzed.

- Chapter 1.0 emphasizes the necessity for this research, presents the general methodology adopted, and lists the core objectives pursued.
- Chapter 2.0 presents a comprehensive literature review and examines several research studies focusing on quantifying the impact of roadway roughness on vehicle fuel use, tire wear, and associated emissions.
- Chapter 3.0 of this report is titled *"Summary of Network-Level Pavement Management System Data"*. The objective of this section is to summarize the network-level ODOT pavement management system data that was used in this study.
- Chapter 4.0 is titled *"Quantification of Network Level Roughness Related Excess Emissions and the Road User Costs "* and details the processing (cleaning) of ODOT Pavement Management System (PMS) data and the prediction of future roughness conditions (IRI) for pavement sections. It also includes projections for future traffic, fuel prices (gas and diesel), tire wear-related emissions and costs, and the anticipated volume

of electric vehicles. This section also analyses cumulative roughness-related excess fuel consumption, tire wear costs, and the associated CO_2 emissions over the past 20 years and estimates future costs and emissions under different maintenance scenarios for the next 10 years, considering ODOT's budgetary constraints and road paving strategies.

- Chapter 5.0 summarizes the key findings and conclusions derived from the research conducted in this study.
- Chapter 6.0 offers a detailed list of all the references cited throughout this report.

2.0 LITERATURE REVIEW

This section, with the literature review, summarizes the important background information needed to understand and evaluate the analysis provided in the following sections. To address this objective, the literature review provided in this section aims to answer the following questions (A summary of the literature review is also provided in Section 2.4.):

- What is pavement roughness, and how is it measured?
- How is pavement roughness affecting the additional vehicle energy use, GHG emissions, and user costs?
- How would the electrification of vehicles affect pavement roughness-related energy use, GHG emissions, and user costs?

2.1 PAVEMENT ROUGHNESS

Road networks influence the nation's economic and environmental development. Their expansion leads to significant emissions generated primarily through fuel combustion. As per the statistics of the Intergovernmental Panel on Climate Change (IPCC) (2022), the transportation sector contributes more than 20% of global energy-related carbon emissions (close to 40% for the U.S.A.). Approximately 8.9 billion tonnes (Gt) of annual carbon emissions were reported in 2019, significantly higher than the statistics reported in 1990 (5.0 Gt). Out of various transportation-related sectors, road network and their use phase are the largest contributors, with around 70% of direct emissions originating from vehicles, as presented in Figure 2.1 (Intergovernmental Panel on Climate Change (IPCC) 2022). These amounts are increasing steadily with the rise in road users, traffic volumes, and increasing congestion, while the improvements in vehicles' energy efficiency help reduce the environmental impact. Identifying the causes, accurately assessing, and providing remedial measures for these energy-related carbon emissions is the need of an hour, necessitating further research in this direction. Focusing on these areas would aid in developing more effective strategies to manage and lower the growing concerns of global warming while balancing economic and environmental considerations.

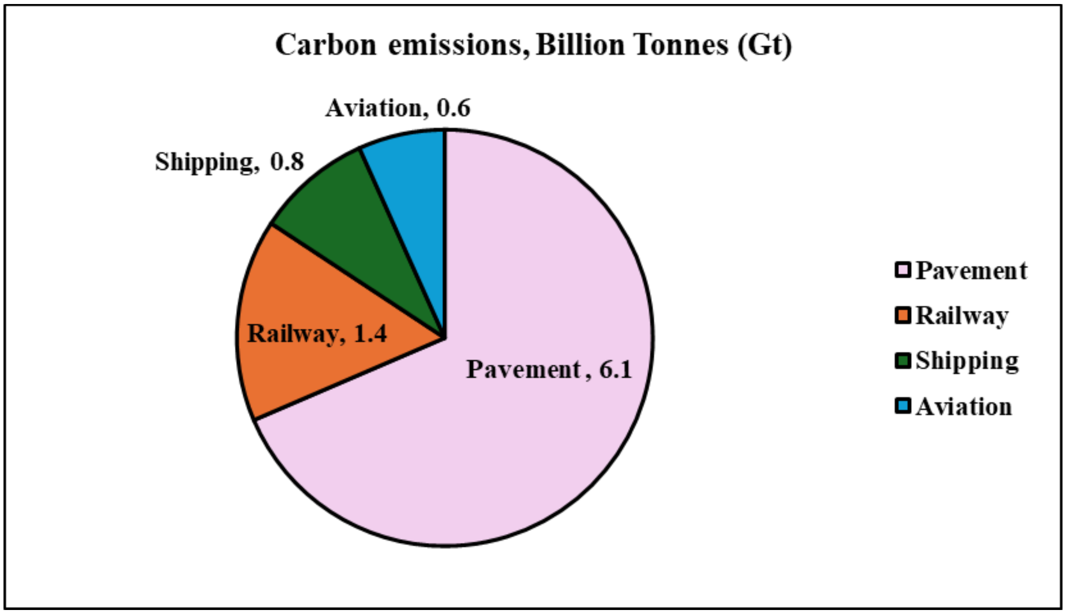


Figure 2.1: Contribution of transportation sectors to carbon emissions (Intergovernmental Panel on Climate Change (IPCC) 2022)

One systematic process that can be adopted to quantify these changes is life cycle assessment (LCA). In the pavement engineering area, LCA provides a comprehensive overview of the potential emission over the entire life cycle of pavement through a structured methodology to assess inputs and outputs starting from the raw material production to the end of the pavement's service life (Aurangzeb et al. 2014; Farina et al. 2017; Sukhija et al. 2022). Figure 2.2 demonstrates the complete LCA phases involved in the pavement life cycle along with their internal components. Among different LCA phases, the use phase often significantly impacts the environmental and economic burdens related to the pavement (Araújo et al. 2014; Gillespie 1985; Robbins and Tran 2016; Sime et al. 2021). This phase is significant as it comprises factors such as rolling resistance, maintenance frequency and performance requirements, and the associated energy use (Trupia et al. 2017). Out of various factors, rolling resistance tends to be the primary contributor (Chatti and Zaabar 2012b; Trupia et al. 2017). In simple words, rolling resistance is energy dissipation as a vehicle tire rolls over the pavement due to the pavement-vehicle interaction (Sandberg et al. 2011; Willis et al. 2015). If the pavement is smooth, rolling resistance will decrease and vice versa. Pavement roughness or smoothness can be defined based on the expression of irregularities in the pavement, influencing the user's ride quality. For a comfortable and safer ride, drivers generally do not prefer rough road segments. However, with traffic flow for several years, the pavement deteriorates, leading to increased pavement roughness and higher rolling resistance (Gupta et al. 2014). It considerably delays travel time and increases energy consumption.

From the context of quality assurance and quality control, continuous maintenance activities should be employed to limit pavement roughness. Although it will incur more costs associated with maintenance and repair, it substantially conserves the allowable road infrastructure budgets. If early maintenance activities are not performed, the increasing severity of pavement distresses and the higher roadway roughness levels will significantly impact vehicle energy use and the associated GHG emissions, primarily due to the altered pavement-vehicle interaction during the use phase (Wang et al., 2020). Statistics indicate that the use phase accounts for more than 50% of the environmental burdens associated with the entire pavement life cycle (Zhu et al., 2024). However, accurately evaluating the environmental impact of the use phase remains complex and uncertain and is often excluded from pavement life cycle assessments (LCA).

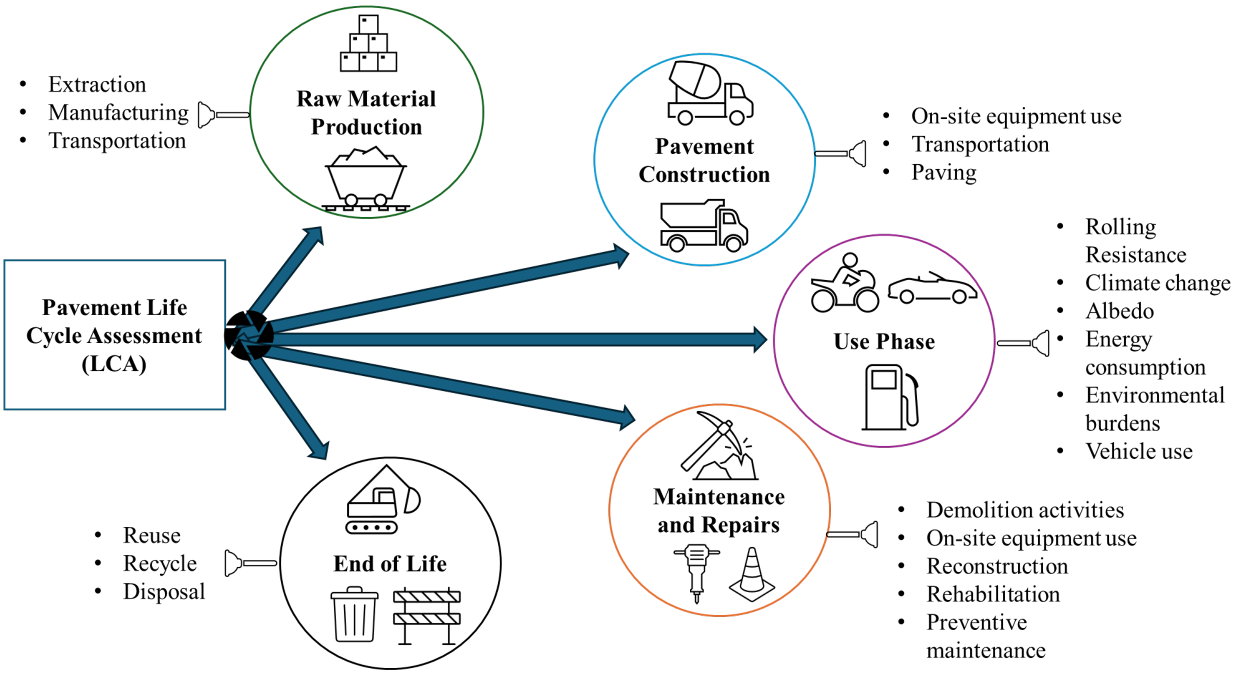


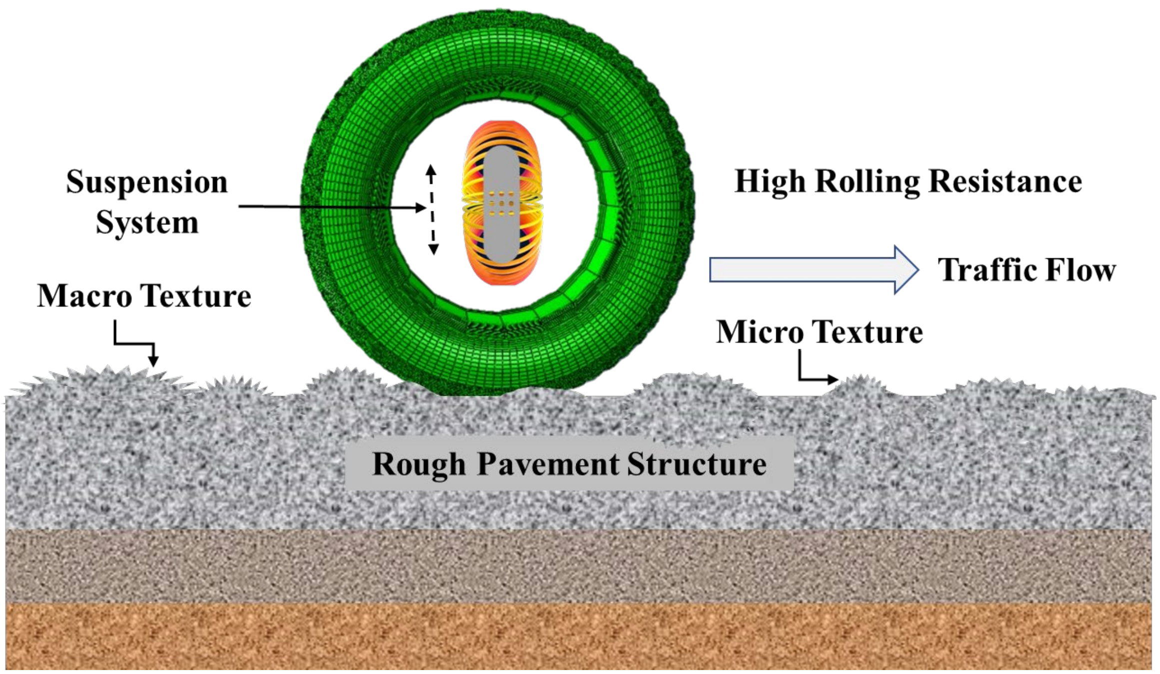
Figure 2.2: Pavement LCA phases

2.1.1 The Difference between Pavement Roughness and Texture

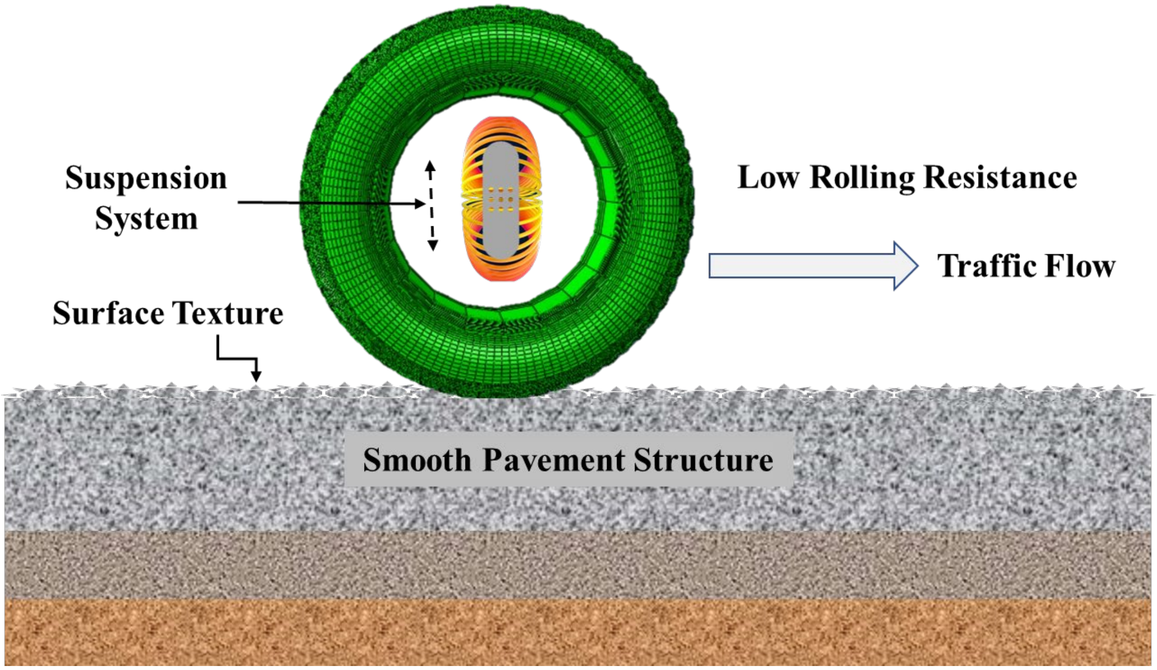
It has to be noted that the term pavement roughness is often confused with the surface texture, but these are distinct characteristics (Coleri et al. 2016; Coleri and Harvey 2017). Figure 2.3 shows the difference between the visual interpretation of these surface characteristics. The figure implies that rough pavement can have a high micro or macro texture on its surface, as can smooth pavements. In other words, a pavement surface with high texture, which leads to higher skid resistance, can still have lower surface roughness if the high texture is distributed uniformly across the roadway. Suppose the surface texture is nonuniform, which generally happens due to construction or material production issues. In that case, roadway roughness is expected to be higher due to the continuous vertical axle movement of the vehicle from high-to-low texture segments. In this study, the discussion is aligned with the pavement roughness, especially the irregularities, such as unevenness, undulations, or bumps, generally greater than 0.5 mm, as described in Table 2.1. These large-scale irregularities directly impact the tire pavement interaction and, consequently, the vehicle suspension and rolling resistance compared to the small-scale surface textures (Sun et al. 2024).

Table 2-1: Categories of pavement texture (Chatti&Zaabar 2012b; Sandberg&Ejsmont 2002)

Texture Wavelength	**Surface Irregularities**	**Influential Paramters**	**Major Influence**
<0.5 mm	Micro-texture	Friction	Tire Wear
0.5-50 mm	Macro-texture	Friction	Tire Wear, Rolling Resistance
50 mm-0.5 m	Mega-texture	Tire/vehicle	Rolling Resistance
0.5 m-50 m	Roughness	Tire/vehicle	Rolling Resistance



(a)



(b)

Figure 2.3: Visual interpretation of the difference between surface texture and pavement roughness (a) Rough Pavement and (b) Smooth Pavement

2.1.2 Roughness Data Collection and Processing Methods

From the perspective of a highway performance monitoring system (HPMS), it is essential to verify the existence of any pavement surface irregularities that could alter the users' serviceability. The surface irregularities are measured in terms of pavement roughness, which can be determined through different proposed roughness parameters. Each parameter has its own perks and perils, and their use/adoption solely depends on the state construction agencies. An ideal parameter should be one that can provide reliable and efficient measures of pavement characteristics and can be easily understood by stakeholders, construction agencies, and policy-makers. Most of the state agencies in the United States use the Present Serviceability Rating (PSR) with the Present Serviceability Index (PSI) and International Roughness Index (IRI) to measure road roughness (Perrone et al. 2015; Tamagusko and Ferreira 2023).

Pavement serviceability rating (PSR) is a subjective approach based on the operator's judgment (Perrone et al. 2015). In this method, the operator drives the truck over the pavement in question and subsequently rates the ride quality based on a subjective scale. The PSR scale ranges from 0-5, where 1 denotes poor ride, and 5 indicates excellent ride (Tamagusko and Ferreira 2023). PSR is generally measured in the present serviceability index (PSI), which changes with the time or movement of traffic, as shown in Figure 2.4. The change in PSI trend depends on many factors not limited to traffic conditions, climate, pavement surface characteristics, etc (Aleadelat et al. 2018b). Based on the development in this direction, very few state agencies use panel rating or 'PSR' as a common practice for evaluating pavement roughness; instead, they stick to using an effective and more quantitative parameter, i.e., the International Roughness Index (IRI) (Ksaibati et al. 1999).

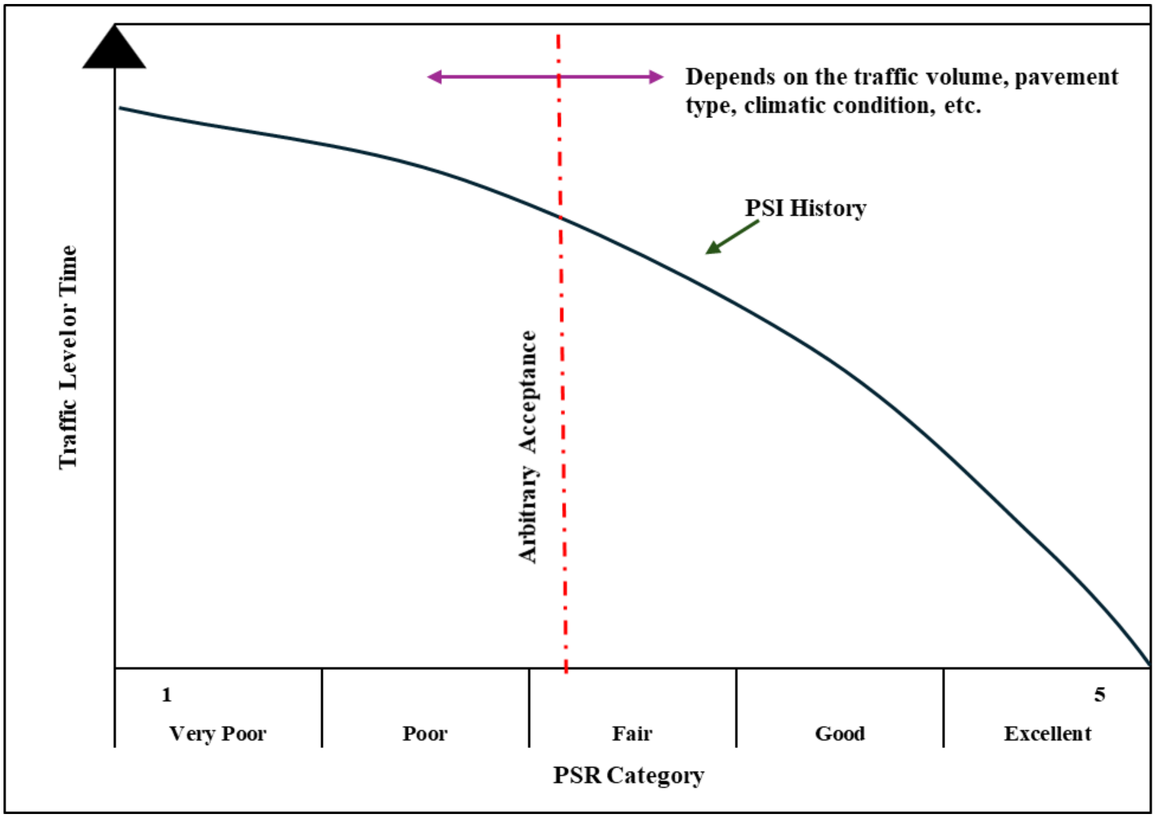


Figure 2.4: Change in PSI with different PSR categories (Perrone et al. 2015)

IRI is a more refined, accurate, and feasible approach for reflecting road roughness (Hettiarachchi et al. 2023; Múčka 2017). IRI was proposed in 1986 as an initiative of the World Bank Highway Development and Management System (HDM) (Sayers et al. 1986a). It is now specified in the standard specifications to determine the pavement roughness (ASTM International 2021). **Typically, IRI is the ratio of the accumulation suspension motion of a standard vehicle running at 50 mph or 80 kmph to the total distance traveled on a given pavement segment (Múčka 2017)**.

Following the data collection using a laser system, the measured pavement profile is processed using a Quarter-car simulation model (QCSM) to assess the actual roughness in terms of IRI. Currently, IRI is treated globally as a common quantitative road roughness scale. IRI is usually measured in inches/mile or m/km, and its scale range varies with respect to the pavement type, as shown in Figure 2.5 (Sayers et al. 1986b). As per previous statistics (Federal Highway Administration (FHWA) 2024), different states in the United States have different IRI and pavement surface smoothness levels, as depicted in Figure 2.6. The difference in these values is due to the variation in the type of road, traffic load, and environmental factors in different states.

According to the Federal Highway Administration (FHWA) (Perrone et al. 2015):

i) a pavement segment with roughness or IRI > 170 inches/mile or 2.7 m/km is ***"unacceptable for users and calls for early routine maintenance and repair"***, whereas

ii) a pavement with IRI < 95 inches/mile is considered as ***"good or very good"*** segments.

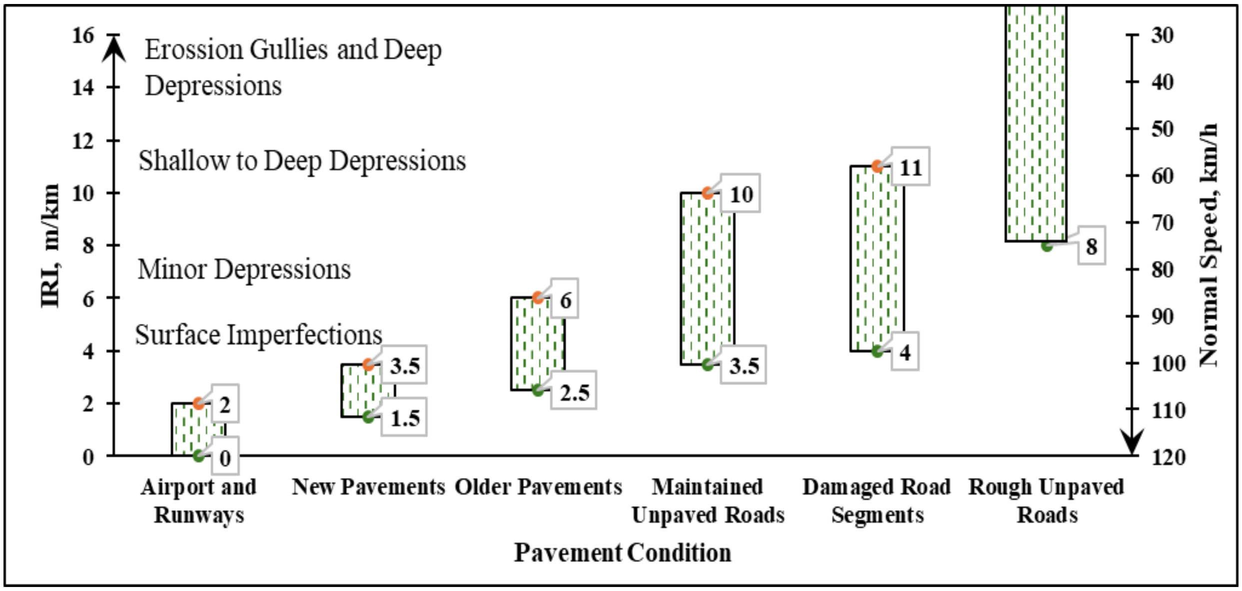


Figure 2.5: Range of IRI corresponding to different pavement conditions and their normal speed characteristics (Sayers et al. 1986b)

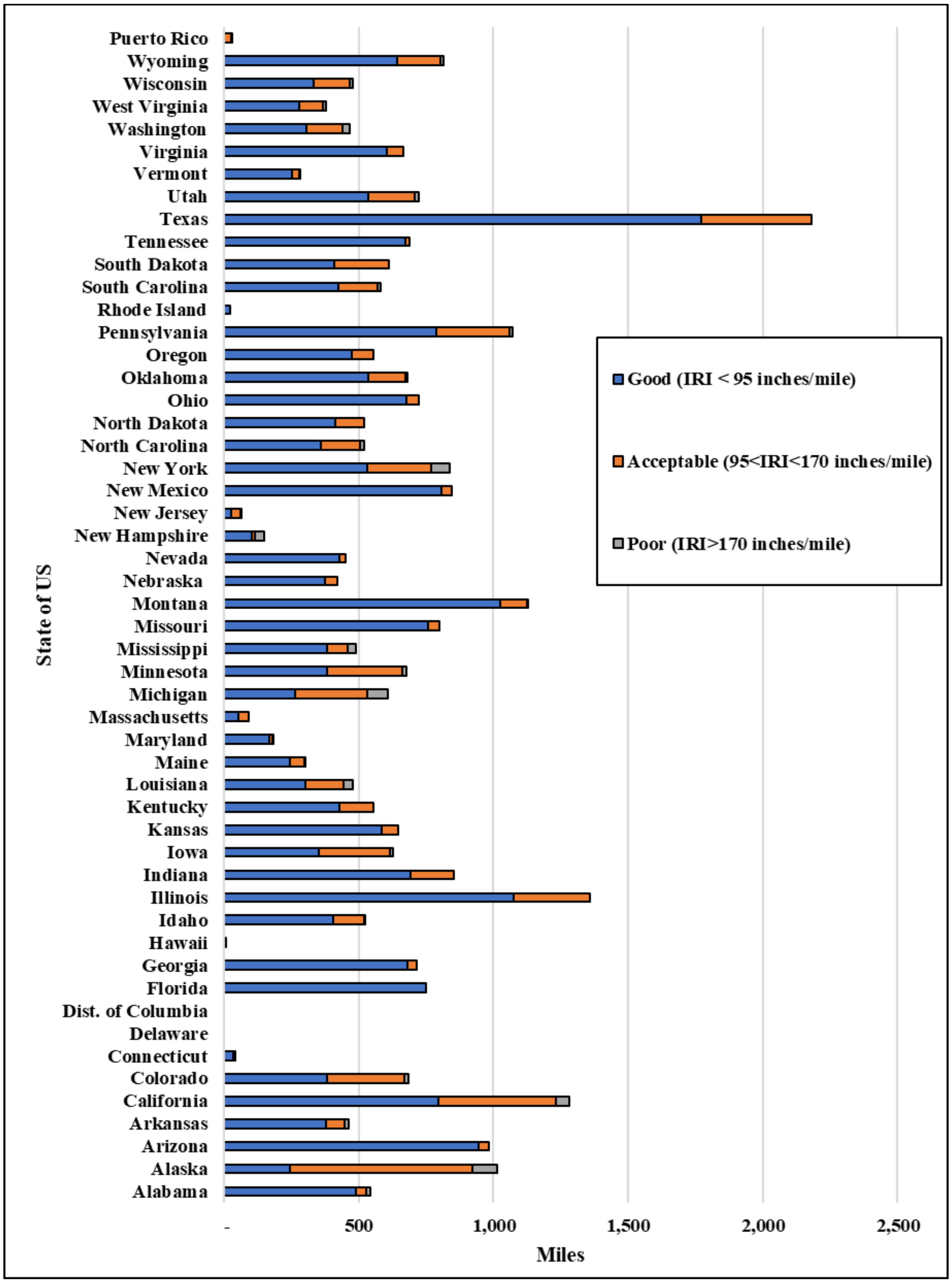


Figure 2.6: Pavement Surface Smoothness by State (Federal Highway Administration (FHWA) 2024)

Researchers also developed other indices and methods, including Ride Number (RN), South Dakota Index (SDI), Root Mean Square Vertical Acceleration (RMSVA), Riding Comfort Index (RCI), Ride Quality Index (RQI), Road Impact Factor (RIF), and many more, with IRI being the prevalent approach used widely (Bridgelall 2014; Ksaibati et al. 1999). The roughness level or the pavement quality obtained from these methods may or may not be the same due to their different mechanism, simulation models, techniques behind the approach, etc. Most of the methods are subjective and depend on the decision of the operator ratings, and the rating may change with the change in operator. Thus, subjective methods are generally not preferred as they may indicate inaccurate and ambiguous trends. Although IRI is often used to predict pavement roughness characteristics, a more effective pavement index for airfield segments was proposed in a previous study (Loprencipe and Zoccali 2019). This Index, typically defined as the Boeing Bump Index (BBI), relies on the aircraft fatigue initiated through rough pavement surfaces. A strong correlation exists between BBI and IRI with an R^2 value of 0.91, particularly for short wavelength roughness. On the contrary, the correlations become weak when the complete data set or the large wavelength roughness is taken for the analysis, as indicated by an R^2 value of 0.11. This suggests the impracticality of the BBI for pavement sections with high roughness characteristics.

Besides selecting the roughness index, deciding on the roughness measuring device used for data collection is challenging since several devices are available worldwide. The working mechanisms of measuring devices differed from each other, hence their data valuation and accuracy. With the advent of time, different devices have been developed to collect the roughness survey data, ensuring high accuracy and less operating time. Table 2.2 presents a brief description of these devices.

Table 2-2: Details of the developed roughness measuring devices and techniques (Múčka 2017; Ningyuan et al. 2001; Pierce et al. 2013; Wambold et al. 1981)

Roughness Measuring Devices/Techniques	Complexity	Mechanism	Inferences
Rod and level survey	Most simple	Elevation change measured by a survey crew member.	Impractical and unaffordable for large projects.
Dipstick profiler	Simple	Measure elevation using an inclinometer and digital displays.	Used to calibrate more complex equipment but feasible for small quantities of pavement profile measurement.
Profilographs	Simple	Consists of a sensing wheel that measures the vertical motion based on a reference plane.	Not recommended for network condition surveys but can detect surface irregularities up to 20 feet in length.
Response type roughness meters	Complex	Measured using a Bump Integrator or any other road meter, it comprises a displacement transducer that correlates vertical response with travel time.	Indicates the necessity of maintenance and repair on the road but poor time stability and reproducibility.

Profile recordation	Very complex	Measures longitudinal profile through the concept of the inertial reference system with the use of accelerometers and profilers (laser system). These sensors are mounted on the vehicles to measure the vertical displacement.	Getting more attention in recent times throughout the globe due to its accuracy, reproducibility, and reliability, but it is costly. Few systems are sensitive to climatic conditions.

Apart from these commonly used devices and techniques, various accelerated methods have been suggested in past studies due to the complexities involved in operating the devices mentioned in Table 2.2 (Alatoom and Obaidat 2022; Aleadelat et al. 2018a; Bisconsini et al. 2021; Du et al. 2016). While some of the accelerated methods are mobile application/software-based, some use location-based accelerometers combined with wireless systems to effectively and accurately reflect the information on the pavement roughness characteristics. However, their selection is entirely up to the state agencies dealing with the construction work.

2.2 CONTRIBUTION OF PAVEMENT ROUGHNESS ON CLIMATE CHANGE

The influence of climate change is getting prominent attention from environmentalists and policy-makers to reduce the environmental burdens originating from the pavements, especially in its use phase. In order to understand and reduce the actual environmental load in the use phase, there is a need to account for the pavement's roughness, which consequently controls the rolling resistance, vehicle fuel consumption, and GHG emissions (Sun et al. 2024). An accurate understanding of the relationship between pavement roughness and GHG emissions would aid in controlling carbon footprints globally, aligning with the goal of the Paris Agreement and Kyoto Protocol to stabilize GHG concentrations in the environment. The global initiative inhibits harmful human interference with climate change. Thus, regarding pavement infrastructure, transportation agencies worldwide are working in this direction by introducing new strategies for constructing sustainable pavements or optimizing the old pavements.

Pavement roughness contributes to the road user's rideability and comfort. Determining and constructing the pavement with a specific level of roughness is crucial. Pavements with high roughness are less enjoyable to drive on and increase vehicle energy consumption, carbon footprints, vehicle maintenance costs, and even pavement noise levels (Chatti and Zaabar 2012b; Hettiarachchi et al. 2023; Janoff 1982). From the perspective of structural design, uneven pavements (bumps) could lead to premature failure in terms of raveling, potholes, rutting, and cracking on the pavements due to the repetition of heavy impact load of vehicles just after the bump, which necessitates maintenance and rehabilitation before the end of their service life.

With every single truck pass, there is additional damage to the pavement in terms of increased roughness, which further leads to the development of additional vehicular dynamic loading (Misaghi et al. 2021). The increase in such dynamic loading is often overlooked during the pavement design. As a result, it continuously increases the rate of deterioration, such as rutting and cracking, and may be the probable reason for the underestimation of the pavement service life. The authors (Misaghi et al. 2021) also found that the rutting life was decreased by a factor of 2.08, and the fatigue life was reduced by a factor of 1.67 when the effect of vehicular dynamic loading (due to increased roughness) is considered in the pavement design models. In addition, Chandra et al. (2013) derived the correlation between IRI and pavement distress using partitioning of weight algorithms in artificial neural network (ANN) modeling. Overall, the correlation between IRI and distresses, such as total cracked area, potholes, and raveling, was found to be stronger relative to rut depth and patchwork.

The literature (Liu et al. 2024; Zhu et al. 2024) makes clear that the effect of pavement roughness significantly influences vehicle fuel consumption and corresponding emissions, which increases the cost (direct or indirect) and environmental burdens. Pavement roughness also causes premature pavement deterioration. Therefore, understanding the relationships and tradeoffs is incredibly important for economic and environmental justification for road maintenance and rehabilitation.

2.2.1 Impact on Energy Use

It has been reviewed that a considerable amount of energy is consumed during the use phase in the life cycle of road infrastructure. These estimates are generally overlooked when making decisions for pavement construction, maintenance, and rehabilitation (Ghosh et al. 2015). One of the critical estimates revolves around the energy dissipation in the vehicle's suspension system due to its vertical motion by the variation in road surface characteristics (level of roughness) during its use (Kim et al. 2019). Basically, road roughness affects the rolling resistance and, consequently, the vehicle energy consumption. In particular, a reduction in rolling resistance can improve fuel savings, estimating an increase of 1-2% with a 10% reduction in rolling resistance (Calwell et al. 2003). Another study showed that the construction of smoother pavements could lower vehicle energy consumption by 2% (Araújo et al. 2014). This percentage may seem low for an individual vehicle, but its influence would be remarkable as all the vehicles using the uneven pavement will be affected. The primary reason is that smoother pavements result in lower rolling resistance and lower fuel consumption, as it also leads to a slow rate of degradation relative to pavement with a high roughness level due to the dynamic load effect (Wang et al. 2012). Regarding pavement stiffness, stiff pavements have lower structural deformations, resulting in reduced rolling resistance than pavements with low stiffness (Bester 1984; Chupin et al. 2013). This effect may become more noticeable, particularly in high-temperature and heavy-loading conditions. Various studies have used different models to predict the effect of pavement roughness on vehicle fuel consumption. A few of the past studies in this direction are summarized next.

In an uneven pavement surface (high roughness), the energy dissipated in the suspension system is counteracted by the engine power of the vehicle, and thus, more energy/fuel is required for the movement of the vehicle. Louhghalam et al. (2015) prepared a mechanistic model to confirm this attribution, wherein the roughness-induced dissipations and the corresponding energy consumption are identified. Different categories of vehicles, including medium cars, SUVs, Vans, light trucks, and heavy trucks at varying vehicle speeds, were used for the model development. Unlike the Highway Development and Management System (HDM), HDM-4 (Chatti and Zaabar 2012b), where energy consumption and pavement roughness are linear, the developed model reveals a quadratic relation between the two parameters. The results indicated that the effect of the vehicle speed on the roughness-induced dissipation is insignificant. Thus, it rejects the hypothesis that variation in vehicle speed was thought to be a reason for high fuel consumption and confirms the importance of road roughness in this direction.

Ziyadi et al. (2018) conducted a sensitivity analysis and showed that the amount of energy consumption changes concerning the type of vehicle (passenger car, small truck, medium truck, and large truck) and their speed (6, 40, and 70 miles per hour). Findings from their study indicated a strong correlation between pavement roughness (in terms of IRI) and energy consumption. Among different vehicle types, passenger cars exhibit the most significant effect of roughness, particularly at high speed, whereas roughness and speed effects are not very sensitive for small and medium trucks. The estimates indicated that potential fuel savings resulting from decreased pavement roughness could reach up to 7% over a 35-year period, depending on the rehabilitation schedule. In addition, their roughness speed impact (RSI) model showed that one unit change in the value of IRI (1 m/km or 63.36 inch/mile) reflects around a 3% increase in fuel consumption. This amount can vary between 0.1% to 6% based on the analytical model used for the analysis, vehicle type and their speed, and uncontrollable variation during the field survey.

In a WesTrack project (Epps et al. 1999), the change in fuel economy was determined at varying roadway roughness using a heavy-duty truck. With the shift in IRI from 1.2 to 2.4 m/km, the fuel economy is reduced from 4.4 to 4.2 miles per gallon, accounting for a 4.5% reduction. The extent of variation in fuel consumption with the change in IRI also depends on the pavement type (Zhang et al. 2010). A previous study analyzed three pavement types: hot mix asphalt (HMA) overlay, concrete, and engineered cementitious composites. According to the authors (Zhang et al. 2010), surface roughness is one of the prominent factors affecting the vehicle fuel economy or total life cycle energy consumption. Their sensitivity analysis indicated that the total life cycle energy consumption increases by 0.5%-3.5% if the annual IRI increment rate is 2% faster than the baseline scenario, depending on the type of pavements. The same calculation projects between 1%-5.7%, if the annual growth rate in IRI is 5%. Figure 2.7 clearly compares these results for different types of pavements obtained in the study by Zhang et al. (2010). Interestingly, these results were derived using a linear LCA model developed based on the outcomes of the WesTrack project (Epps et al. 1999). The authors assured that the model can be applied to any state pavement system by altering the local traffic parameters.

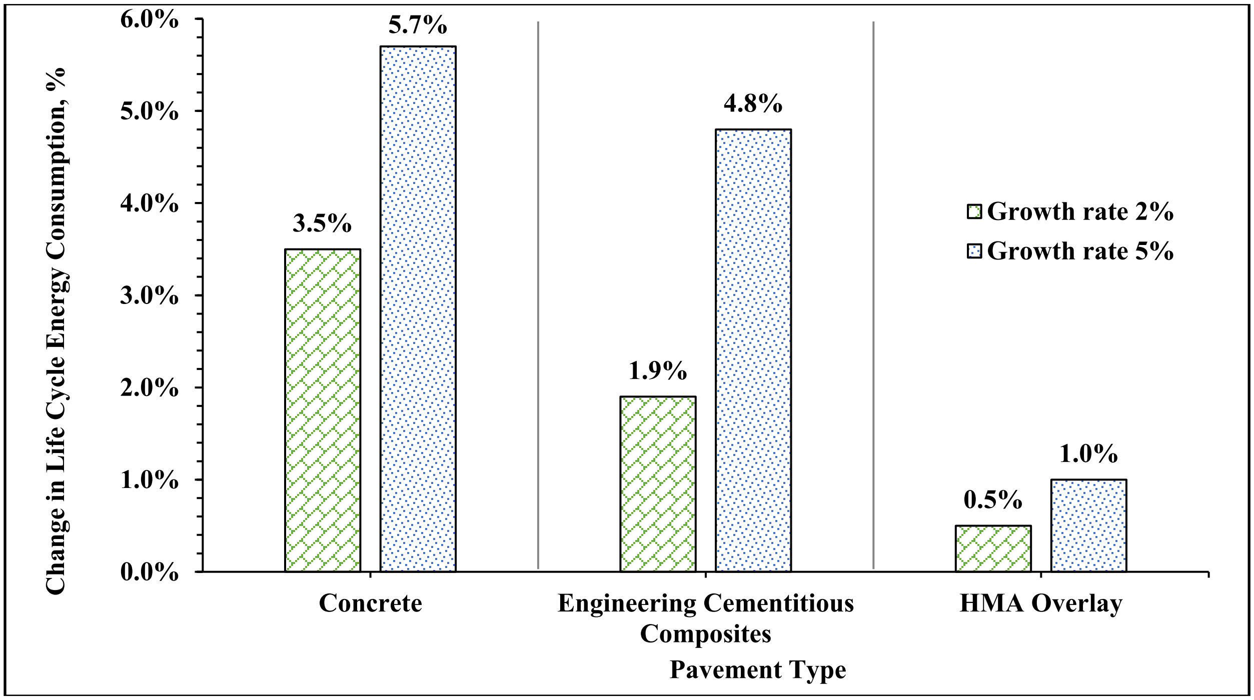


Figure 2.7: Percent change in life cycle energy consumption with the increase in IRI at different growth rates (Zhang et al. 2010)

Similarly, the change in fuel consumption with the pavement roughness was also demonstrated in another study (Wang et al. 2012). Four rural roads with different materials and traffic volume combinations were analyzed using an LCA model. The modeling was done by considering different materials used in the production of pavement, roughness level, traffic growth rate, etc., to compare energy consumption during the production of raw material, construction phase, and use phase. The research team indicated the significance of the use phase over the material production and construction phases as far as fuel consumption is concerned. It was found that adopting a smooth rehabilitation (implying that IRI is down to 1 m/km) on a pavement segment results in about 2.5% lower annual fuel consumption, particularly in the use phase of LCA. This amount is equivalent to approximately 0.5-0.6 million equal liters of fuel used by the vehicles on a one-way pavement section with a length of 16.1 km. Similar to the study conducted by Zhang et al. (2010), at 0% traffic growth rate and smooth rehabilitation, the savings in energy consumption during the use phase were found to be more significant in the case of concrete pavement, indicated by 5.5-6 times the savings observed in asphalt pavements. The variation in the energy consumption of both pavement types is because the obtained results were not normalized for the traffic and analysis periods. A long analysis period was considered in concrete pavement (10 years) compared to asphalt pavements (5 years), leading to more cumulative savings. Regarding traffic volume, the pavement segment with relatively high traffic volume results in more energy savings, irrespective of the pavement type, as depicted in Figure 2.8.

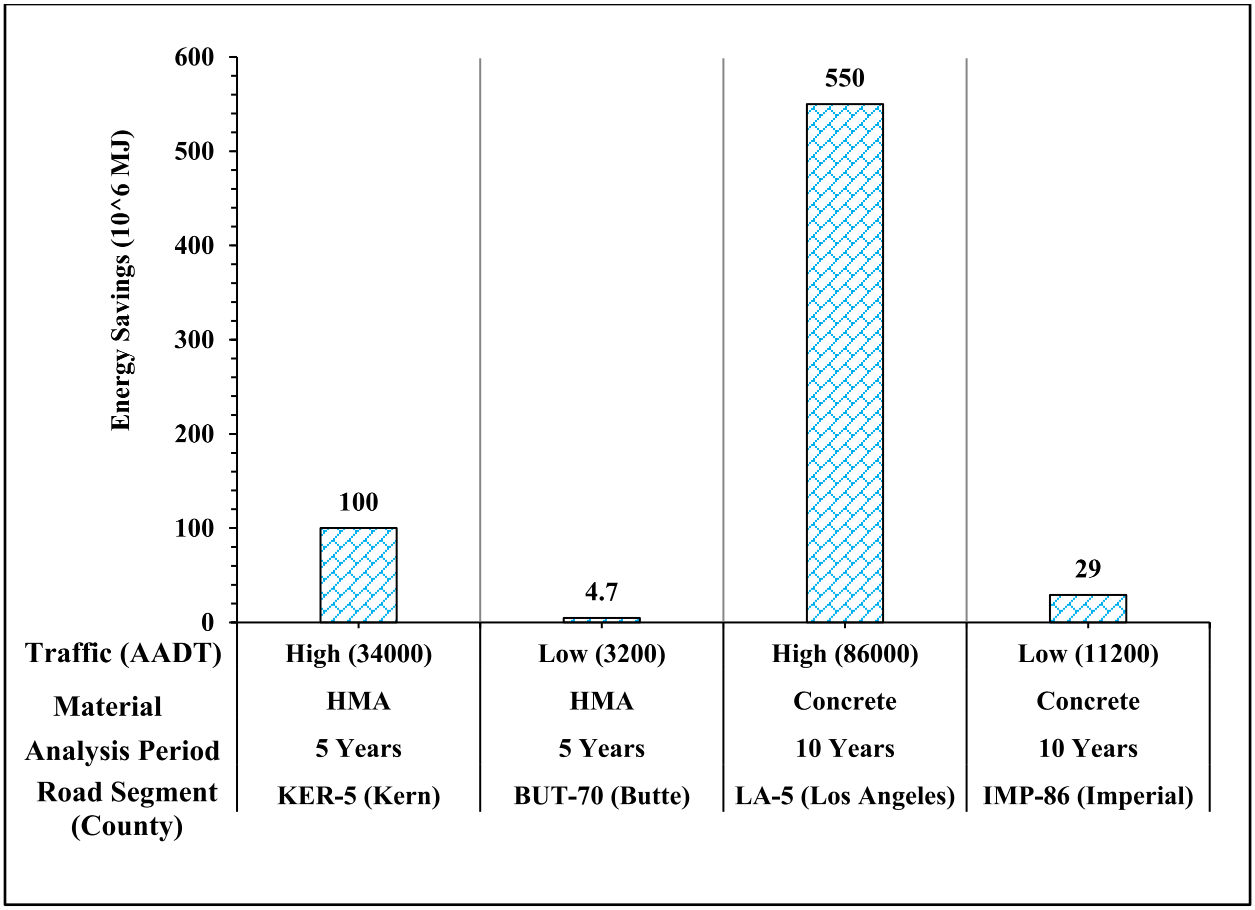


Figure 2.8: Energy savings due to reduced roughness (Wang et al. 2012)

Alam et al. (2020) evaluated the percent change in fuel consumption with the change in IRI using different vehicle types based on a staggered approach of dividing roughness into three interval levels. Similar to the findings of other studies, an increase in IRI increases fuel consumption. Nevertheless, the actual estimate depends on the vehicle type, as represented in Figure 2.9. The authors recommended that the vehicle type be considered when assessing the effect of pavement roughness on the vehicle's energy consumption. Based on their analysis, medium cars and large cars require more fuel, followed by buses/trucks and big trucks, regardless of the IRI range. Considering the effect of vehicle type, Ko et al. (2009) examined two pavement segments with different roughness levels and showed that the fuel consumption (Litre/100km) of medium and large cars rises seven times faster than the increase in IRI around 3.5 m/km, at speeds between 40 and 100 km/h. A few studies in the literature revealed that fuel consumption increases by 1% with an increase in IRI by 1 m/km (Islam and Buttlar 2012; Zaabar and Chatti 2010). On the other hand, Azevedo et al. (2021) found that a unit increase in IRI reflects a 3.5% increment in fuel consumption.

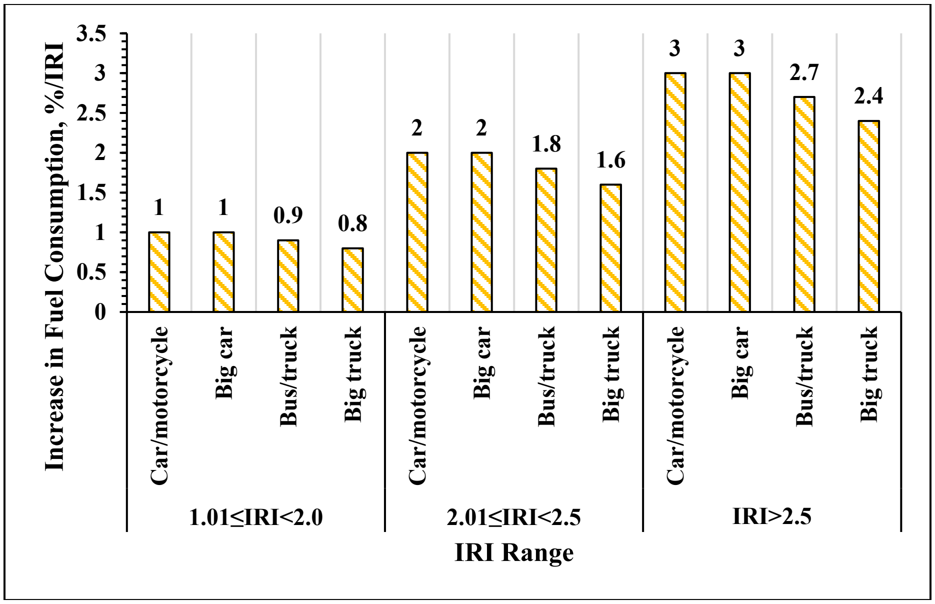


Figure 2.9: Increase in fuel consumption for different vehicle types at different IRI ranges (Alam et al. 2020)

Overall, an increase in pavement roughness or unevenness leads to more bouncing of vehicles, indirectly increasing fuel consumption. Even a small change in pavement roughness can cause a noticeable variation in vehicle fuel usage trends. The emissions may rise up to 700 times higher than the construction phase estimated in an analysis period of 20 years (Araújo et al. 2014). Since the fuel consumption due to high levels of roughness is higher (around 15-20%), it can be considered to have a significant environmental impact (Louhghalam et al. 2017). Based on the review of past studies (van Haaster et al. 2015; Hernandez et al. 2017; Kumar and Gupta 2021; Sun et al. 2024; Wang et al. 2020), the complex interaction between pavement roughness and fuel usage is associated with different factors, including the model used for the analysis, traffic condition, vehicle type and speed, vehicle tire condition, and type of pavement surface. A few studies in the literature (Chen et al. 2023; Zhu et al. 2024) also divulged that the key variables affecting pavement roughness and fuel consumption depend on the climate, and their extent may differ in different climatic regions. This suggests that roughness-based studies should be explored for each state with regional climatic and traffic data to better understand its relation to vehicle energy/fuel consumption in the use phase of the pavement structure life cycle.

2.2.2 Impact on Carbon Emissions

Carbon emissions have risen globally and are expected to increase steadily if preventative measures are not undertaken. This rise is not ascribed to any individual source but rather the result of the combination of several other daily routine factors. However, regardless of the specific causes, this would significantly contribute to global climate change and further lead to environmental issues.

In terms of road infrastructure, similar to energy consumption, GHG is also influenced by pavement roughness, as shown in Figure 2.10. An R^2 value of 0.80 implies a strong correlation between the two factors. The compiled data was based on a previous study conducted by Alam et al. (2020), wherein the effect of roughness on carbon emissions was predicted. This variation in carbon emissions is primarily due to vehicle fuel combustion, which is generally affected by pavement roughness. It is well known that a strong relationship exists between fuel usage and the corresponding carbon emissions, suggesting that the more fuel usage, the more carbon emissions will be (Wang et al. 2012). A clear observation of this attribution is presented in Figure 2.11. This data was measured at a constant speed (30 miles per hour) considering different variables such as pavement types (asphalt and concrete), average vehicle mass (ranging from 3,000-7,000 pounds), and vehicle miles traveled (between 5,016-21,944 million miles/year) by a research team in the United States (Sumitsawan et al. 2009). Although a linear correlation was observed, there is a difference in fuel consumption and carbon emissions for both pavement types, as shown in Figure 2.12. This implies the significance of considering different influential variables in the pavement LCA, particularly in the use phase, where the difference is more noticeable.

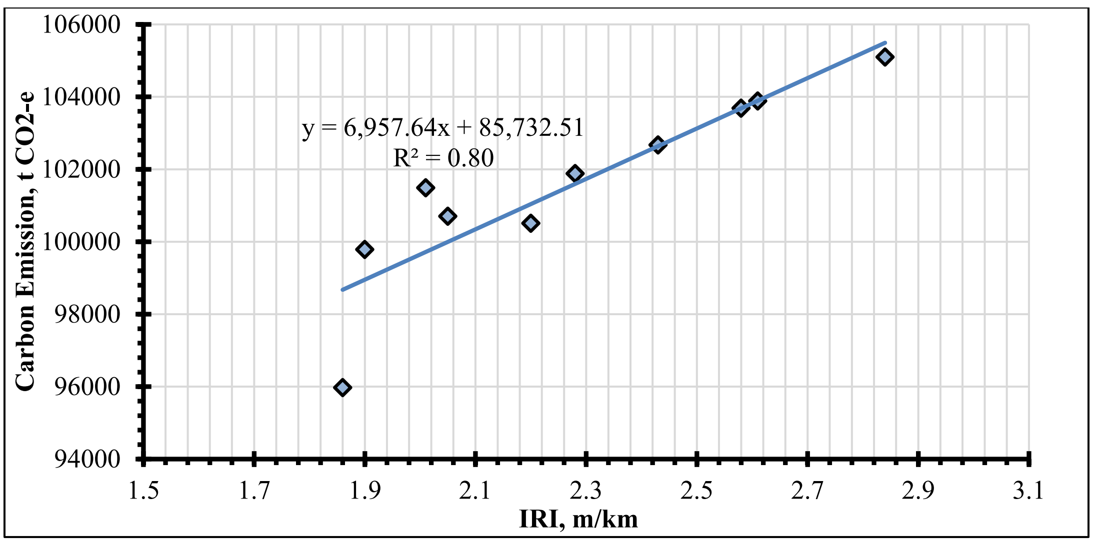


Figure 2.10: Relation between the pavement roughness (in terms of IRI) and carbon emissions (Alam et al. 2020)

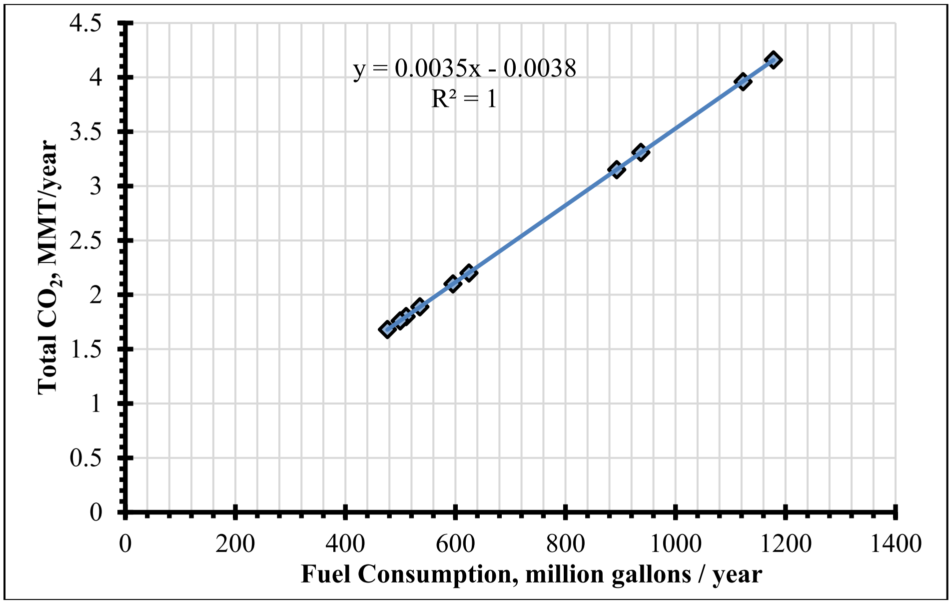


Figure 2.11: Dependency of carbon emissions on vehicle fuel consumption (Sumitsawan et al. 2009)

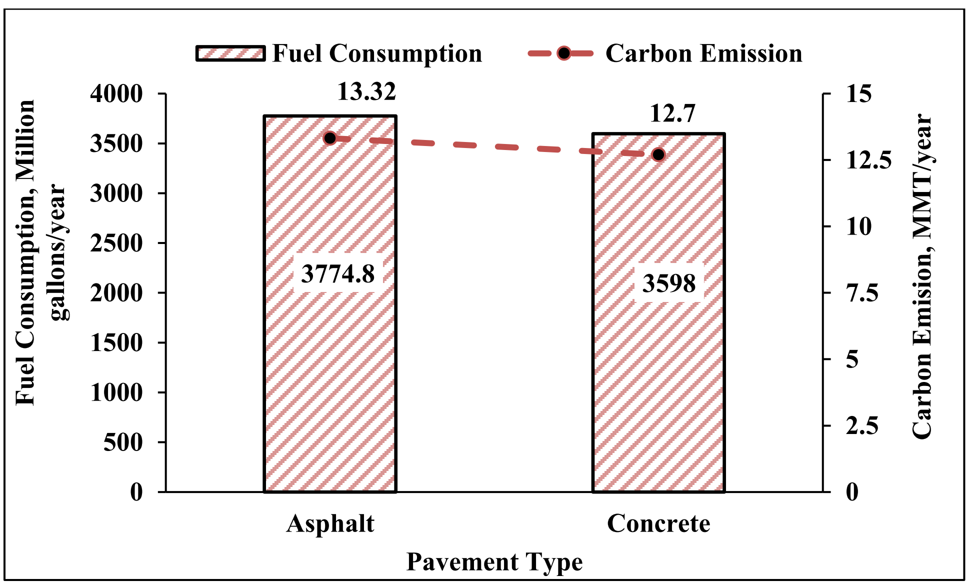


Figure 2.12: Fuel consumption and carbon emissions in the use phase on asphalt and concrete pavement (Sumitsawan et al. 2009)

Low rolling resistance or pavement roughness level leads to lower carbon emissions. To get a deeper understanding of this direction, Kawakami et al. (2020) performed a pavement environmental impact analysis incorporating different roughness levels. Four test sections of 300 meters in length were prepared with different evenness, i.e., 0.87 mm, 0.75 mm, 0.58 mm, and 0.55 mm. A single vehicle was driven over all the test pavement segments, and the exhaust gas concentrations were evaluated using a portable gas measuring device. The vehicle speed also varies to understand the effect of roughness more broadly. As per their LCA, the pavement segment with 0.58 mm and 0.55 mm evenness results in lower carbon emissions ranging from 1.3-5.3% and 1.8-6.6%, relative to the section with high roughness levels, respectively. Again, the reason is the vehicle's low rolling resistance on such pavement segments. Therefore, various construction agencies are working on specifying the appropriate roughness levels (in terms of IRI) on the pavements to achieve the desirable rolling resistance and control carbon emissions. However, maintaining a low and uniform level of roughness necessitates early maintenance and rehabilitation, eventually increasing the economic burdens and affecting the overall available budget. Thus, a proper decision process is required before the final implementation of any strategy. Only a few agencies worldwide are developing methods to make pavement maintenance and rehabilitation decisions by using a maximum limit of IRI, defined as IRI trigger, to lower vehicular emissions. Caltrans reduces the IRI trigger value to 2.86 m/km, irrespective of the pavement type, from 3.54 m/km for asphalt roads and 3.36 m/km for concrete roads, respectively (Wang et al. 2014). This shift is to overcome the budget limitation since it takes a long time to receive funding for maintenance and rehabilitation of the poor condition pavement, due to which the pavement roughness often surpasses the IRI trigger value and indirectly leads to higher carbon footprints.

Figure 2.13 shows the influence of reduced IRI trigger on the carbon emissions analyzed for a time period of 10 years compared to the *Do Nothing* strategy (no major rehabilitation). The analysis clearly showed that reducing the IRI trigger could aid in improving the environmental cost by a considerable amount, accounting for around 44% more reduction in CO_2-e. Also, the authors stated that timely rehabilitation of the deteriorated pavement is critical. If the maintenance and rehabilitation are delayed, then there will be a significant change in the rate of reduction in CO_2-e. For instance, a 1-mile section of the rural freeway with two lanes (per direction) was analyzed for a period of 10 years. The annual average daily traffic for one direction was approximately 12,000, and 10% trucks. To predict the rate of change in CO_2-e values, the authors consider an IRI trigger of 2 m/km, and the analysis was carried out by hypothesizing that the pavement treatment is delayed by 1, 2, and 3 years after the IRI crossed the selected trigger (2 m/km). The change in CO_2-e value with different hypothesized cases is shown in Figure 2.14. As can be seen, the reduction rate decreases with the delay in the treatment period. Compared to on-time treatment, the rate of CO_2-e reduction is 0.06, 0.13, and 0.18 times less when the treatment is delayed by 1, 2, and 3 years, respectively.

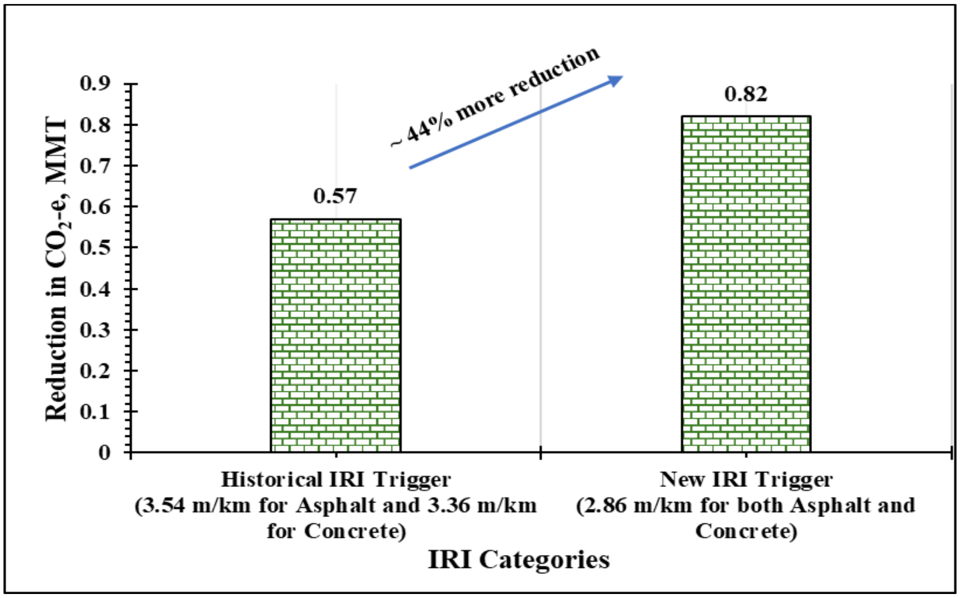


Figure 2.13: Reduction in emissions due to shift in IRI trigger value (Wang et al. 2014)

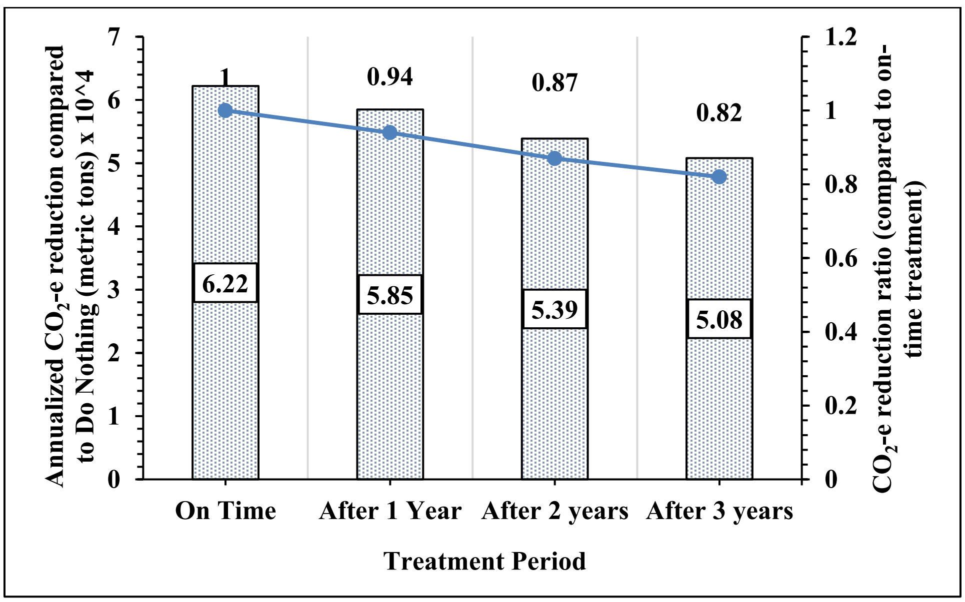


Figure 2.14: Reduction in emissions based on the delay in the rehabilitation period (Wang et al. 2014)

A research team also analyzed the variation in carbon emissions for different road segments categorized based on the IRI values (Azevedo et al. 2021). The authors determined that CO_2 emissions increase by 1.3% and 3.6% when the road quality (in terms of roughness) degraded from good (2<IRI<4) to regular (4<IRI<6) and regular to bad (IRI>6), respectively. This amount corresponds to the emission of a single test vehicle, and the quantity would be much higher if the total traffic volume using the pavement is considered in the analysis. Notably, the pavement with excellent quality (0<IRI<2) performs well in terms of ride quality as well as economic and environmental aspects.

Different analytical approaches, variables, and strategies to lower the carbon emissions imparted due to pavement roughness have been highlighted in previous studies (Liu et al. 2024; Louhghalam et al. 2017; Wintruff and Fernandes 2023). These studies reflect the data structure and analysis developed for a specific state using local test parameters. Nevertheless, it should be conducted for each state to support the global initiative for reducing carbon emissions due to the use of road infrastructure.

ODOT is looking forward to understanding and incorporating the effect of pavement roughness to mitigate the environmental impact of pavement roughness, as much as possible. Along with this initiative, ODOT is utilizing sustainable materials such as reclaimed asphalt pavement (RAP) in the construction work to produce eco-friendly pavement structures. Adopting RAP or any sustainable material for construction comes under the material and construction phase of the pavement LCA. On the other hand, the use phase of pavement LCA should also evaluate Albedo effects on urban heat island phenomenon, pavement roughness, climate change, lightning, carbonation, and leachates, with pavement roughness as the primary contributor (Chatti and Zaabar 2012b; Xu et al. 2019; Zhu et al. 2024).

Although the LCA of pavement in terms of material production, transportation, and construction are readily available, the LCA, including the effect of vehicular use phase (particularly pavement roughness), is comparatively less and often neglected. Nevertheless, pavement roughness considerably affects rolling resistance and is depicted as the key variable that alters GHG emissions. The carbon emissions in the use phase are far higher than those generated from the raw material production and construction phases, accounting for 1,000 times more carbon emissions (depending on the traffic volume) (Araújo et al. 2014). Thus, proper in-depth research will assist the policy-makers, environmentalists, stakeholders, and construction agencies in making appropriate decisions on the budget allocation to maintain and rehabilitate the deteriorated pavement concerning environmental impacts due to the unevenness in the road segment.

2.2.3 Impact on User Costs

It is well understood that pavement roughness intensively affects energy consumption and increases carbon footprint. These changes also directly or indirectly contribute to user expenses (Sime et al. 2021). The direct expenses include the cost incurred due to increased fuel consumption, wear and tear of vehicle tires, vehicle maintenance, etc. Balancing the comfort level with the costs can be crucial. With the deterioration in the pavement (in terms of roughness), more force acts within the tire, and thus, more power is dissipated in the tires, creating an additional burden on the vehicle engine (Sime et al. 2021). In addition, it is challenging for drivers to tolerate the effect of roughness or unevenness on the pavement for more than a few hours, especially when the IRI exceeds 150 inches/mile (Epps et al. 1999). To overcome this concern, drivers prefer smooth pavements in order to enjoy comfortable and safer rides, and they can also help avoid vehicle damage. However, the tradeoff is that selecting a smooth pavement may require a longer route to follow than usual, indirectly increasing travel time and fuel consumption (Islam and Buttlar 2012). Nevertheless, the extension in route often implies that the drivers need to spend more fuel, eventually increasing the overall travel cost, despite the potential benefits of a comfortable and safer ride.

Past scientific reports by the National Center of Asphalt Technology (NCAT) presented information on the direct and indirect costs that change with increased pavement roughness (Robbins and Tran 2015, 2016). Islam and Buttlar (2012) evaluated the change in user cost with variation in IRI forecasted using AASHTO MEPDG software. With the increase in IRI of the pavement from 63 inches/mile to 250 inches/mile, the total relative increase in user cost was around $0.053 per mile. Although the magnitude of the numbers is very low as it is the estimate of one vehicle, it becomes more significant when all the vehicles are considered for the analysis. For instance, a total of 10,000 vehicles with an annual average travel of 12,000 miles were considered for the analysis. The total cost per vehicle per vehicle was calculated and presented in Figure 2.15. For an adequate, smooth interstate highway with an IRI of 100 inches/mile, a single user could incur an additional $84/year compared to the reference IRI of 63 inches/mile. This extra amount could be around 629$ if the IRI is shifted to 250 inches/mile. In real-world applications, 250 inches per mile IRI is excessively high and is not feasible for many state highways and rural roads.

The analysis by Islam and Buttlar (2012) also showed the sensitivity of user cost to the traffic level, initial selected IRI, and analysis period. The research team stated that the user cost would be higher if the traffic movement is higher throughout the use phase of the pavement. With an increase in traffic level by 2,000 average daily traffic, the increase in user cost ranged from 20-25%, depending on the IRI. The authors recommended putting extra cost into maintenance (on time) to reduce pavement roughness and save millions of dollars in terms of user cost in the use phase.

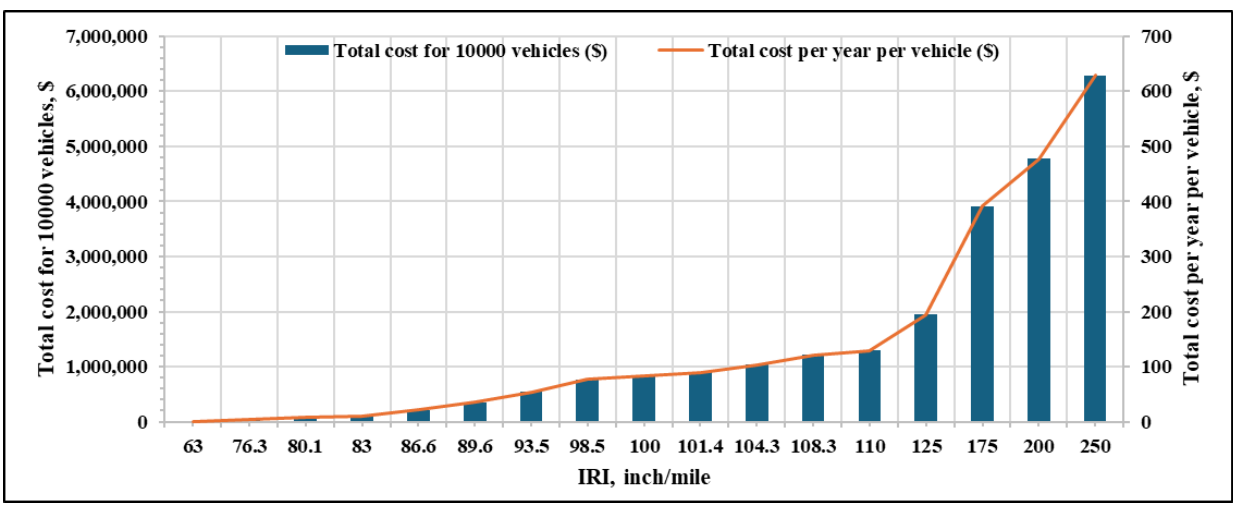


Figure 2.15: Variation in total cost at different IRI levels (Islam and Buttlar 2012)

Apart from the above-mentioned cost benefits with reduced roughness, extra savings can be anticipated in terms of maintenance and repair of vehicles, tire wear and tear, and depreciation. A previous study predicted that the cost associated with these components increases when pavement roughness goes over the baseline limits (Barnes and Langworthy 2003). Table 2.3 shows the increase in cost for different vehicle types due to extremely rough pavement surface (IRI = 170 inches/mile). This confirms that pavement roughness significantly affects the user as well as vehicle operating costs. Similarly, Amos (2006) observed that reducing an IRI from an average value of 130 inches/mile to 61 inches/mile leads to a reduction in the application of brakes by 58 times per night, resulting in the longevity of vehicle tires as well as brake pads, consequently lowering the repair and maintenance cost of the user. In addition, fuel efficiency improved by 2.46% with such a reduction in IRI. According to Chatti and Zaabar (2012b), a 3% decrease in fuel consumption with improved road conditions could save fuel costs as much as 24 billion dollars per year, considering 255 million passenger cars in the United States. Nevertheless, the economy's rate depends on the type of vehicle, wherein the cost effect is more significant on heavy trucks, followed by medium trucks, light trucks, pickups, large cars, medium cars, and small cars (Zaniewski et al. 1982).

Table 2-3: Increase in cost per mile due to pavement roughness (Barnes and Langworthy 2003)

Cost Components	**Increase in Costs per Mile**		
	Automobiles	**SUVs/Pickup/Van**	**Commercial Trucks**
Tire Wear and Tear	0.2 cents per mile	0.2 cents per mile	0.8 cents per mile
Maintenance and Repair	0.8 cents per mile	1.0 cents per mile	1.8 cents per mile
Depreciation	25% higher than baseline limits for each type of vehicle		

2.3 VEHICLE ELECTRIFICATION AND ITS POTENTIAL IMPACT ON ROUGHNESS-RELATED EXCESS EMISSIONS

Since fuel consumption is the major source of emissions generated while using the pavement, understanding the impact of vehicle electrification on this equation is crucial. In recent times, there has been a consensus that vehicle electrification (or electric vehicles (EVs)) is more environmentally sound than conventional fossil fuel-powered vehicles (Das et al. 2024; Hawkins et al. 2013). This strategy aimed to counteract the embodied carbon emissions emitted because of the excess fuel consumption due to increased pavement roughness. However, transitioning from fossil fuel-powered vehicles to EVs would take years to penetrate globally due to the challenges associated with EVs, including high prices, limited charging ports, lack of proper incentives, battery capacity, expected heavy load on the grid, and safety concerns (Abdul Qadir et al. 2024; Mahmud et al. 2023). While noticeable reductions may not be apparent before 2030, significant future environmental and economic benefits are anticipated with EVs (Alam et al. 2020).

Only limited studies in the literature address vehicle fleet change as an effective strategy to control such emissions. In a case study by Barkh et al. (2022), the implementation of vehicle electrification lowers carbon emissions associated with pavement roughness. According to the research team, reducing the roughness-induced emission by as much as 25% is possible by replacing all fossilfueled vehicles with EVs. The lower emissions from EVs are attributed to the difference in the fuel economy and carbon footprints of electricity compared to conventional gasoline and diesel-based fuel sources. In another study, Chun et al. (2024) showed that the variation in the reduction rate in released carbon emissions with the use of EVs depends on the local traffic conditions, travel distance, vehicle type, pavement type, thickness of pavement, and traffic volume. They also reported that the reduction rate can be improved using fully EVs rather than hybrid EVs. Considering these influential variables, the predicted pavement roughness-based emissions can be lowered by 25-54% with the transition of vehicles from conventional to EVs. Using EVs leads to zero tailpipe emissions and promotes the mission of carbon neutrality (Ma et al. 2012). However, electricity and battery production also produce GHG emissions and harm the environment. However, the carbon footprint of electricity has continuously decreased over the past several years, with the change in sources, making it a cleaner alternative in the long run.

Although EV manufacturing, especially their battery production, generates significant emissions, their overall life-cycle emissions are lower than those of conventional vehicles due to reduced emissions during use (Reichmuth et al. 2022a). The total lifetime GHG emissions caused by a gasoline sedan and truck would be potentially reduced by 52% and 57% with the use of electric-based sedan cars and trucks, respectively, assuming a 300-mile range battery (Reichmuth et al. 2022a). These estimates could be further improved by promoting the reuse of batteries, using sustainable materials and clean energy sources on the electric grid, and replacing fossil fuels with renewable and biofuels (Davies et al. 2024; Sanguesa et al. 2021). In the same context, Chun et al. (2024) determined the cumulative emissions, including the emissions generated due to the production of electricity, fossil fuels, and pavement roughness-induced emissions. As per their results, using EVs is beneficial in most cases, even when the amount of upstream emissions is considered.

Based on the description mentioned above, while vehicle electrification holds promise for reducing emissions associated with pavement roughness and overall life-cycle impacts, some challenges remain, particularly concerning battery production and the environmental impact of electricity sources. Research studies are currently focusing on integrating innovative and sustainable or cleaner material sources for battery manufacturing with the goal of low social and environmental impacts. In addition, the sources of electricity are becoming cleaner every year to maximize the benefits of EVs. Since the percent reduction in energy use depends on the geographic location, future studies should integrate local influential parameters as different states have different electric grids, environmental conditions, and vehicular traffic to predict the effect of EVs on pavement roughness-induced carbon emissions. In addition, when all vehicles are electric in the future, a major concern will be the impact of heavy electrification on the grid. Since smoother pavements reduce vehicle energy use, reduced roadway network roughness can potentially improve vehicle energy efficiency and contribute to reducing the load on the grid while the number of EVs is increasing within the next several decades. For this reason, initiatives to reduce roadway network roughness will always be critical, even when all the vehicles are electric.

2.4 SUMMARY

The pavement use phase contributes towards user costs and affects the environment in many ways, especially with respect to roughness-related excess fuel consumption. The pavement surface characteristics, particularly the roughness, are the primary contributors to such factors. As more fully explained in Section 2.1 above, pavement roughness is defined as the irregularities and unevenness over the road surface. Among the different available roughness measurement parameters, the International Roughness Index (IRI) is the most widely used and prevalent parameter that accurately reflects the pavement roughness characteristics. IRI values can be predicted/forecasted through various models and mathematical analysis using the data obtained through a reliable measurement device.

Maintaining the value of IRI within limits is crucial as it determines the quality and efficiency of pavement infrastructure, influencing driver comfort level, rideability, vehicle life, and environmental impacts. In fact, maintaining smoother pavements could translate to saving billions of dollars per year and thus facilitate economic growth. Consequently, proper maintenance and timely treatments are desired on the rough and deteriorated pavements. Rough pavements increase fuel consumption, produce more emissions, and necessitate more direct and indirect costs. In addition, roughness affects tire wear and tear and vehicle depreciation. The extent of each result (fuel use, emissions, costs, and wear and tear) associated with pavement roughness depends on local factors such as traffic volume, pavement type, vehicle type, climate, percentage of trucks, vehicle speed, and vehicle efficiency. Therefore, research should focus on identifying cost-effective and environmentally friendly strategies for reducing fuel consumption and GHG emissions generated due to high pavement roughness tailored to specific local conditions. Since the pavements deteriorate significantly when the damage accumulates, early pavement maintenance is critical to avoid excessive long-term pavement rehabilitation and reconstruction costs. For all of the reasons described in this paragraph, keeping the paving budgets at levels that are needed for periodic maintenance is essential.

The impact of the electrification of vehicles on pavement roughness-induced fuel consumption and energy use has not been extensively analyzed. Nevertheless, it is clear that EVs are not immune to the results caused by rough pavements. Additionally, it should be kept in mind that electricity and the components of an EV are also not carbon-free, and their production also results in GHG emissions. The potential challenges regarding the electrification of vehicles can be reduced by improving vehicle efficiency and smoother roads, which, in a sense, improve vehicle efficiency.

3.0 SUMMARY OF NETWORK-LEVEL PAVEMENT MANAGEMENT SYSTEM DATA

3.1 INTRODUCTION

The research team received detailed spreadsheets from the ODOT Pavement Management Office containing comprehensive information about the roadway network in Oregon, including pavement history (underlying pavement structure type), IRI over the years (2003-2022) (with some missing years), speed limits, truck and non-truck traffic data (only for 2021). This section summarizes the network-level pavement management system data used in this study.

3.1.1 Objectives

The major objectives of this section are as follows:

- Describe the parameters provided in the received spreadsheets.
- Define overall trends and summarize traffic, pavement types, and roughness data for Oregon's roadway network.

3.2 PARAMETERS OF THE NETWORK-LEVEL DATA

ODOT Pavement Management System (PMS) provided the network-level data for the roadway network managed by ODOT. The length of the entire ODOT Roadway network is 8,264.2 miles, according to the PMS dataset. The length of the concrete-surfaced pavement sections is 444.4 miles (around 5.4% of the total), while the length of the asphalt-surfaced sections is 7,819.8 miles (around 94.6% of the total). The total lane mile length of the roadway is 18,097 miles.

This study used two datasets provided by ODOT. The first dataset is IRI data based on ODOT roadway sections. The information shown below are the items from this dataset that were included in the calculations/simulations for the study.

- BEG MP: Begin mile post
- END MP: End mile post
- SECTION NAME: Section name in PMS
- SEC ID: Unique section ID for each roadway section
- LEN: Length of the section
- LM: Lane miles (number of road lanes * length of the section)
- 2021 AVG ADT: 2021 Weighted average 2-way ADT (Average Daily Traffic)
- 2021 AVG TRUCK ADT: 2021 Weighted average truck ADT
- SPEED: Speed limit

- PVMT_CATEGORY: Pavement structure type
- IRI VALUES: Average of left and right IRI for PMS segments - Includes bridges
- STUDY: Whether ODOT recommends using this section in the study or not
- Slope Future IRI: Estimated future IRI calculated from the ODOT's roughness progression model for the year entered

The second dataset was the IRI data based on the sections and surface number. The information shown below is the column titles from this dataset that were included in the calculations and simulations for this study.

- SECT_ID: Section name in PMS
- SURF_NO: Surface number for sections (the number is updated when maintenance is done for the section; a smaller number shows a more recent pavement surfacing).

3.3 SUMMARY OF PAVEMENT CATEGORIES

Figure 3.1 presents the type of roads under ODOT's control based on 2022 data. The graph shows that 17,003.5 lane miles of roadway are asphalt concrete (AC), accounting for 94% of the entire network, while concrete sections comprise approximately 5.8% (1,048.8 lane miles).

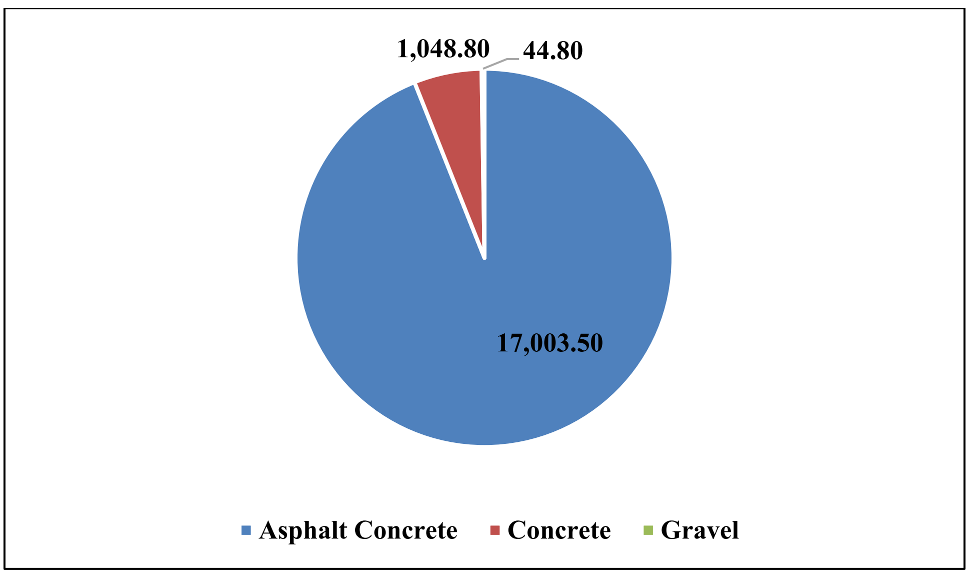


Figure 3.1: Distribution of ODOT-managed roadways by pavement category as of 2022, AC: 94%, Concrete 5.8%, Gravel 0.2%

Figure 3.2 shows the distribution of pavement surface categories. The graph shows that most Asphalt Concrete (AC) sections under ODOT control consist of dense-graded asphalt concrete (accounting for 54.7 %). Cold mix asphalt covers 16.4%, and open-graded asphalt surfaces 4.1% of the total roadway network. Besides that, approximately 3,000 miles of roadway have mostly asphalt-based maintenance treatments such as chip seal, fog seal, etc. It is important to note that this graph represents the most current pavement surface classification (as of 2022) and does not account for pavement thickness or underlying pavement categories. Based on the data presented in Figure 3.1 and Figure 3.2, focusing on asphalt concrete and asphalt surfaced roads to achieve a lower roughness roadway network, along with the application of recent innovations in materials, mix design methods, maintenance strategies, and construction techniques that ensure a smoother pavement surface (especially for the asphalt concrete (AC) pavement), is crucial for a more economical and sustainable future. For this reason, this research study quantified the impact of roadway roughness on vehicle operating costs (fuel consumption, tire wear, etc.) and the associated emissions.

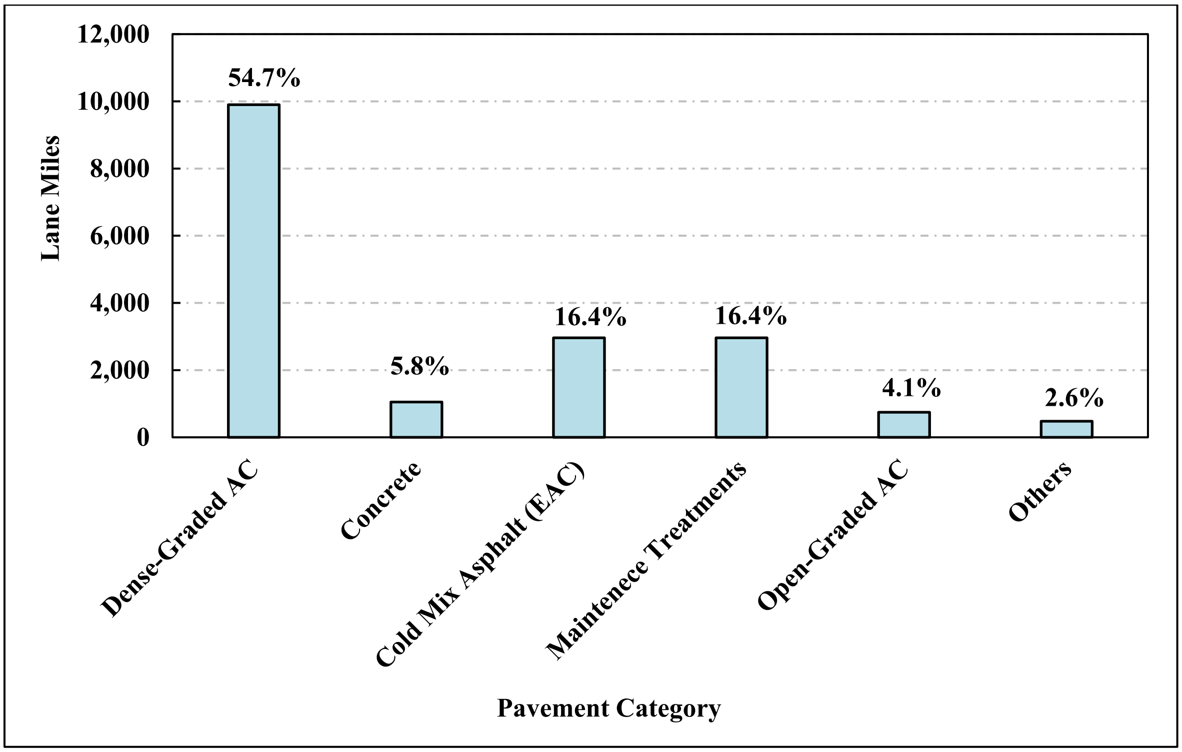


Figure 3.2: Distribution of ODOT's pavement types by percentage

3.4 SUMMARY OF TRAFFIC DATA

Figure 3.3 illustrates the distribution of lane mile length by average daily traffic (ADT), and Figure 3.4 shows the distribution of lane mile length by average daily truck traffic based on 2021 traffic data. According to ODOT pavement design guidelines (ODOT Pavement Services Unit 2019), roads with less than 3,000 ADT are classified as low-volume roads, those with 3,000-10,000 ADT are considered medium-volume roads, and roads with more than 10,000 ADT are classified as high-volume roads. Based on this classification, 43% of the roadway network consists of low-volume roads, 25% consists of medium-volume roads, and 32% is classified as high-volume roads, as shown in Figure 3.3.

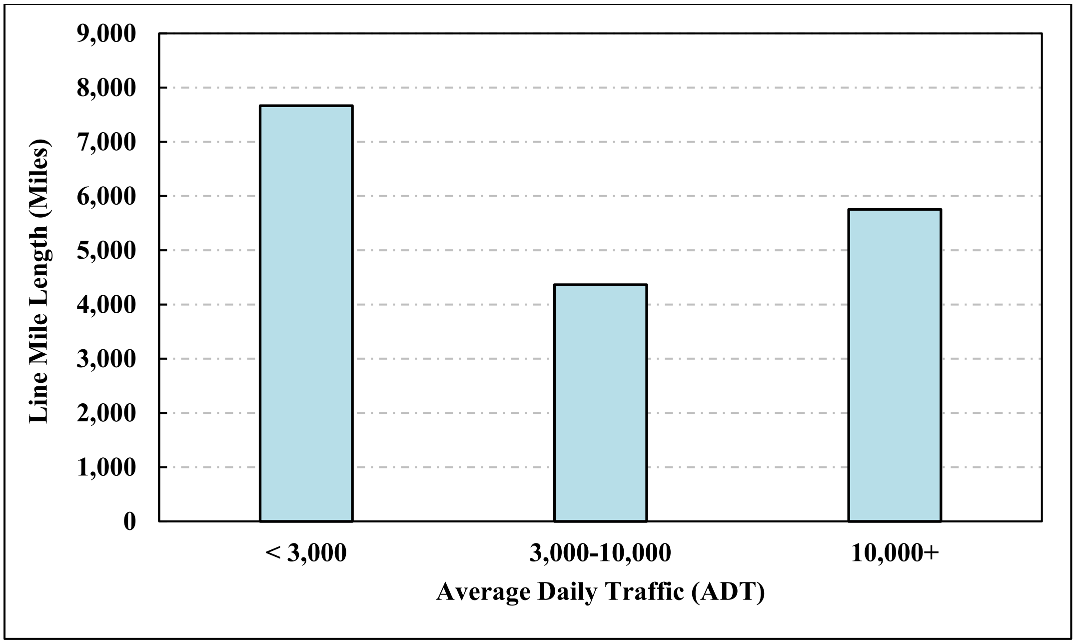


Figure 3.3: Distribution of lane mile length by average daily traffic (ADT) across ODOT roadways.

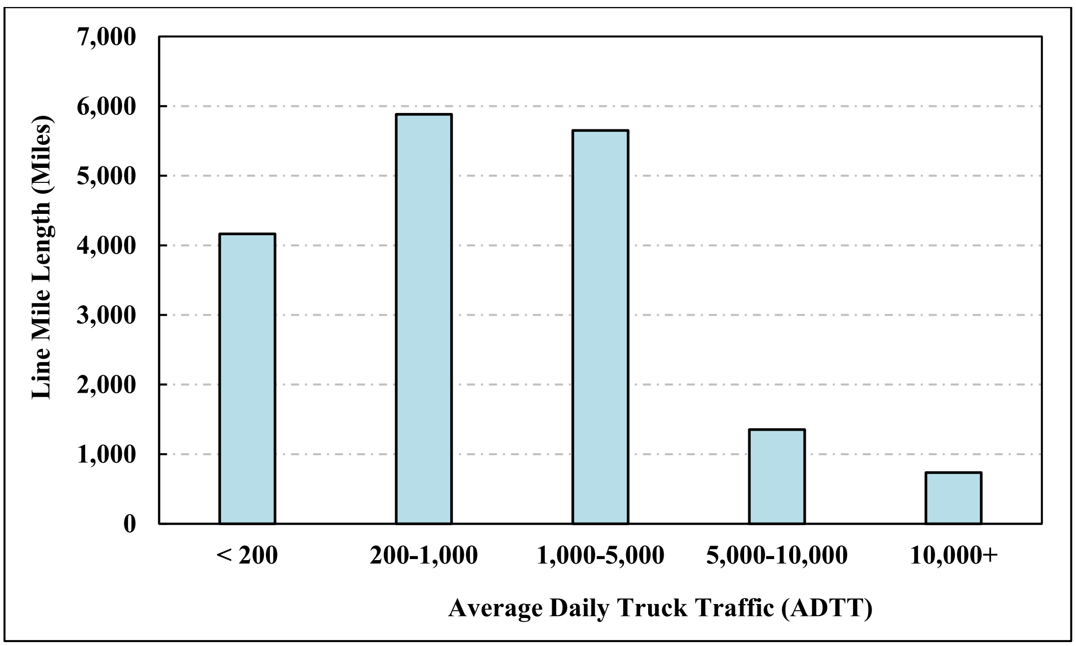


Figure 3.4: Distribution of lane mile length by average daily truck traffic (ADTT) across ODOT roadways.

3.5 SUMMARY OF IRI DATA

In Oregon, the International Roughness Index (IRI) data for most major high-traffic roadways is collected every other year. IRI data is also gathered post-construction for quality assurance purposes. For some sections (ramps, structure, low-speed sections), the collected IRI data was missing.

Figure 3.5 shows the IRI trends over the years. It should be noted that the data represents the lane mile-weighted average IRI (the sum of lane miles × IRI for each section / total lane mile length). The reason for showing even-numbered years is that IRI data is regularly collected during those years. No data pre-processing was applied when obtaining this graph (ramps and low-speed sections are also included in the analysis). If IRI data for a particular section was missing in the specified year, that section was excluded from the dataset and not considered in the calculation. Figure 3.6 displays the total length of sections excluded from the lane mile-weighted average IRI calculation due to missing IRI data for the given year. From this graph, it can be inferred that there was significant missing IRI data between 2004 and 2008. After 2008, IRI data collection became more consistent, and the average IRI values shown in Figure 3.5 for the years 2010-2022 were calculated using data from 83% to 89% of all roadways under ODOT's control, providing a broad representation of how IRI trends have evolved over the years.

Figure 3.5 shows that the IRI trend generally fluctuated between 92-98 in/mile from 2004 to 2010. After 2010, the IRI value displayed a significant decreasing trend until 2016. Between 2016 and 2020, a slight increase was observed compared to 2016. The average IRI value for 2022 was calculated as 87.7 in/mile, slightly below that of 2016. Figure 3.5 also shows a linear trend line from 2010 to 2016 (linear curve fit for the years between 2010-2016), projected for 2022. If the decreasing trend from 2010 to 2016 had continued, an average IRI value of around 80 in/mile would have been achieved for 2022. While there is a general decline in the trend, it can be concluded that the decrease in average IRI has slowed since 2016. As was also stated in the Introduction section (Section 1.0), the reductions in funding in previous years have already started to show their effects, as there has been a decline in pavement network conditions for all five regions in Oregon (Coplantz 2023) (see Figure 9 in the 2022 ODOT Pavement Condition Report). This decreasing trend in pavement conditions will result in a significant hike in IRI values within the next couple of years (meaning rougher pavement surfaces for road users). Consequently, the IRI values shown in Figure 3.5 will increase significantly within the next few years, reducing user comfort and vehicle operating costs.

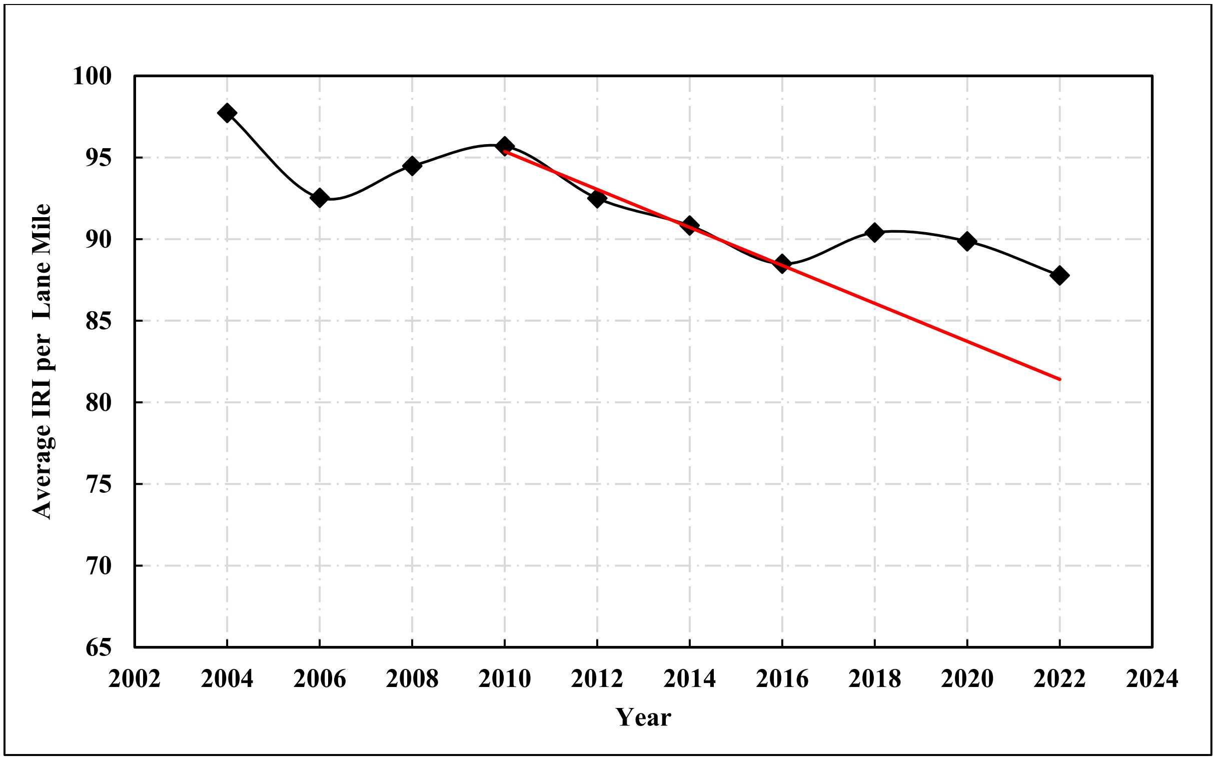


Figure 3.5: Lane mile weighted average IRI values over the years (The red line represents the curve fit for the observed downward trend from 2010 to 2016, with a projection extending to 2022)

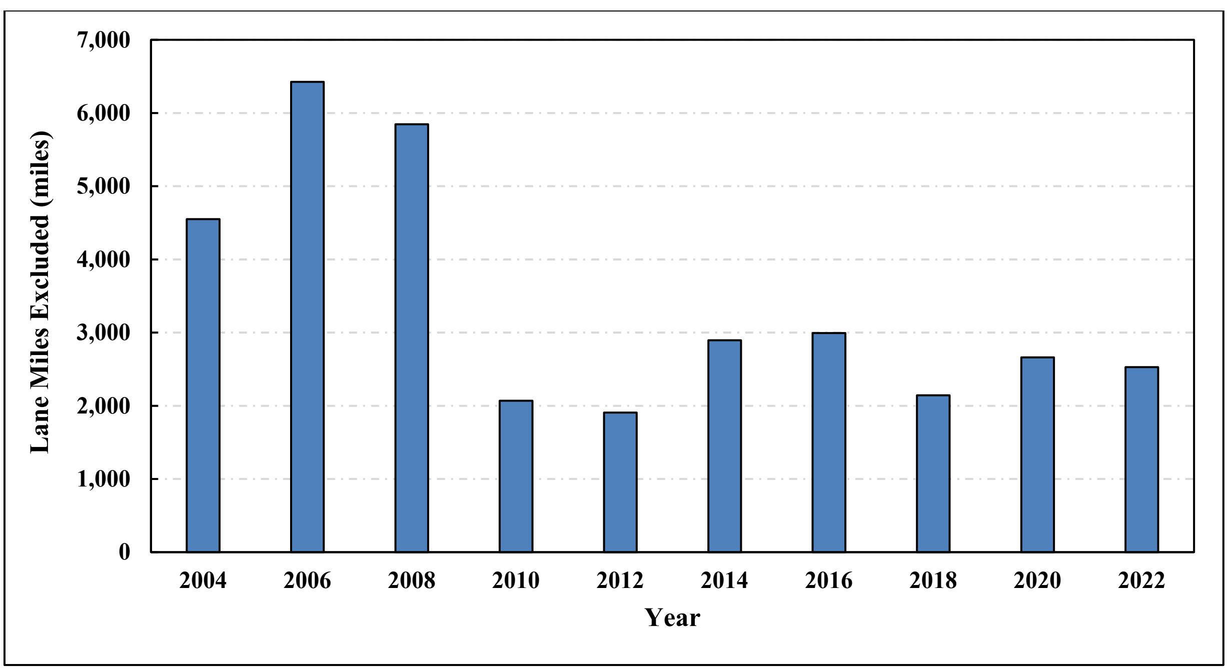


Figure 3.6: Annual exclusion of section lengths from lane-mile weighted average IRI calculations due to missing data

Figure 3.7 shows the relationship between Average Daily Traffic (ADT) and the Average International Roughness Index (IRI) per lane mile. The graph shows a clear trend where, as ADT increases, the IRI tends to decrease. This trend suggests that roads with higher traffic volumes are maintained more frequently, resulting in smoother pavement surfaces, as expected.

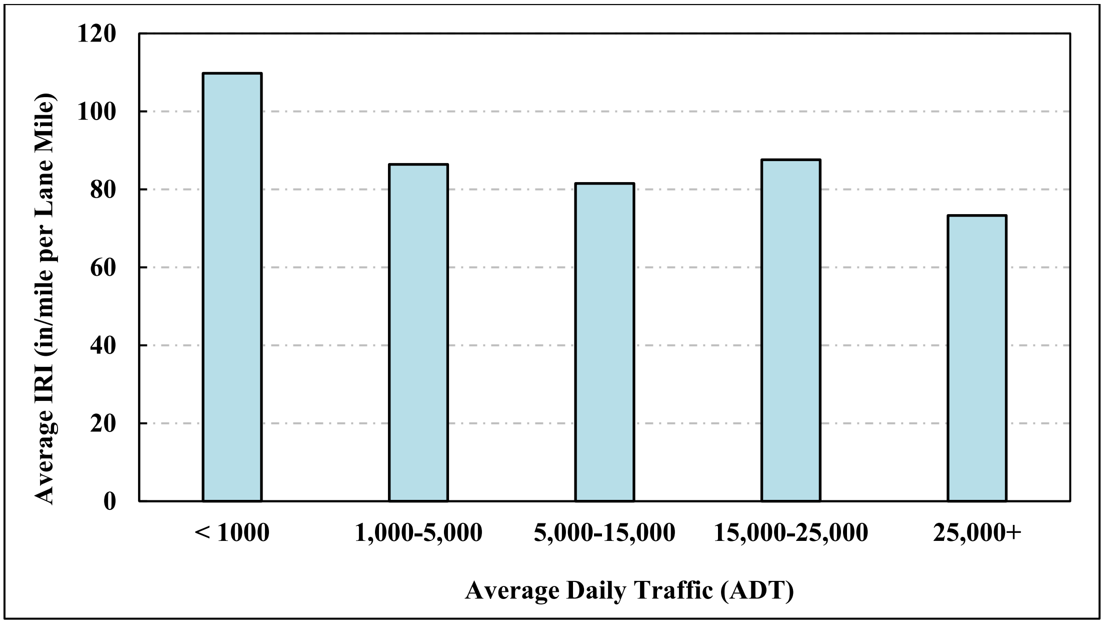


Figure 3.7: Relationship between Average Daily Traffic (ADT) and average IRI per lane mile

3.6 CONCLUSIONS

In this section, the ODOT Pavement Management System (PMS) data is summarized, and descriptive statistics are provided. The following conclusions are drawn from the conducted statistical analysis:

1. 94% of the roadway network managed by ODOT consists of asphalt concrete (AC), and asphalt surfaced pavements, while 5.8% is Portland cement concrete. Among AC sections, the most common pavement type is dense-graded AC, followed by cold-mix AC and open-graded AC. A significant number of asphalt-based maintenance treatments, such as chip seal and fog seal, were also observed.
2. Although a general decreasing trend in average IRI (roughness) has been observed since 2010, a slowdown in this trend has been noted since 2016. Since lower IRI numbers mean smoother pavements, funding and more frequent paving are needed to reduce the network-level IRI values. As was also stated in the Introduction section (Section 1.0), the reductions in funding in previous years have already started to show their effects, as there has been a decline in pavement network conditions for all five regions in Oregon (Coplantz 2023) (see Figure 9 in the 2022 ODOT Pavement Condition Report). This decreasing trend in

pavement conditions will result in a significant hike in IRI values within the next couple of years.

3. In general, roads with higher traffic volumes are observed to have smoother surfaces due to more frequent maintenance.

4.0 QUANTIFICATION OF NETWORK LEVEL ROUGHNESS RELATED EXCESS EMISSIONS AND THE ROAD USER COSTS

4.1 INTRODUCTION

As detailed in the literature review (Section 2.0), rougher roads generate higher dynamic loads and increase rolling resistance, which leads to excessive fuel consumption and faster tire wear. This increased fuel consumption and tire wear ultimately result in higher costs for users and excess GHG emissions. This chapter details how we analyzed ODOT Pavement Management System (PMS) data and used that data to predict future roughness conditions. It also includes projections for future traffic, fuel prices (gas and diesel), tire wear-related emissions and costs, and the anticipated volume of electric vehicles. This section also presents analyses for cumulative roughness-related excess fuel consumption, tire wear costs, and the associated CO_2 emissions over the past 20 years and estimates future costs and emissions under different maintenance scenarios for the next 10 years, considering ODOT's budgetary constraints and road paving strategies.

4.1.1 Objectives

The major objectives of this section are as follows:

- Detail the processing of ODOT PMS data and the adoption of the roughness progression model.
- Explain the assumptions made for projecting future gas, diesel, and tire prices and the associated carbon emissions.
- Outline the methodology and dataset used to predict the future volume of electric vehicles.

4.2 DATA PROCESSING AND ADAPTATION OF A ROUGHNESS PROGRESSION MODEL

ODOT Pavement Management System (PMS) data was summarized and explained in Section 3.0. Since achieving a clear trend for the sections with nine or more missing IRI data points between 2003 and 2022 was not feasible, those sections were removed to allow for more accurate analysis and predictions. ODOT also recommended omitting certain sections, such as very short sections, ramps, and low-speed areas, to achieve a more accurate dataset. After these omissions, the total road length was reduced from 8,264.2 miles to 4,662 miles. Cost and carbon emission calculations were performed for the 4,662 miles and linearly projected for the 8,264.2-mile-long ODOT roadway network.

4.2.1 Data Processing

Initially, sections that ODOT recommended not to be used for this research study (ramps, bridge decks, sections with very low-speed limits - where IRI data could not be reliably collected) were removed from the ODOT Pavement Management System (PMS) dataset. After removing those sections, there were still some sections where most of the IRI data was missing. To determine excessive fuel consumption and related CO_2 emissions for each year, complete IRI data is required, and any missing values in the dataset must be addressed. The research team developed and used the following criteria: If a section had more than 9 missing IRI data points between 2003 and 2022, that section was excluded from the dataset since it is not possible to capture a clear trend for roughness progression prediction. If a section had fewer than 9 missing IRI data points between 2003 and 2022, the missing IRI data was predicted based on the previous years' IRI increase and added to the spreadsheet i.e., if no maintenance was performed in the year with missing IRI data, and both the previous and following years' IRI data were available, the average of these two values was used. The average was then rounded down to the nearest integer.

The surface data provided in the spreadsheet was used for the calculations. Table 4.1 illustrates an example of IRI estimation. The surface type number in the second column changes when maintenance is performed on the existing pavement. As seen in the table, diamond grinding was conducted on the concrete pavement surface in 2021, significantly reducing the measured IRI values. In the same year, the surface type changed to 0 from 1. A lower surface type number indicates a newer pavement surface. As shown in Table 4.1, the IRI values for 2013, 2015, and 2017 are missing. It is evident that the surface type for the missing years is "1," indicating no change in the pavement surface. The IRI values were obtained by averaging the IRI data from the previous and following years and rounding down. Original IRI data and predicted IRI values (added IRI) for section I-5 PM 0-11.4 are also plotted and shown in Figure 4.1

Table 4-1: An example section showing IRI prediction (I-5 PM 0-11.4)

Section	Year	Surface No	Surface Type	Pavement Category	IRI Measured	IRI Predicted
I-5 PM 0-11.4	**2003**	1	-	CRCP	97	97
	2004	1	-	CRCP	98	98
	2005	1	-	CRCP	97	97
	2006	1	-	CRCP	101	101
	2007	1	-	CRCP	100	100
	2008	1	-	CRCP	101	101
	2009	1	-	CRCP	101	101
	2010	1	-	CRCP	101	101
	2011	1	-	CRCP	103	103
	2012	1	-	CRCP	103	103
	2013	-	-	-	-	103
	2014	1	-	CRCP	103	103
	2015	-	-	-	-	102
	2016	1	-	CRCP	101	101

	2017	-	-	-	-	100
	2018	1	-	CRCP	100	100
	2019	1	-	CRCP	100	100
	2020	1	-	CRCP	99	99
	2021	0	D. GRIND	CRCP	77	77
	2022	0	D. GRIND	CRCP	52	52

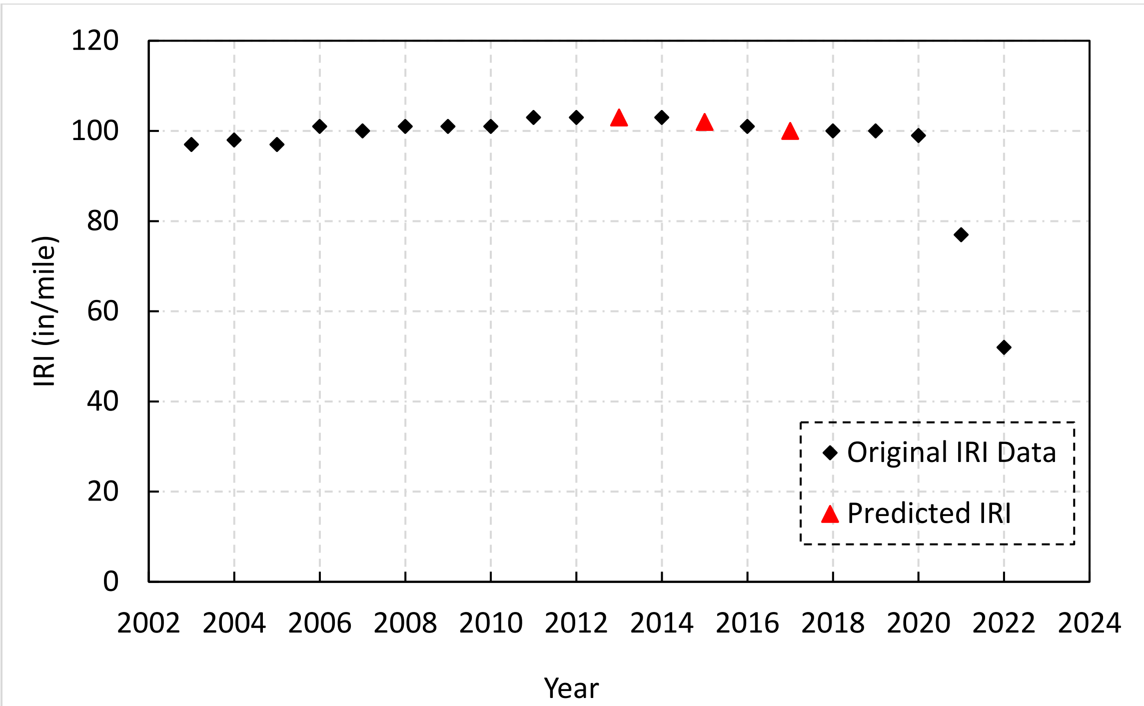


Figure 4.1: IRI estimation for missing data points (Section: I-5 PM 0-11.4)

If there is a missing surface number and IRI value between the old and new surface numbers, the algorithm assumes that a measurement was taken at the time of maintenance, and it copies the previous IRI and surface values instead of averaging, as shown below:

- **Surface Numbers: [1, ' ', 0]** (Data is always collected same year as maintenance, so the missing number can be assumed to be 1)
- **IRI numbers: [166, <u>166</u>, 95]** (Does not average 166 and 95, only copies 166).

If a missing number is surrounded by other missing numbers, they will also copy the closest same surface number IRI numbers.

- **Surface Numbers: [1, ' ', ' ', ' ', 0, ' ', ' ', 0]**
- **IRI numbers: [80, <u>80</u>, <u>80</u>, <u>80</u>, 56, <u>56</u>, <u>58</u>, 58]**

Another example of IRI prediction to fill the data gaps by following the process described in the previous paragraph is provided in Table 4.2 and Figure 4.2 for Section I-5 PM 240.4-241.3.

Table 4-2: An example section showing IRI prediction (I-5 PM 240.4-241.3)

Section	Year	Surface No	Surface Type	Pavement Category	IRI Measured	IRI Predicted
I-5 PM 240-241.3	2003	2	-	OGAC THK	115	115
	2004	-	-	-	-	115
	2005	-	-	-	-	115
	2006	1	-	OGAC	72	72
	2007	1	-	OGAC	72	72
	2008	1	-	OGAC	70	70
	2009	1	-	OGAC	80	80
	2010	1	-	OGAC	81	81
	2011	1	-	OGAC	82	82
	2012	1	-	OGAC	86	86
	2013	-	-	-	-	91
	2014	1	-	OGAC	97	97
	2015	-	-	-		99
	2016	1	-	OGAC	101	101
	2017	-	-	-	-	101
	2018	0	-	DGAC	68	68
	2019	0	-	DGAC	70	70
	2020	0	-	DGAC	72	72
	2021	0	-	DGAC	72	72
	2022	0	-	DGAC	67	67

Note: OGAC: Open-Graded Asphalt Concrete, DGAC: Dense-Graded Asphalt Concrete

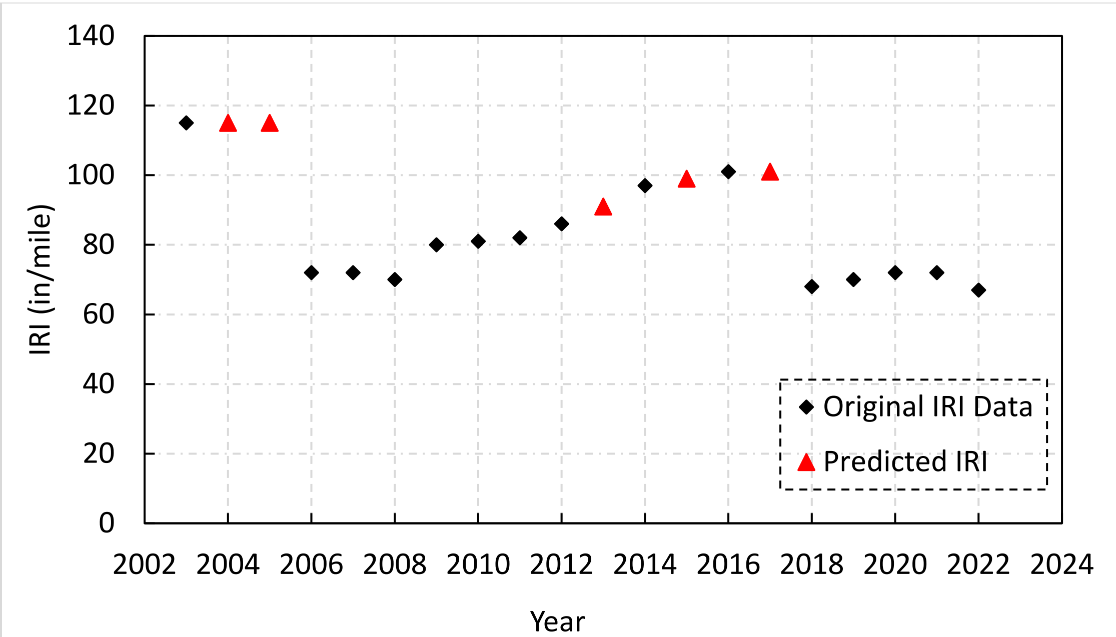


Figure 4.2: IRI estimation for missing data points (Section: I-5 PM 240.4-241.33)

Once the IRI data for all sections between 2003 and 2022 were calculated, the research team focused on adopting an IRI progression model that aligns with Oregon's traffic and climate conditions for future projections.

4.2.2 Roughness Progression Model Adaptation

For the future 10-year roughness assessments, the roughness of the roadways was predicted by adapting roughness progression models. Those models were developed by using the typical trends of the roughness change over the past years for different pavement types and surfacings. Then, those developed models for different roadway sections and traffic levels were integrated into the developed computer code to predict the future roughness of different pavement sections for the next 10 years.

4.3 ADOPTING IRI-BASED SMOOTHNESS METRICS FOR PREDICTING VEHICLE FUEL USE AND TIRE WEAR

The relationships between the International Roughness Index (IRI) and both fuel consumption and tire wear outlined in the NCHRP 720 report (Chatti and Zaabar 2012a) were utilized to determine the impact of pavement roughness on fuel consumption and tire wear. In the NCHRP 720 report, various vehicle classes (Medium Car, Van, SUV, Light Truck, Articulated Truck) were tested at different speeds (56, 88, 112 km/h – 35, 55, 70 miles/h) on pavements with various IRI levels (1, 2, 3, 4, 5, and 6 m/km) to assess the effect of roughness on fuel consumption and tire wear of the vehicles.

Table 4.3 shows the effect of IRI on fuel consumption. As seen in the table, 1 m/km IRI was selected as the base, and the increase in IRI resulted in an increase in fuel consumption, shown as "adjustment factors from the base value." The numbers in the columns (2, 3, 4, 5, and 6 m/km IRI) indicate the multiplier needed to find the fuel consumption corresponding to the respective IRI value. For example, for a medium car, fuel consumption on a pavement with 1 m/km IRI is 70.14 ml/km. For a road with an IRI value of 3 m/km, the fuel consumption increases by 5%, resulting in 70.14 × 1.05 = 73.65 ml/km.

The ODOT Pavement Management System (PMS) data provides only truck and non-truck traffic data. Therefore, this study used data for medium cars, SUVs, and articulated trucks. The data for these vehicle types, provided in Table 4.3, is plotted in Figure 4.3. An increase in IRI corresponds to an increase in fuel consumption. The graph also illustrates that fuel consumption increases with speed. Overall, changes in speed and IRI have a greater impact on truck fuel consumption compared to medium cars and SUVs.

Table 4-3: Impact of road surface roughness on fuel consumption (Data from Chatti and Zaabar (2012))

Speed	Vehicle class	Base (ml/km)	Adjustment factors from the base value				
		IRI (m/km)					
		1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13
	Van	76.99	1.01	1.02	1.03	1.04	1.05
	SUV	78.69	1.02	1.05	1.07	1.09	1.12
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11
88 km/h (55 mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13
	Van	96.98	1.01	1.02	1.03	1.04	1.05
	SUV	101.29	1.02	1.04	1.07	1.09	1.11
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08
112 km/h (70 mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12
	Van	128.96	1.01	1.02	1.03	1.03	1.04
	SUV	140.49	1.02	1.04	1.06	1.08	1.10
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06

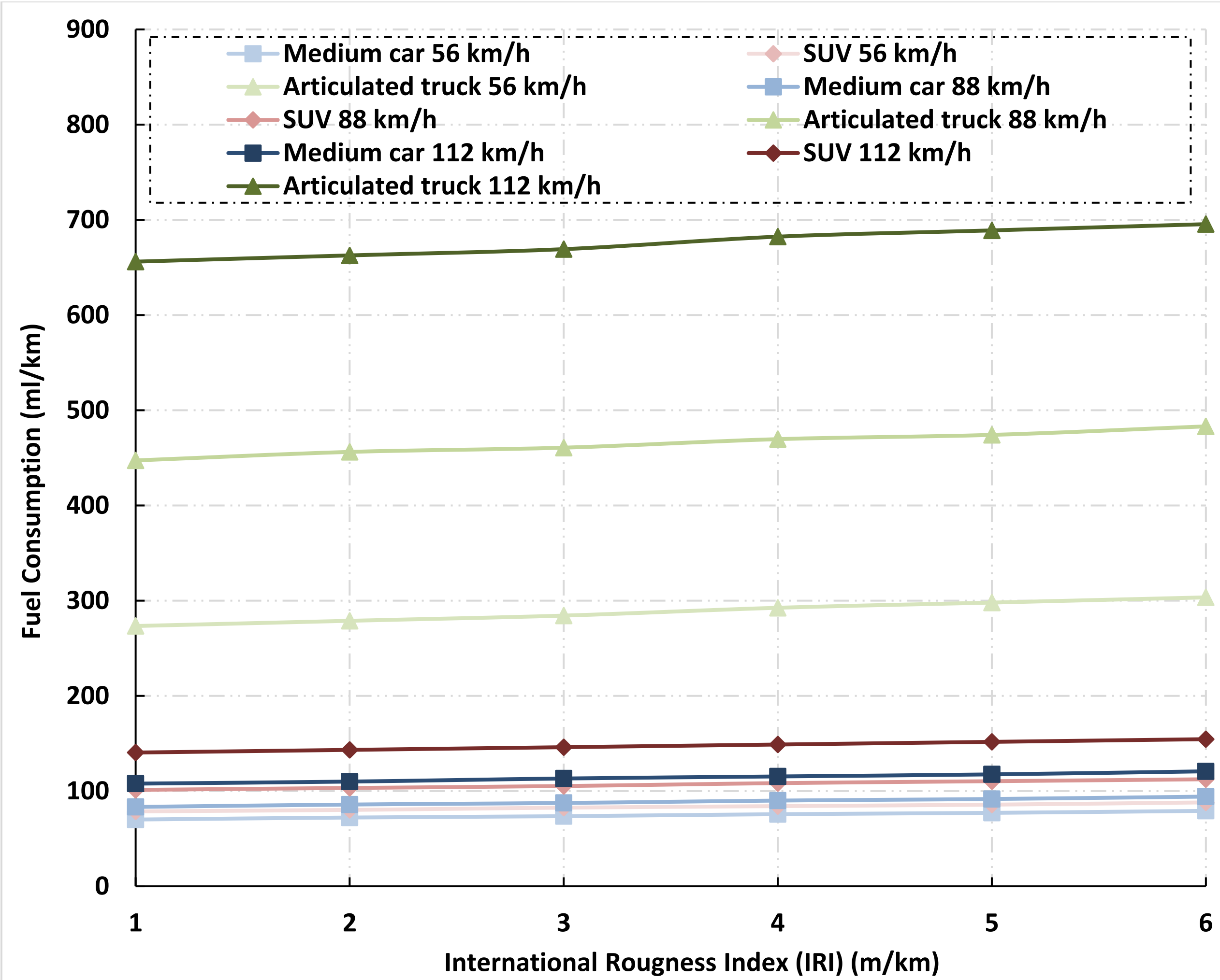


Figure 4.3: The effect of IRI on fuel consumption of medium car, SUV, and articulated Truck (Reproduced data from Chatti and Zaabar (2012))

Table 4.4 presents the effect of pavement roughness on the tire wear of different vehicles. The baseline condition column in the table indicates tire wear as a percentage of new tire volume (%) per kilometer for a pavement with an IRI of 1 m/km. The adjacent columns show the adjustment factors for different IRI values. The data for medium cars, SUVs, and trucks, provided in Table 4.4, is plotted in Figure 4.4. The figure shows that tire wear increases with both speed and roughness level, regardless of the vehicle type.

Table 4-4: Impact of road surface roughness on tire wear (Data from Chatti and Zaabar (2012))

Speed	Vehicle class (Number of wheels)	Baseline conditions (%/km) *	Adjustment factors from the base value (fraction per tire)				
		IRI (m/km)					
		1	2	3	4	5	6
56 km/h (35 mph)	Medium car (4)	0.0013	1.01	1.01	1.02	1.02	1.03
	Van (4)	0.0011	1.00	1.01	1.01	1.02	1.02
	SUV (4)	0.0011	1.01	1.02	1.03	1.04	1.05
	Light truck (4)	0.0012	1.01	1.02	1.03	1.04	1.05
	Articulated truck (18)	0.0006	1.01	1.01	1.02	1.02	1.03
88 km/h (55 mph)	Medium car (4)	0.0014	1.01	1.02	1.03	1.04	1.05
	Van (4)	0.0013	1.01	1.01	1.02	1.03	1.04
	SUV (4)	0.0013	1.01	1.03	1.05	1.06	1.08
	Light truck (4)	0.0018	1.01	1.02	1.04	1.05	1.06
	Articulated truck (18)	0.0007	1.01	1.02	1.03	1.04	1.05
112 km/h (70 mph)	Medium car (4)	0.0015	1.01	1.03	1.04	1.06	1.08
	Van (4)	0.0018	1.01	1.02	1.03	1.04	1.04
	SUV (4)	0.0017	1.02	1.04	1.06	1.08	1.10
	Light truck (4)	0.0029	1.01	1.02	1.04	1.05	1.06
	Articulated truck (18)	0.0009	1.01	1.02	1.03	1.04	1.06

**Note: percentage of new tire volume*

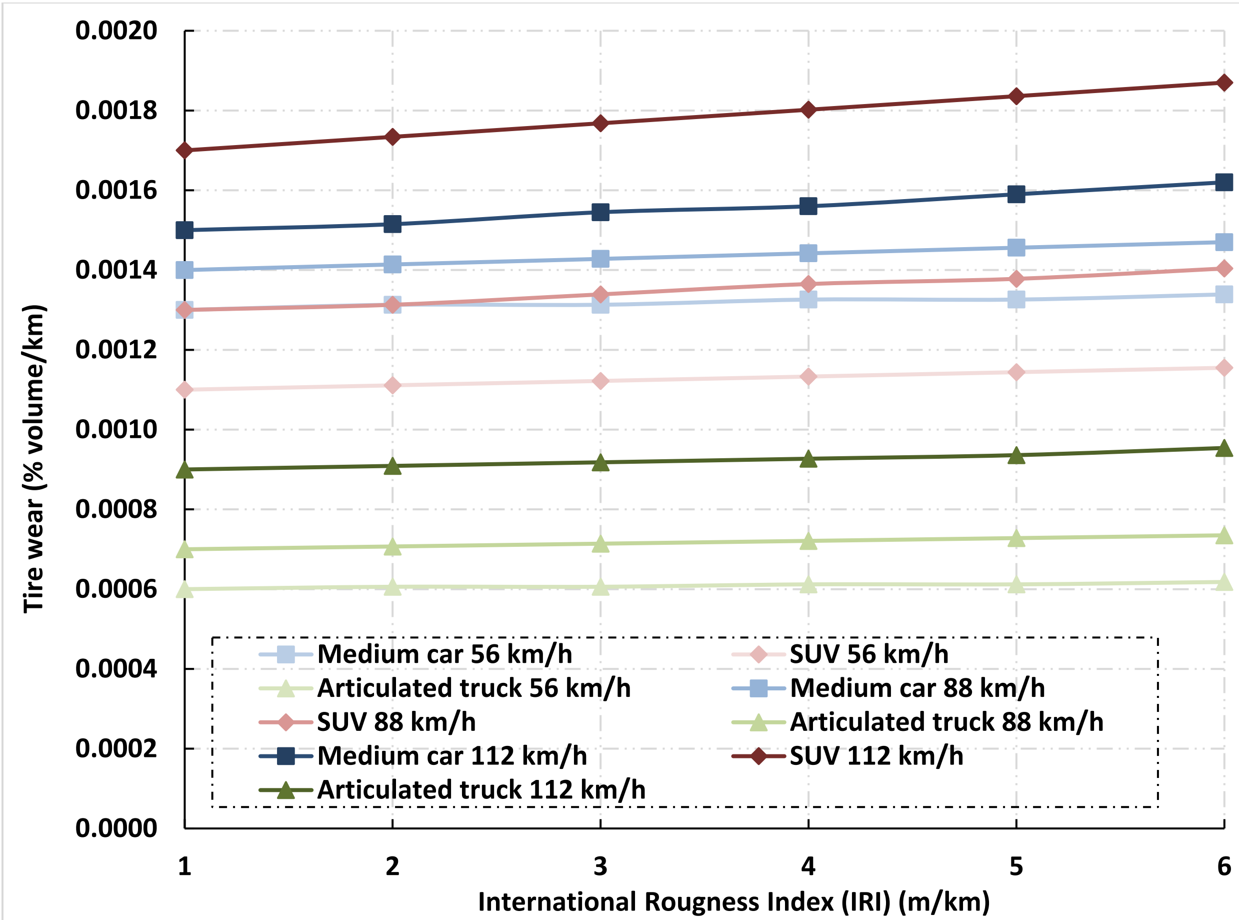
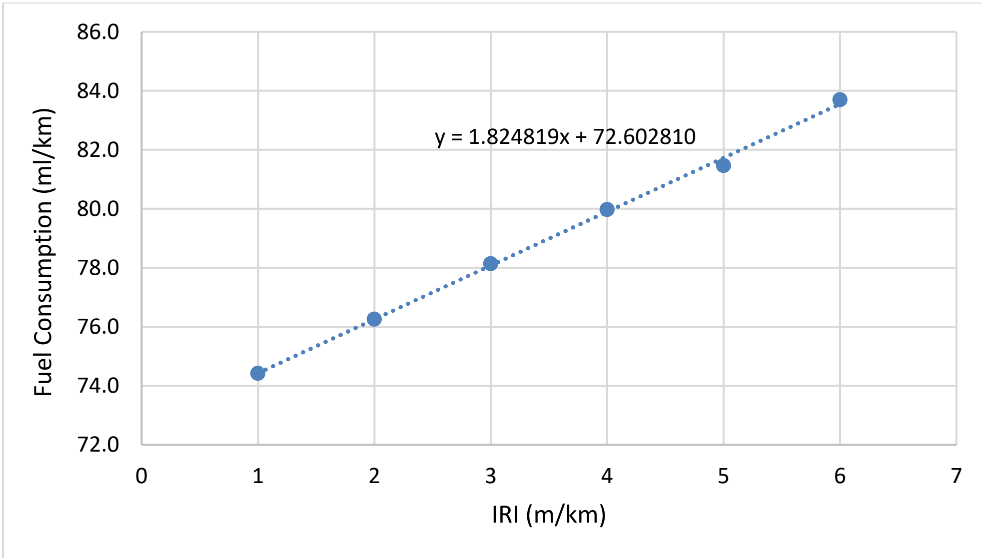
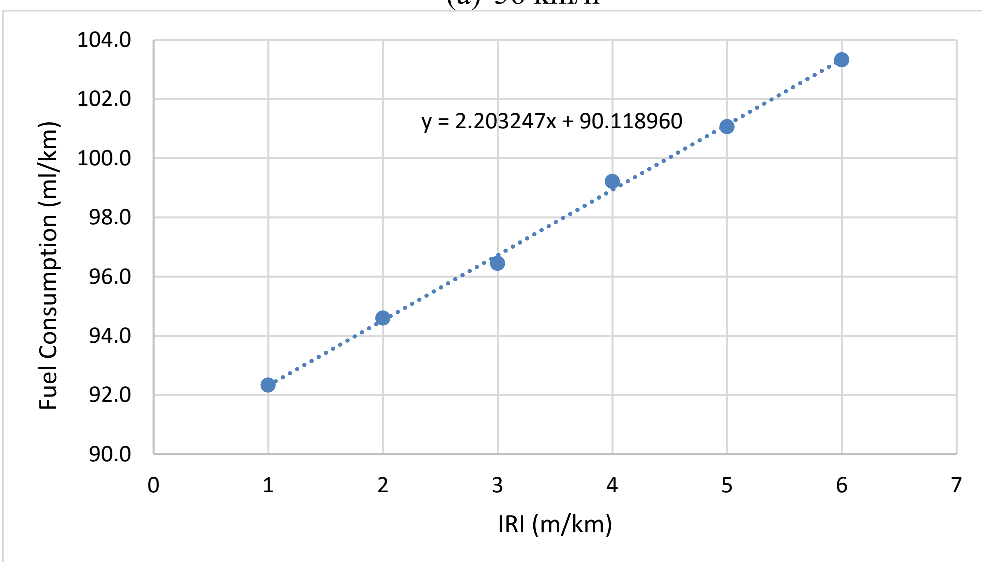


Figure 4.4: The effect of IRI on tire wear of medium car, SUV, and articulated Truck (Reproduced data from Chatti and Zaabar (2012))

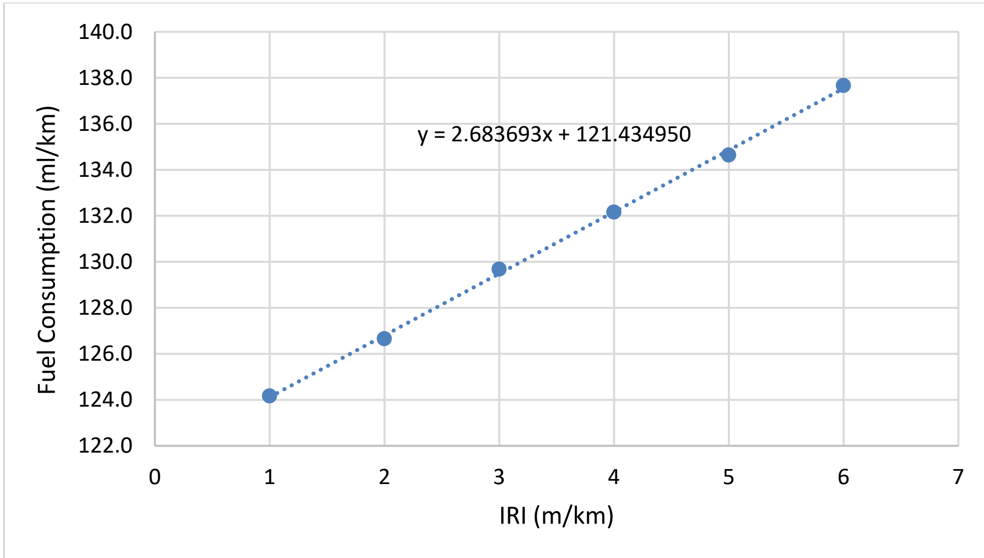
Using the data presented in Table 4.3, IRI (m/km) – Fuel Consumption (ml/km) correlations were established at three speeds (56, 88, and 112 km/h). Figure 4.5 shows the IRI-Fuel consumption correlation for passenger vehicles, while Figure 4.6 presents the IRI-Fuel consumption correlation for trucks.



(a) 56 km/h

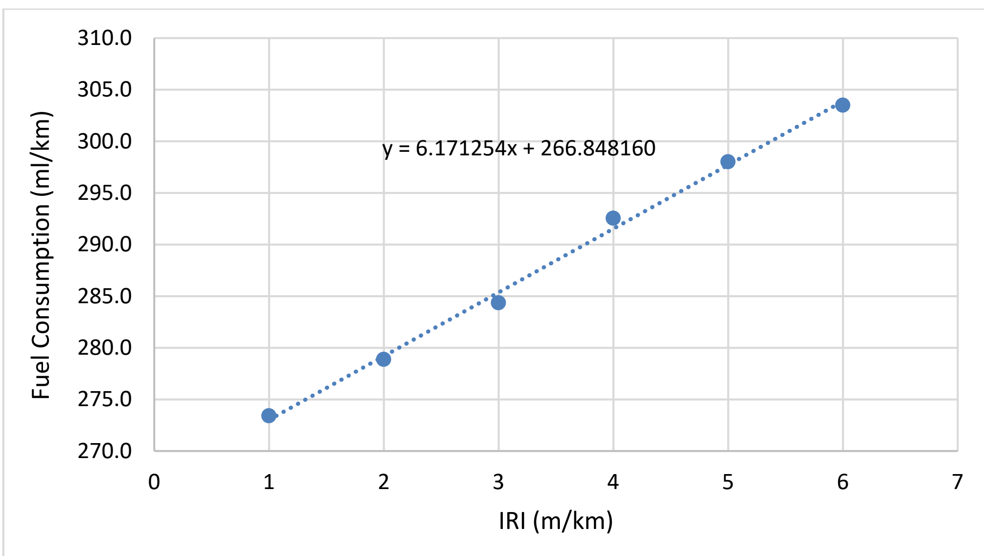


(b) 88 km/h

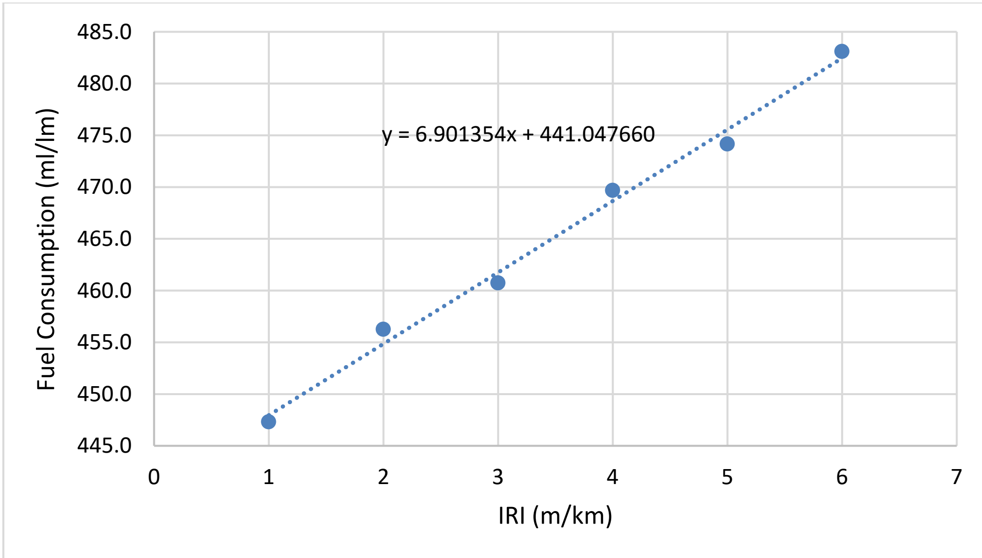


(c) 112 km/h

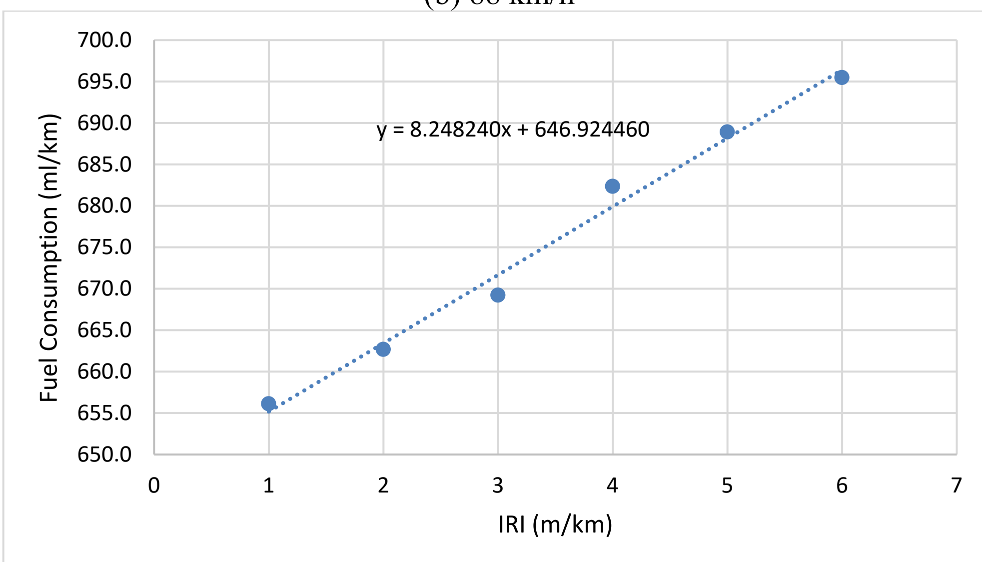
Figure 4.5: IRI-Fuel consumption relationship for passenger vehicles at different speeds, (a) 56 km/h, (b) 88 km/h, and (c) 112 km/h (Reproduced data from Chatti and Zaabar (2012))



(a) 56 km/h



(b) 88 km/h



(c) 112 km/h

Figure 4.6: IRI-Fuel consumption relationship for the truck at different speeds, (a) 56 km/h, (b) 88 km/h, and (c) 112 km/h (Reproduced data from Chatti and Zaabar (2012))

Similarly, using the data shown in Table 4.4, IRI (m/km) – Tire wear (%/km) correlations were established at three speeds (56, 88, 112 km/h). It should be noted that while calculating fuel consumption and tire wear for SUVs and medium cars, the values were averaged to represent both vehicle types, as the traffic data provided by ODOT only provided truck (ADTT) and all traffic (ADT). The correlation equations established to calculate fuel consumption based on IRI values are presented in Table 4.5, and those for tire wear are provided in Table 4.6.

Table 4-5: IRI-Fuel consumption model used in this study

Speed	Fuel consumption (ml/km)	
	Passenger vehicles	Trucks
56 km/h (35 mph)	1.824819*(IRI in m/km) + 72.602810	6.171254*(IRI in m/km) + 266.848160
88 km/h (55 mph)	2.203247*(IRI in m/km) + 90.118960	6.901354*(IRI in m/km) + 441.047660
112 km/h (70 mph)	2.683693*(IRI in m/km) + 121.434950	8.248240*(IRI in m/km) + 646.924460

Table 4-6: IRI-Tire wear model used in this study

Speed	Tire wear (%/km)	
	Passenger vehicles	Trucks
56 km/h (35 mph)	0.0000090286*(IRI in m/km) + 0.0011919	0.0000032571*(IRI in m/km) + 0.0005976
88 km/h (55 mph)	0.0000175857*(IRI in m/km) + 0.0013308667	0.000007*(IRI in m/km) + 0.000693
112 km/h (70 mph)	0.000029*(IRI in m/km) + 0.0015685	0.0000102857*(IRI in m/km) + 0.000888

To determine the final fuel consumption and tire wear based on the speed limit and IRI of a section for a given year, the following steps were followed:

1. The IRI value measured/predicted at each location was used in the equations provided in Table 4.5 (for fuel consumption) and Table 4.6 (for tire wear) for passenger vehicles and trucks at 56, 88, and 112 km/h speeds.
2. An exponential curve was fitted to the speed-fuel consumption and speed-tire wear graphs obtained from the calculations.
3. The speed limit at each location was then applied to the respective exponential functions (which vary with different IRI values) to determine the fuel consumption in ml/km and tire wear as %/km at each location. It was assumed that the vehicles travel at the speed limit at each section at all times. This assumption is expected to result in an underestimation of fuel consumption and the associated GHG emissions in many locations where most vehicles exceed the legal speed limit.
4. The total fuel consumption was calculated for each section for each year using the section length and traffic data. To find the total vehicle tires worn in a day, the tire wear calculated for a given IRI and speed (%/km) was multiplied by the length of the section, traffic value, and the number of tires - 4 (for passenger vehicles) and 18 (for trucks). This value is then multiplied by 365 to find annual tire wear at given locations.

4.4 PREDICTING THE FUTURE VALUE OF VARIABLES

4.4.1 Traffic Prediction

2021 Traffic data for every section was included in the dataset provided by ODOT. The traffic growth rate used for this study was 2%. Although the traffic growth rate is expected to vary based on location and vehicle type, a constant rate for all vehicles and locations was used in this study for simplicity. The annual compound truck growth rate in the Mechanistic-Empirical Pavement Design (MEPDG) software ranges from 2% to 4%. The traffic data included both average Daily Traffic (ADT) and Average Daily Truck Traffic (ADTT). To calculate the non-truck data (cars & SUVs), the following equation is used:

$$\textit{Car/SUV Traffic}_{2021} = \textit{Traffic (ADT)}_{2021} - \textit{Truck Traffic (AADTT)}_{2021} \qquad \textbf{(4-1)}$$

To predict the traffic data for the next 10 years, the following process (compound growth rate) was used to create the annual traffic dataset:

- Car Traffic $_{2022}$ =Car Traffic $_{2021}$ × 1.02
- Truck Traffic $_{2022}$ =Truck Traffic $_{2021}$ × 1.02
- Car Traffic$_{(Year)}$ = Car Traffic 2022 × (1.02$^{(Year - 2022)}$)
- Truck Traffic$_{(Year)}$ = Truck Traffic 2022 * (1.02$^{(Year - 2022)}$)

The formulas for the past 20 years of traffic:

- Car Traffic$_{(Year)}$ = Car Traffic 2021 × (1.02$^{(Year-2021)}$)
- Truck Traffic$_{(Year)}$ = Truck Traffic 2021 × (1.02$^{(Year-2021)}$)

4.4.2 Gas and Diesel Price Predictions

Gasoline and diesel prices for the past years were acquired from the U.S. Energy Information Administration's website (2024). The average of every dataset per year was then adjusted for inflation using the annual U.S. inflation rates supplied by the U.S. Bureau of Labor Statistics (2024). Because gas prices significantly fluctuate for various reasons (including political factors, wars, the supply rate of the major oil-producing countries, etc.) and it is impossible to predict future prices accurately, no gas price growth rate is applied for the next 10 years. However, a rate of 2.5% was still applied per year to simulate the effect of the inflation rate on gas prices.

4.4.3 Gas and Diesel Carbon Emissions

The joint Environmental Protection Agency (EPA) and Department of Transportation rulemaking in 2010 established the National Program fuel economy standards based on a comprehensive assessment (EPA and DOTs 2010). The following emission conversation factors for gasoline and diesel were obtained from those standards and used in this study. These numbers show the amount of carbon emissions created by burning one gallon of fuel (for gasoline or diesel). Those conversion factors are also available on the U.S. Environmental Protection Agency (2024) website.

- 8.887kgCO_2/gallon of gasoline
- 10.180kgCO_2/gallon of diesel

The conversation factors listed above are for tailpipe emissions and do not include oil extraction, transportation, processing, and distribution. Well-to-wheel carbon intensities needed to be determined for a more realistic assessment. The emissions for diesel and gasoline were determined by following the data provided (in Table 7) by Unnasch et al. (2023), which are:

- Gasoline: 97.3 gCO_2e/MJ
- Diesel: 99.3 gCO_2e/MJ

Using the calorific value of diesel and gasoline (Unnasch et al. 2023) as 137.8 MJ/gallon and 132 MJ/gallon, respectively, the well-to-wheel emission conversation factors for diesel and gasoline are 13.684 kgCO_2/gallon (multiplication of 99.3 gCO_2e/MJ and 137.8 MJ/gallon) and 12.844 kgCO_2/gallon (multiplication of 97.3 gCO_2e/MJ and 132 MJ/gallon), respectively.

Simulations and predictions also include electric vehicles (EVs) using the projected electric vehicle volumes. Reichmuth et al. (2022) provided a direct comparison of life cycle global warming emissions for EVs vs Gasoline cars and trucks. Based on their assessment, EVs reduce total lifetime emissions by about 52%. This reduction percentage is used to develop an approximate emission conversion factor for EVs, which must be used in this report because none of the experiments conducted in Chatti and Zaabar (2012) included EVs.

- EV car emission = 6.17kgCO_2 /33.7 kWh*

**The energy in 1 gallon of gas equals 33.7 kWh of electricity.*

4.4.4 Tire Emissions and Costs

The Centre for Remanufacturing and Reuse (2019) measured the carbon emissions released during the production of one tire. Results of their analysis showed that manufacturing an SUV/medium vehicle tire emits 31 kgCO_2eq while a semi-truck tire production emits about 86.9 kgCO_2eq. An average today's price of $200 and $350 for SUV and semi-truck tire prices, respectively, were also used for the roadway roughness-related tire wear cost calculations. Then, just as was done with the future gasoline and diesel calculations, the numbers are scaled up via the annual expected U.S. inflation rates for future cost predictions.

4.4.5 Electric Vehicle Volume Predictions

In the last decade, the use of electric vehicles (EVs) has significantly increased (EV Adoption 2024). The effect of pavement smoothness on excess fuel consumption and the associated CO_2 emissions should differ for EVs compared to fossil fuel vehicles. This study also analyzes the impact of pavement smoothness on related road user costs and CO_2 emissions, considering the anticipated increase in EV usage in the future. EV volume predictions for the entire U.S. and for only Oregon were separately used for the simulations in this study. The projections for the U.S. are called *"Federal,"* while the predictions for Oregon are called *"Oregon"* in this research report.

Figure 4.7 shows a forecast of cumulative U.S. EVs in operation until 2030. The graph shows that the cumulative number of electric vehicles in the U.S. is expected to reach around 25 million by 2030.

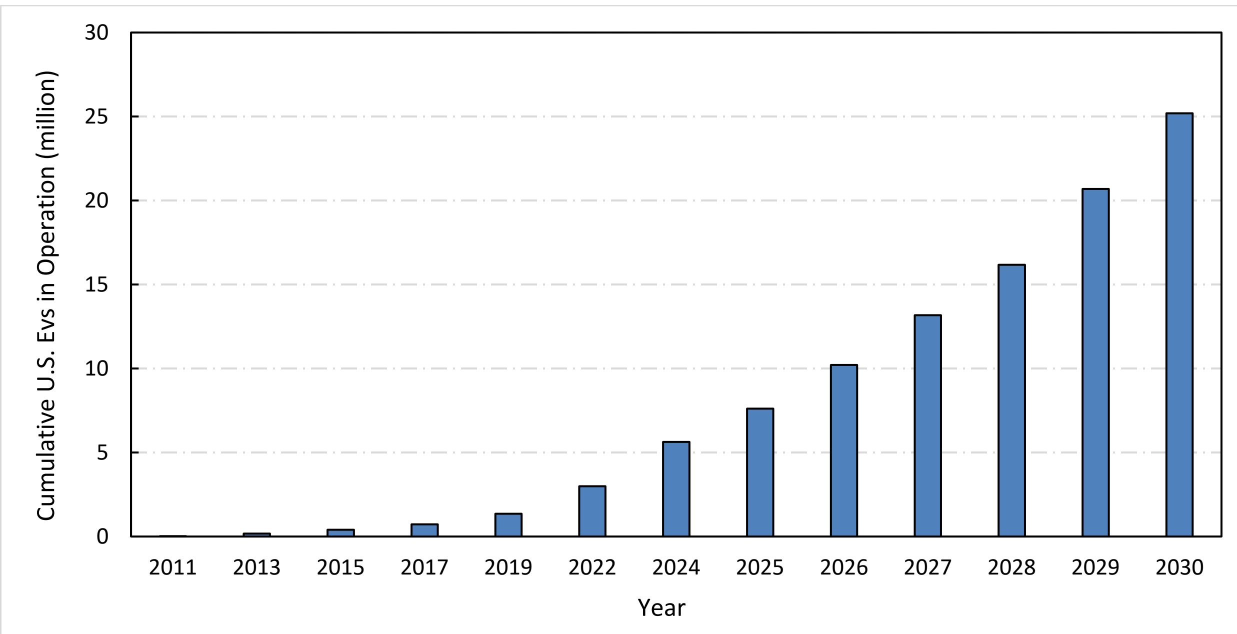


Figure 4.7: A Forecast of Cumulative EVs in operation in the U.S. from 2010 to 2030 (Graph reproduced data from EVAdoption (2024))

The future number of EVs for the entire U.S. (Federal) was estimated using the following method when calculating future smoothness-related excess fuel consumption and associated excess CO_2 emissions.

- For years up to 2021, the total number of vehicles is derived from the BTS (Bureau of Transportation Statistics) (2023) database. For years beyond 2021, the total vehicle count is estimated using the following formula:

$$\text{Total Vehicles in Year} = 0.585 \times \text{U.S. Population in Year} \quad \textbf{(4-2)}$$

Where 0.585 represents the 10-year average of light-duty vehicles per person in the U.S. The U.S. population forecast for the corresponding year was adopted from the CDC website (Centers for Disease Control and Prevention 2023) to predict the total number of vehicles in future years using Eqn. (4-3).

- An EV ratio is calculated as follows for each year:

$$\text{EV ratio: Cumulative EV in Year / Total Vehicles in Year} \quad \textbf{(4-3)}$$

An exponential curve was regressed to Figure 4.7 in order to find EVs in the years between 2003-2010. The equation is given below:

$$\text{Cumulative EV in Year} = 9841 \times e^{(0.264*(\text{Year - 2002}))} \quad \textbf{(4-4)}$$

The EV projections just for the state of Oregon were also used in this study. Oregon EV predictions were directly taken from the “https://www.oregontransportationemissions.com/resources” website. The Oregon-specific vehicle regulations passed by the Oregon DEQ in 2022 were used for the Oregon EV simulations. The projections for the U.S. (called Federal) and Oregon for trucks and cars are shown in Figure 4.8. The number of electric trucks (heavy-duty vehicle powertrains) was estimated to be zero within the next 10 years, according to the Federal Standards (Oregon Transportation Emissions Website 2024). For this reason, electric trucks were not included in the Federal simulations. However, electric trucks were also included in the Oregon EV projections based on the data provided on the Oregon Transportation Emissions Website (2024).

The calculations in this study were made for fossil fuel vehicles and then modified based on the EV ratio calculated for each year, as provided in Figure 4.8. The process for fuel consumption and the associated emission calculations are described in Section 4.4.3.

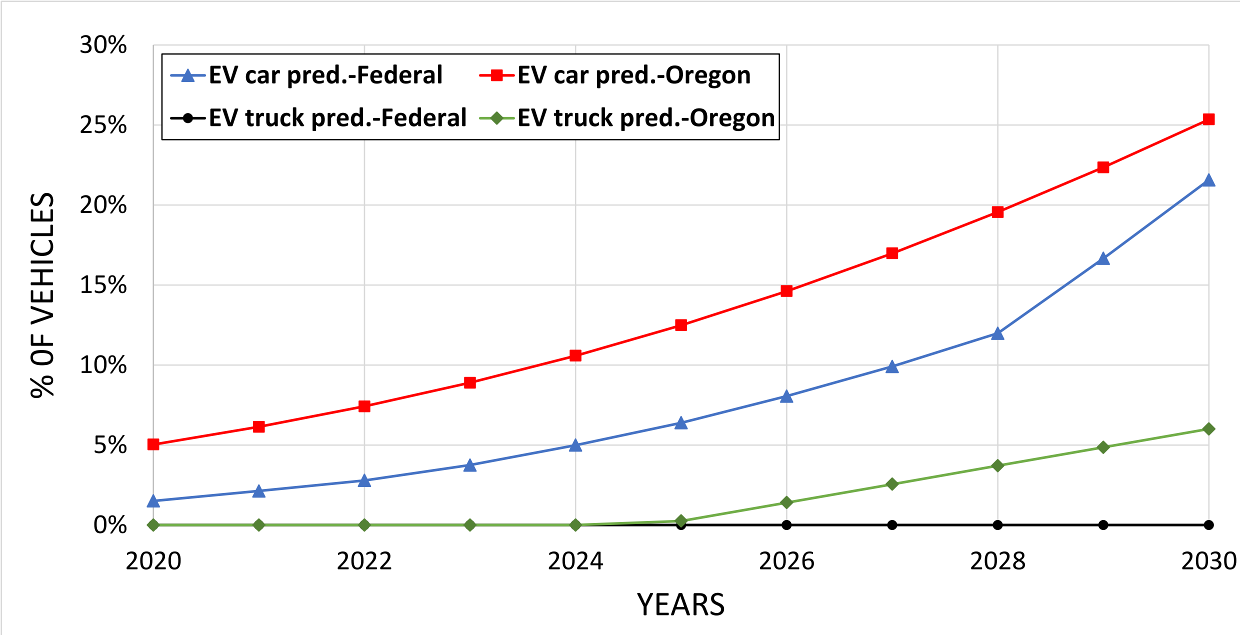


Figure 4.8. EV predictions for the U.S. (Federal) and Oregon.

4.5 INTEGRATION OF ALL INPUTS TO PREDICT ROUGHNESS-RELATED COSTS AND EMISSIONS

This section presents the analyses for cumulative roughness-related fuel consumption, tire wear costs, and the associated CO_2 emissions over the past 20 years. It also includes estimates of future costs and emissions under different maintenance scenarios for the next 10 years, considering ODOT's budgetary constraints and road paving strategies. Table 4-7 summarizes all the cases simulated and analyzed.

Table 4-7: Summary of all the cases simulated and analyzed

Case #	Simulation Category	Simulated case information	Figure to check for cost savings	Figure to check for CO_2 savings
1	Past 20 years	Savings if IRI levels had been maintained at 40 in/mile and 65 in/mile, on average, over the past 20 years	Figure 4.9	Figure 4.10
2	Future 10 years	Savings that can be created within the next 10 years by reaching four different roadway network level IRI values *(keeping the entire roadway network at the same constant IRI level for the next four years)*	Figure 4.12	Figure 4.13
3	Future 10 years	Savings that can be created within the next 10 years by annually maintaining	Figure 4.14	Figure 4.15

		the top 6% (by length) of the roads with the highest IRI or traffic levels		
4	Future 10 years	Savings that can be created within the next 10 years by annually maintaining the top 3%, 6%, and 12% (by length) of the roads with the highest IRI or traffic levels	Figure 4.16	Figure 4.17

Simulations were conducted with the ODOT PMS data, utilizing the assumptions and models from Section 4.2, Section 4.3, and Section 4.4, to analyze roughness-related excess fuel consumption, tire wear costs, and excess CO_2 emissions over the past 20 years at the network level, considering various maintenance scenarios *(Case#1 in Table 4-7)*. For instance, annual roughness-related cost savings and emission reductions were estimated based on maintaining average IRI values at specific levels (40 in/mile and 65 in/mile) during this period, using current ODOT IRI data as the baseline. Similarly, projections for the next 10 years (up to the year 2032) were made to estimate roughness-related excess fuel consumption, tire wear costs, and CO_2 emissions under different average IRI maintenance levels, with the baseline assuming no maintenance is conducted over the next decade *(Case#2 in Table 4-7)*.

Lastly, the potential benefits in terms of cost savings and emission reductions were simulated by calculating the impact of ODOT paving more (twice as much as now) or less (half as much) of its roadway network over the next 10 years *(Case#3 and Case#4 in Table 4-7)*. Currently, ODOT can pave about 6% of its roadway network annually with the existing budget (Coplantz 2023). If this number changes to 3% or 12% for the next 10 years, roughness-related excess costs and emissions were calculated for scenarios where either the highest traffic volume roads or the highest IRI roads are maintained by considering that the road roughness is reduced to either 40 in/mile or 65 in/mile after each maintenance.

4.5.1 Summary of Objectives

The major objectives of this section are as follows:

- Analyze roughness-related fuel consumption, tire wear and associated costs, and CO_2 emission savings over the past 20 years using ODOT PMS data's IRI values *(Case#1 in Table 4-7)*.
- Project potential fuel consumption, tire wear and associated cost, and CO_2 emission savings for the next 10 years based on different scenarios (the scenarios are compared to performing no maintenance for the next 10 years) *(Case#2 in Table 4-7)*.
- Estimate the cost savings and emission reductions if ODOT adjusts its annual paving capacity from the current 6% to 3% (half of the current level) or 12% (twice the current level), considering scenarios for maintaining the highest traffic volume first or highest IRI roads, with roughness levels reduced to 40 in/mile or 65 in/mile *(Case#3 and Case#4 in Table 4-7)*.

4.5.2 Process Summary

After obtaining the ODOT Pavement Management System (PMS) data, the sections to be analyzed were identified (bridge decks, ramps, and low-speed areas were removed from the dataset since IRI collected from those sections are not reliable), and missing IRI data for the past years (if any) was estimated based on assumptions detailed in Section 4.2.1. Then, an IRI progression model was adopted (detailed in Section 4.2.2) to project IRI values for the next 10 years (up to the year 2032). Using the IRI-fuel consumption and IRI-tire wear models detailed in Section 4.3, road roughness-related excess fuel and tire wear-related savings were calculated at the network level. Future traffic, fuel and tire prices, emissions, and electric vehicles were taken into account (as described in Section 4.4) to calculate roughness-related excess fuel consumption cost and excess emissions savings.

An initial step was to analyze the past 20 years *(Case#1 in Table 4-7)*. The annual average roughness-related excess fuel and tire wear cost savings, as well as the associated emission savings, were calculated assuming the average IRI value had been 40 in/mile or 65 in/mile for the entire ODOT roadway network over this period. The analysis baseline was the roughness levels for ODOT's roadway network for the past 20 years. These simulations were called as *"Past 20-year simulations"* and the results were presented in the next section. The comparisons between the actual IRI values and the "what if?" scenarios (40 in/mile and 65 in/mile) show the magnitude of the relationship between IRI and fuel consumption, tire wear, and emissions. The magnitude of the relationship is extremely helpful in considering the next 10 years because it helps verify the benefits of investing in measures to improve smoothness.

In analyzing the future 10 years, we calculated the costs and emissions for average IRI values of 40, 65, 95, and 115 in/mile *(Case#2 in Table 4-7)*. For these simulations, the baseline was to perform no maintenance.

Lastly, roughness-related excessive emissions and road user costs were calculated under the scenario where 6% of the roadway network (with the highest IRI or traffic sections) is maintained annually (6% is current paving capacity with available budget) *(Case#3 in Table 4-7)*. Additionally, the impacts of reducing pavement maintenance to 3% or increasing it to 12% were assessed *(Case#4 in Table 4-7)*. The future analyses also considered the growing adoption of electric vehicles (Section 4.4.5) using both Federal and Oregon predictions.

4.5.3 Results and Discussion

4.5.3.1 Past 20-year Simulations

Figure 4.9 illustrates the annual costs of tire wear and excess fuel consumption if IRI levels had been maintained at 40 in/mile and 65 in/mile, on average, over the past 20 years. It should be noted that the ODOT PMS data has been used as the baseline, using the IRI values from the past 20 years (2002-2022). If the roads were maintained to achieve an IRI level of 40 in/mile, on average, approximately 142 million dollars would have been saved annually. This amount exceeds ODOT's approximate yearly paving budget of ≈ \$110 million (for the years 2021-2024) (Coplantz 2023) – in other words, had ODOT invested enough in its pavements to achieve a 40 in/mile IRI, the resulting financial savings would be more than the total ODOT currently spends in a year to maintain its pavements (i.e., spending money to lower IRI values has a direct and significant return on the investment).

If the roads were maintained to achieve an IRI level of 65 in/mile, an estimated approximately $45 million would have been saved annually. It is worth noting that after removing roads with missing IRI data, ramps, bridge decks, and slow roads, the lane mile-weighted average IRI value for the remaining 10,495.86 lane miles was calculated as 75.7 in/mile as of 2022. It is clear that in the coming years, a significant increase in funding and the construction of smoother pavements will be necessary to reduce the average IRI value at the network level.

Newly paved road sections in Oregon are required to have a maximum IRI of 60 in/mile (ODOT Pavement Services Unit 2019). However, it is possible to lower the IRI to 40 in/mile or lower with continued investment in research and innovation, proper construction equipment, and high-quality and more uniform materials. By reaching this smoother surface standard, significant cost savings can be realized in terms of reduced fuel consumption and tire wear. Achieving a smoother pavement surface also reduces the environmental burden associated with roughness-induced fuel consumption and tire wear while also improving driving comfort, rideability, and safety. As also stated in the Introduction, smoother pavements last longer due to lower dynamic truck loads (See Table 1.1). Smoother pavements result in improved overall performance, durability, and safety.

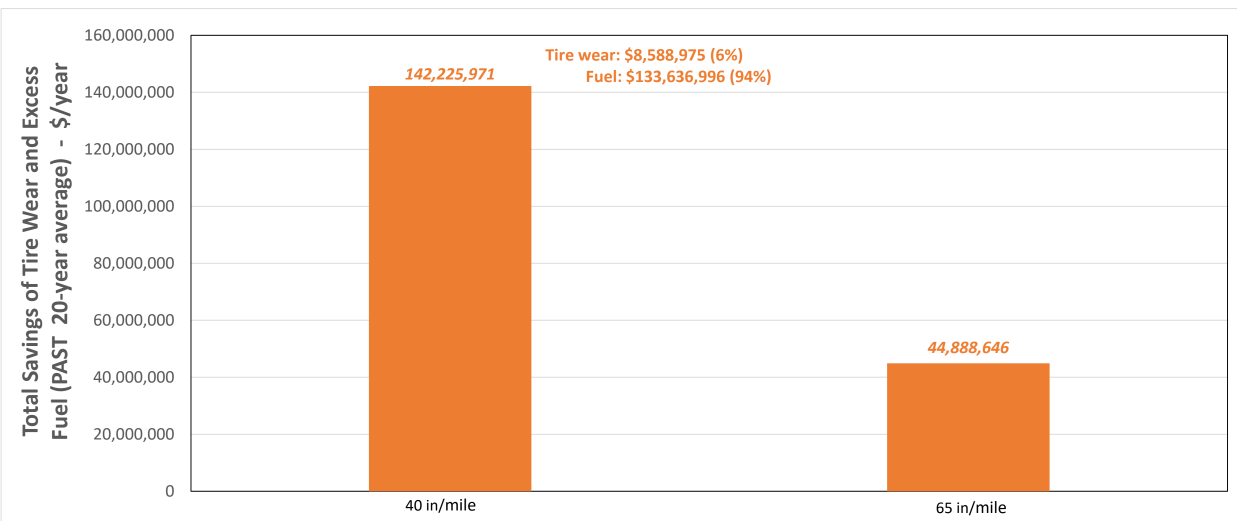


Figure 4.9: Estimated annual total cost savings of tire wear and excess fuel consumption over the past 20 years (on average) if all the roads had IRI values of 40 in/mile or 65 in/mile.

Figure 4.10 illustrates the total annual excess CO_2 emissions due to road roughness for two different IRI levels, 40 in/mile and 65 in/mile (20-year average). The base is again ODOT PMS's past 20 years of IRI data. At an IRI of 40 in/mile, the total emission savings is 423,462 metric tons (MT) of CO_2 per year. It is important to note that this value is about 2.3 times higher than ODOT's annual emissions from all the operations, which is 182,592 MT CO_2e/year and includes the emissions from construction, construction material production, equipment and facilities operated by ODOT, and several other contributors. The results from their assessment are provided in Figure 4.11 (Proudfoot and Toneys 2022).

The excess emissions at an IRI of 65 in/mile are lower at 134,927 MT CO_2e/year yet still significant and close to ODOT's total annual emissions. The graph highlights the potential environmental impact of maintaining roads, as higher roughness leads to substantially increased CO_2 emissions. By maintaining lower IRI levels (smoother roads), a significant reduction in excess emissions can be achieved while also improving the long-term performance of the pavements (please see Table 1.1).

It should be noted that this study did not consider the impact of achieving smoother roads on long-term pavement performance and the associated cost and emission savings. Smoother roads will reduce the dynamic truckloads due to reduced vertical axle movement and result in better longevity. The significant emission and cost savings outlined above do not include this improved long-term performance effect. The improved performance effect is expected to significantly improve the calculated emission savings. For this reason, all the findings in this research study point out the immense importance of roadway network maintenance – maintaining a smooth pavement network has major financial and environmental benefits.

Figure 4.10 emphasizes the critical role of the use phase within the pavement life cycle (material production, construction, use phase, and maintenance). Harvey et al. (2016) highlighted that the most impactful factor in evaluating pavement sustainability is the use phase, which drives key vehicle operating costs such as fuel usage, tire wear, and maintenance expenses. As shown in Figure 4.10, smoother roads at the network level can result in great emission reductions.

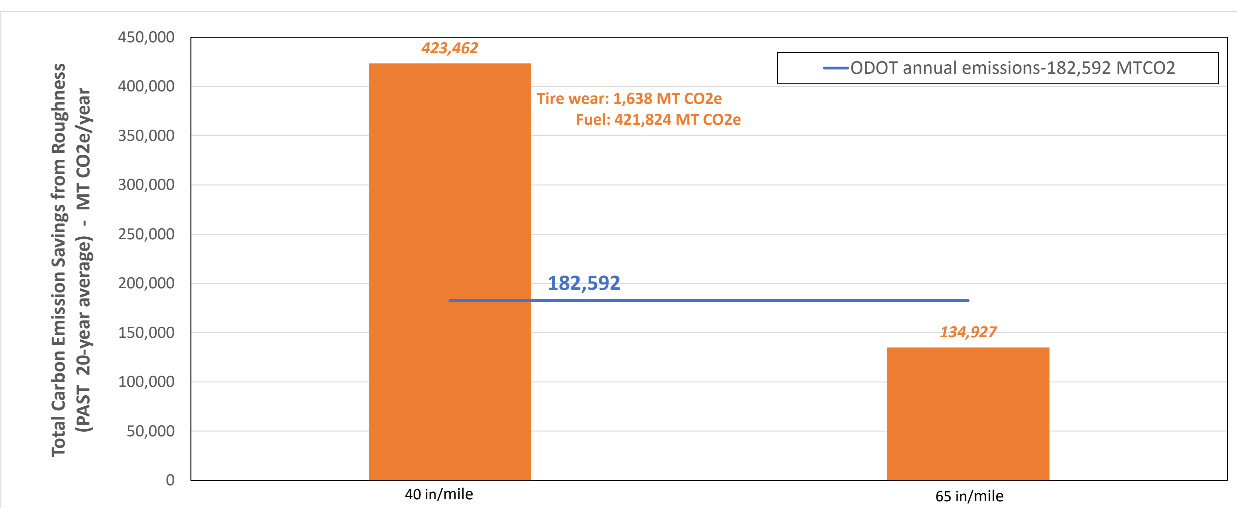
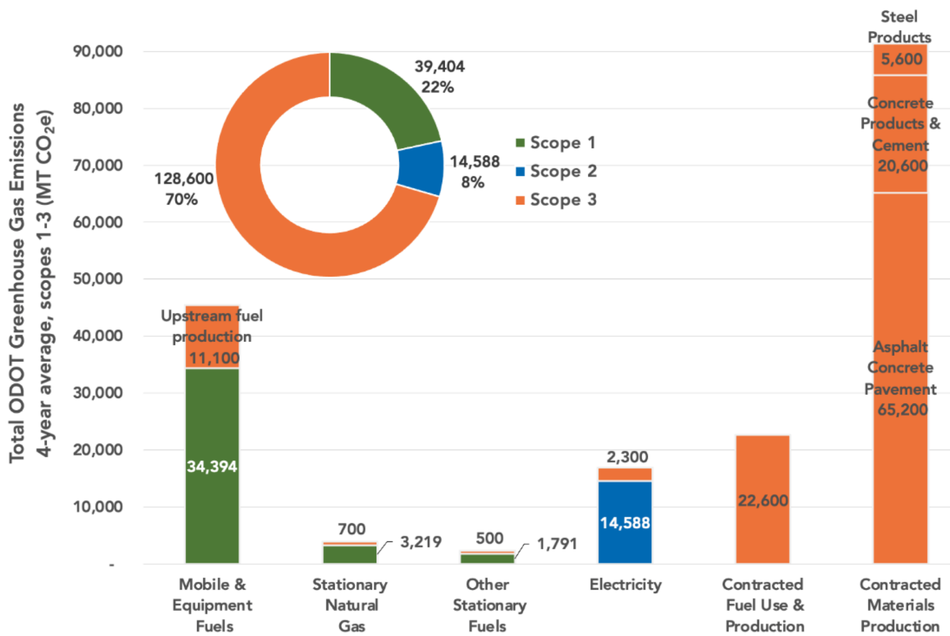


Figure 4.10: Total excess CO_2 emission savings (past 20-year average) due to pavement roughness at different average IRI levels (40 in/mile and 65 in/mile) and ODOT's annual emissions as of 2016-2019 (4-year average)



Scope 1: *Direct GHGs from equipment and facilities owned or operated by ODOT.*
Scope 2: *Indirect GHGs from electricity purchased for equipment and facilities owned or operated by ODOT.*
Scope 3: *All other indirect emissions sources that result from ODOT's activities but occur from sources owned or controlled by ODOT Tier 1 contractors and other downstream supply chain vendors (e.g., asphalt and concrete plants and concrete and cement manufacturers).*

Figure 4.11: Total GHG emissions across all analyzed sources of emissions (4-year average FY16-19) (Proudfoot and Toneys 2022)

4.5.3.2 Future 10-year Simulations

Figure 4.12 shows the total cost savings (in \$/year) over the next 10 years from tire wear and excess fuel consumption when the roads were maintained for various IRI levels, both with and without electric vehicles (EVs). The assumption is to bring all roads to the corresponding IRI level (40, 65, 90, and 115in/mile) and keep them constantly at this IRI level for the next 10 years. The scenarios with EVs were performed separately for the Federal and Oregon predictions since the predictions are different. The base scenario assumes no pavement maintenance for the next 10 years (2022-2032).

For the scenarios that do not consider EVs, smoother roads (40 in/mile IRI) will result in significant potential savings, estimated at approximately \$221 million per year. Roads with an IRI of 65 in/mile would also achieve considerable savings of around \$73 million per year. Conversely, rougher roads (90 and 115 in/mile IRI) would lead to losses (worse than now) of roughly \$74 million and \$222 million/year, respectively.

When EVs are taken into account with the federal projections, similar trends are observed. Maintaining an IRI of 40 in/mile leads to an annual savings of $212 million, while an IRI of 65 in/mile yields around $69 million/year in savings. However, rougher roads with IRIs of 90 in/mile and 115 in/mile would result in losses of approximately $75 million and $219 million per year, respectively. Since the Oregon EV predictions have faster growth in EVs than the Federal predictions, the savings in tire wear and fuel consumption reduced to $190 million, $63 million, -$76 million, and -$214 million for the IRI values of 40in/mile, 65in/mile, 90in/mile, and 115in/mile, respectively. Although the scenarios with EVs result in less fuel savings due to the lower energy use, the savings are nonetheless significant – and significantly higher than ODOT's annual paving budget for the cases in which the IRI values for the entire roadway network were reduced to 40in/mile.

Although the wide adoption of electric vehicles brings environmental and financial benefits, Figure 4.12 indicates that it does not drastically affect the savings from roughness-induced costs since, within the next 10 years, the percentage of EVs will not be very high. Moreover, EVs are also not carbon-free, and electricity production also has a carbon footprint. With the adoption of EVs, electricity usage will significantly increase worldwide, making electricity savings an important concept. For this reason, improving the energy efficiency of vehicles through smoother pavements will always be a critical concept.

Ensuring lower IRI levels contributes significantly more to cost savings from reduced fuel consumption (or vehicle energy use) and tire wear, making pavement maintenance a crucial factor for maximizing both economic and environmental benefits. **In other words, even if EVs are adopted at the rate assumed by Oregon, investing in smoother pavements yields significant savings in terms of cost and emissions.**

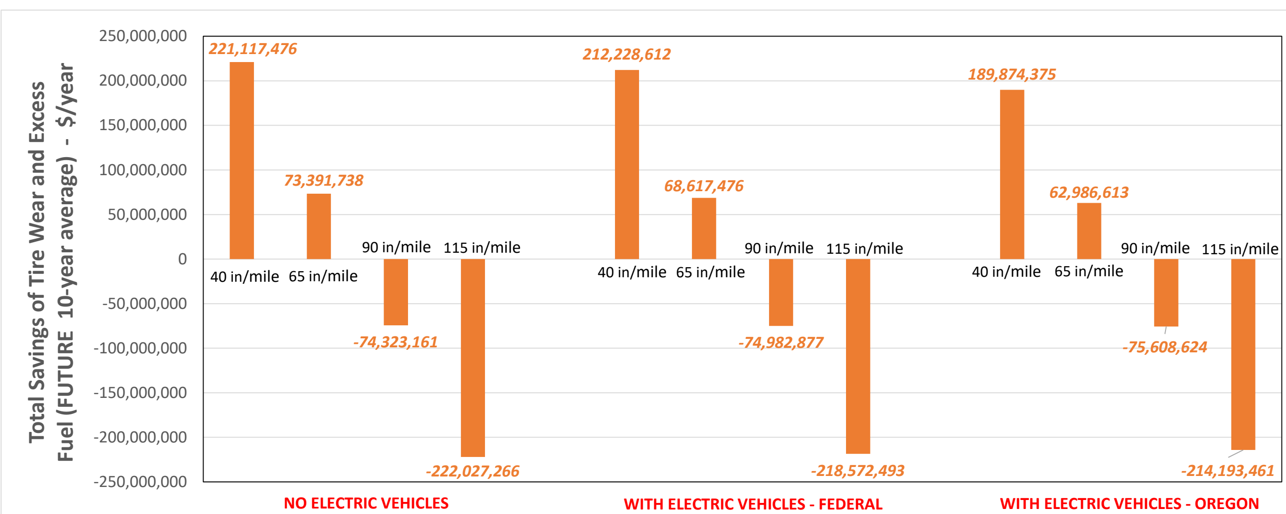


Figure 4.12: Projected total cost savings from tire wear and excess fuel consumption over the next 10 years under different average IRI scenarios, with and without electric vehicles (positive values showing potential saving compared to base scenario (do nothing for next 10 years)

Figure 4.13 illustrates the total CO_2 emissions savings from road roughness over the next 10 years under different IRI levels, comparing scenarios with and without the adoption of EVs. In those scenarios, the assumption is to bring all roads to the corresponding IRI level (40, 65, 90, or 115in/mile) and keep them constantly at this IRI level for the next 10 years. The scenarios with EVs were performed separately for the Federal and Oregon predictions. The blue line represents ODOT's annual emissions of 182,592 MT CO_2 (also given in Figure 4.11).

As shown, smoother roads (40 in/mile IRI) result in the highest potential emission savings of around 578,751 MT CO_2/year- without electric vehicles, 561,606 MT CO_2/year with EVs based on Federal EV vehicle projections, and 542,741 MT CO_2/year based on Oregon EV projections. As the IRI increases (i.e., rougher roads), roughness-related potential emission savings decrease. At 115 in/mile, an excess emission of -580,471 MT CO_2/year without EVs, and -573,808 MT CO_2/year based on Federal EV projections, and -565,844 MT CO_2/year based on Oregon EV projections, reflecting the significant increase in emissions compared to the baseline (which is "do not maintain any roads in the next 10 years").

Although EVs contribute to a modest reduction in roughness-related emissions, the influence of pavement smoothness on overall emissions remains substantial. By targeting a 40 in/mile of average IRI of the roadways, an excess emission saving of more than three times ODOT's total annual emissions can be achieved. This underscores the significance of the 'use phase' in pavement life cycle assessment. **Increasing the paving budgets will not only result in substantial cost savings but also significantly reduce excess CO_2 emissions.**

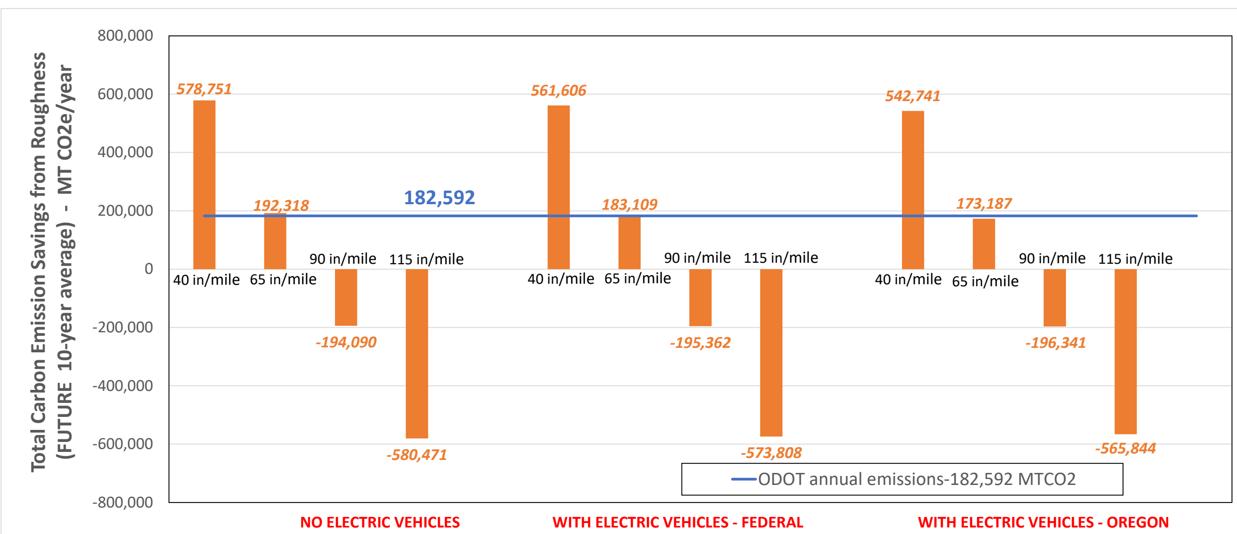


Figure 4.13: Total excess emission savings due to road roughness over the next 10 years at different IRI levels, with and without electric vehicle adoption

At current funding levels, ODOT can annually pave about 6% of the roadway sections (Coplantz 2023). This paving percentage includes all mill and fill, surface treatments, and reconstructions. ODOT decides which section to pave first, considering factors such as funding, traffic, condition of the roadway, and several other factors. In this study, the research team analyzed two scenarios involving the annual maintenance of the top 6% of roads with the highest IRI and traffic volumes. Following maintenance, the IRI for each section was reduced to 40 in/mile and 65 in/mile, depending on the scenario. The potential savings due to reduced excess fuel consumption and tire wear were calculated over a 10-year period with and without electric vehicle (EV) adoption (again, based on both Federal and Oregon EV volume predictions).

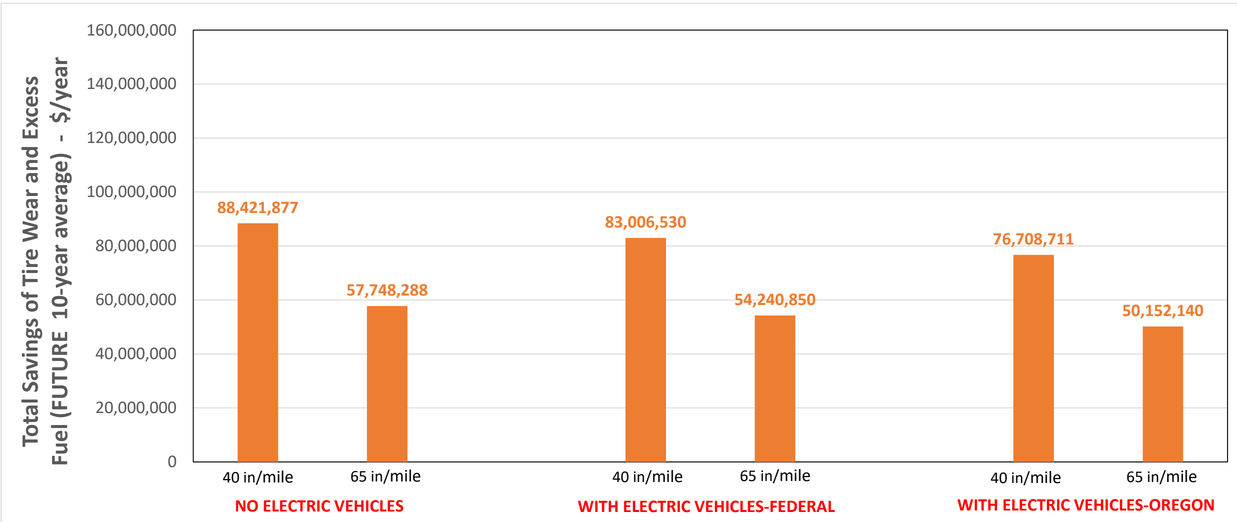
Figure 4.14 shows projected costs for tire wear and excess fuel consumption over the next 10 years under different road maintenance strategies (paving the top 6% IRI or top 6% traffic first) and vehicle conditions (with and without EVs). It examines the costs when rough roads (sections with the highest 6% IRI) are maintained annually versus when high-traffic roads (paving the top 6% highest traffic annually) are maintained. Each year, 6% of the sections with the highest traffic or IRI were added to the "maintain" list, and their roughness values were reduced to 40 or 65 in/mile. If a section is identified based on the top IRI or traffic percentage, the developed algorithm immediately adds it back to the list. However, if it is identified based on the highest traffic, to avoid repeated maintenance on the same sections, it is placed on a "do not maintain" list, effectively excluding it from maintenance for the next 9 years of calculations. The roughness progression models given in Section 4.2.2 were then used in the developed computer code to annually increase the IRI values on all maintained sections. Those roughness progression models were also used to increase IRI on the existing sections without any maintenance.

Figure 4.14(a) shows the cost savings when the roughest 6% of road sections are maintained annually. Without the presence of EVs, maintaining 6% of the roads to an IRI of 40 in/mile is projected to result in potential savings of approximately $88 million per year due to reduced excess fuel consumption and tire wear caused by road roughness. If roads are maintained at a higher IRI of 65 in/mile, the savings decrease to around $58 million per year.

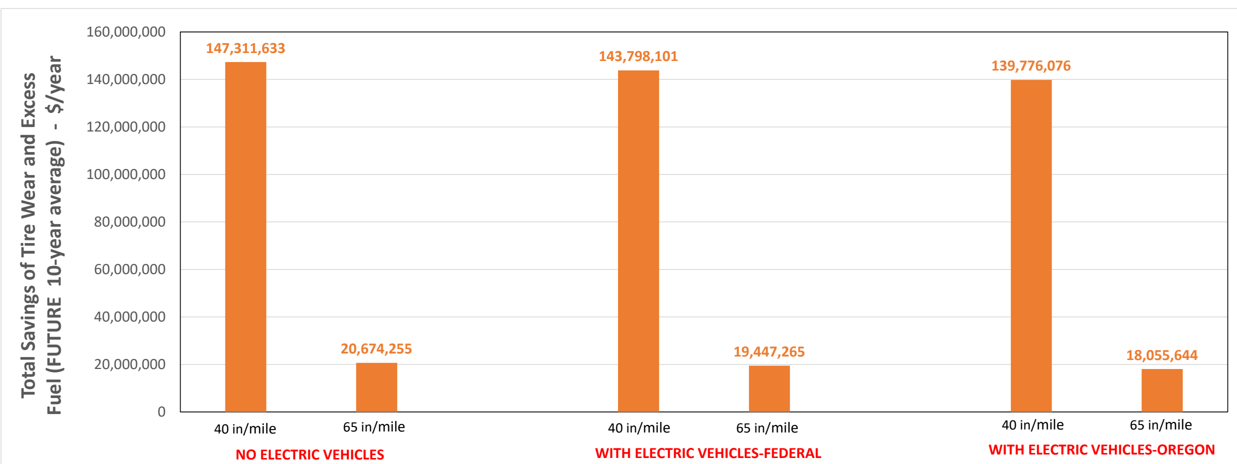
When EVs are taken into account, total cost savings decrease slightly. For roads maintained at an IRI of 40 in/mile, the savings with EVs included based on the Federal predictions amount to approximately $83 million per year. At an IRI of 65 inches per mile, the savings are around $54 million per year. Since Oregon EV predictions suggest a higher number of EV vehicles in the future than the Federal predictions, the annual cost savings for 40 in/mile and 65 in/mile decrease to $77 million and $50 million. These results suggest that including the EVs slightly reduces overall road roughness-related excess energy use and the associated costs – and the savings nonetheless remain significant.

Figure 4.14(b) shows the results of the analysis when the maintenance decisions were made based on the traffic levels rather than the IRI levels. In this scenario, the potential cost savings are significantly greater for the 40in/mile target IRI level due to the higher number of vehicles and, hence, the higher potential vehicle operating cost (VOC) savings. However, the cost savings significantly dropped when the roads were maintained to 65 in/mile IRI levels. **Since most high-traffic roadways (such as the I-5 corridor) are generally prioritized for maintenance, their IRI levels, on average, are close to the 65 in/mile after maintenance IRI target. Accordingly, the savings are less when maintenance decisions are made using traffic levels. Considering these results, the after-construction target IRI levels for high-volume pavements should be chosen to be less than the current target of 60in/mile. Even if reducing the IRI levels to**

40in/mile is hard or costly in the short-term, IRI-based maintenance decisions should be made to keep the roadway network as low as is reasonably possible and preferably no less than 65 in/mile.



(a)



(b)

Figure 4.14: Projected total cost savings from tire wear and excess fuel consumption over the next 10 years (a) when the top 6% of the highest IRI sections were maintained each year, (b) when sections with the top 6% of traffic were maintained, with and without electric vehicles

As shown in Figure 4.14b for the case of Oregon-EV predictions, the savings that can be created by reducing the roughness level from 65 in/mile to 40 in/mile is about $122million/year. As mentioned in the previous paragraph, reducing the roughness to 40 in/mile might be challenging and may increase the paving costs.

However, this high saving level tells us that even in the case when the roughness is reduced to 50in/mile and 55 in/mile, the savings (compared to 65 in/mile savings) will be around $73.2 million and $48.8 million (calculated by linear interpolation), respectively. This result also suggests that targeting an IRI level lower than the current 60 in/mile will create significant savings even when it is not possible to achieve 40 in/mile during construction.

Figure 4.15 shows the projected emission savings from reduced road roughness over the next 10 years. Similar to the cost-based analysis presented in the previous paragraphs, Figure 4.15 compares emission savings under two road maintenance scenarios where the top 6 percent of roadway maintenance activities are prioritized based on IRI and traffic volumes. Additionally, the analysis considers both scenarios with and without the anticipated growth of electric vehicles (EVs). In both figures, the blue line represents ODOT's annual CO_2 emissions of 182,592 metric tons, providing a reference point for assessing the contribution of road roughness to overall emissions.

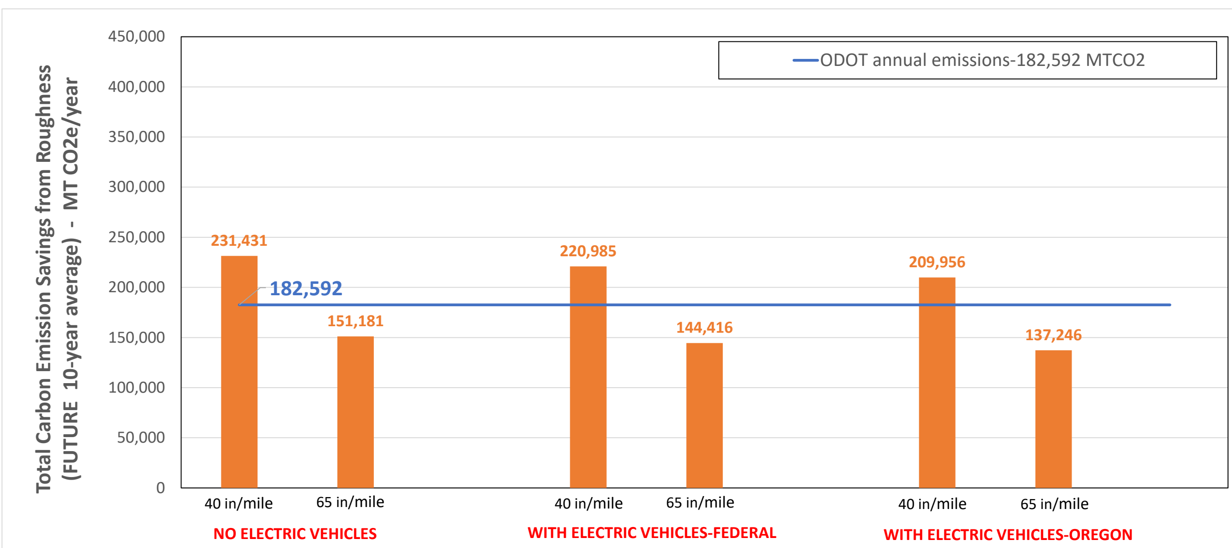
Similar to the cost-saving projections (Figure 4.14), maintaining road sections to 40 in/mile IRI level by ranking the sections based on the top traffic volumes (maintaining the top 6% annually) offers greater potential for emission reduction compared to maintaining the top 6% of sections based on the highest IRI values. However, when the target IRI level for the maintained sections was increased to 65 in/mile, the savings for the traffic volume-based ranking significantly decreased. This significant change in the emission savings is a result of the lower IRI levels for the high-traffic roadways in Oregon. Since most high-traffic roadways (such as the I-5 corridor) are generally prioritized for maintenance, their IRI levels, on average, are close to the 65 in/mile *"after maintenance IRI target"*. For this reason, the savings are less when maintenance decisions are made using traffic levels. As previously noted in this section, for high-volume roadways, the after-construction target IRI levels should be chosen to be less than the current target of 60in/mile.

Figure 4.15 (a) shows the results for annually maintaining the top 6% of roads with the highest IRI levels. Without EVs, maintaining these sections to an IRI of 40 in/mile is expected to yield potential emission savings of 231,431 MT CO_2/year, while maintaining roads at a higher IRI of 65 in/mile reduces the potential emission savings to 151,181 MT CO_2/year. These figures are comparable to ODOT's annual total CO_2 emissions of 182,592 MT CO_2/year (See Figure 4.11). When EV adoption is introduced into the analysis based on the Federal EV volume projections, total emission savings decrease slightly. For roads maintained at an IRI of 40 in/mile, emission savings drop to 220,985 MT CO_2/year, while maintaining roads at 65 in/mile results in 144,416 MT CO_2/year. When the Oregon EV volume projections were used in the analysis, these emission savings were further reduced to 209,956 MT CO_2/year and 137,246 MT CO_2/year for the 40 in/mile and 65 in/mile roughness targets, respectively. These results show that EVs provide a slight reduction in emissions related to road roughness, similar to cost simulations provided in Figure 4.14. The impact of including the EV vehicles in the analysis appears small due to the following reasons:

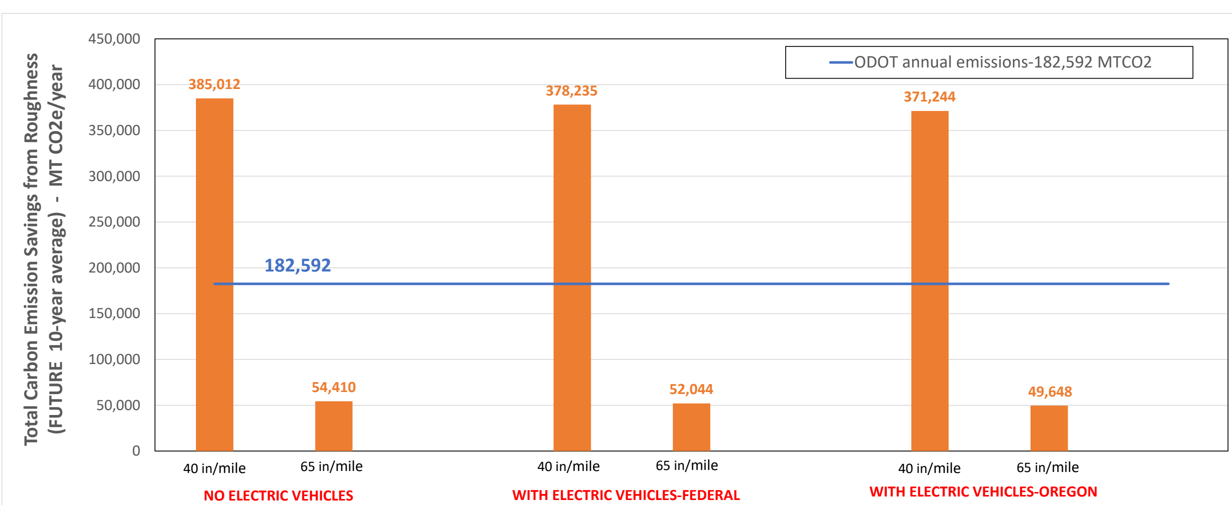
- Electric commercial trucks are not expected to significantly increase within the next 10 years (zero electric commercial trucks in the next 10 years, according to the Federal projections)

- Electric cars are expected to increase within the next 25 years. Still, the increase within the next 10 years is not that high (25% increase according to Oregon projections, while this number reduces to 20% for the Federal projections).
- Although the EVs have a 52% lower carbon output, they still have a carbon footprint.

Figure 4.15 (b) shows the results for annually maintaining the top 6% of roads with the highest traffic levels. Without EVs, maintaining roads at an IRI of 40 in/mile leads to significantly higher potential emission savings, around 385,012 MT CO_2/year, compared to 54,410 MT CO_2/year when roads are maintained at 65 in/mile. If a smoother roadway network is encouraged by increasing the current ODOT paving budgets, an average annual emission saving of more than twice the amount caused by ODOT's operations could be achieved over the next ten years. Similar to the previous analysis, the inclusion of EVs slightly reduced the potential emission savings from roughness-related excess fuel consumption and tire wear, which are presented in Figure 4.15 (b).



(a)



(b)

Figure 4.15: Projected total excess emission savings from road roughness over the next 10 years, comparing scenarios with and without electric vehicles (a) Emissions when annually maintaining the top 6% of the roughest road sections (b) Emissions when annually maintaining the top 6% of roads with the highest traffic volumes.

It can also be observed from Figure 4.15b that for the case of Oregon-EV predictions, the emission savings that can be created by reducing the roughness level from 65 in/mile to 40 in/mile is about 321,596 MT CO_2/year. As mentioned in the previous paragraph, reducing the roughness to 40 in/mile might be challenging in the short term and would increase the paving costs. **However, the savings tell us that even in the case when the roughness is reduced to 50in/mile and 55 in/mile, the savings (compared to 65 in/mile savings) will be around 192,958 MT CO2/year and 128,638 MT CO2/year (calculated by linear interpolation), respectively. In other words, targeting an IRI level lower than the current 60 in/mile will create significant emission savings even when it is not possible to achieve 40 in/mile during construction.**

Figure 4.16 presents the projected annual cost savings of roughness-related tire wear and excess fuel consumption over a 10-year period under different roadway maintenance scenarios. The charts compare how maintaining either the roughest sections of the network first (top 3%, 6%, and 12% ranked by IRI) or the most heavily trafficked sections first (top 3%, 6%, and 12% ranked by traffic volume) influences the potential cost savings, based on the smoothness achieved by the maintenance—either by reducing road roughness to 40 inches per mile or 65 inches per mile. Since ODOT's average paving budget within the last 3 years allowed the maintenance of about 6% of the roadway network length annually (Coplantz 2023), the impact of any increase (to pave 12%) or reductions (to pave 3%) in this budget on roughness related fuel and cost savings and the associated carbon emission savings were simulated. The baseline was *"do nothing"* for the next 10 years. These analyses were conducted with future increases in electric vehicle adoption taken into account based on Oregon EV projections for the next 10 years. For simplicity, simulations without electric vehicle adoption are not shown. As demonstrated in Figure 4.14 and Figure 4.15, the inclusion of electric vehicles based on Oregon projections creates about a 6% to 16% reduction in cost savings, while the emission savings reduce by 4% to 10%, depending on the analysis. Although those percentages of reduction are significant, they are not critical enough to affect the significance of the roadway roughness effect and its impact on road user costs and the environment.

Figure 4.16(a) shows the cost savings for annually maintaining the top 3%, 6%, and 12% of the road sections with the highest IRI. In the 40 in/mile scenario, the potential cost savings increase as more of the roughest sections are maintained (ODOT currently can maintain about 6% with the available budget). When 3% of the network is maintained, the potential cost savings are reduced to around $49 million per year, increasing to about $77 million per year for 6% of the network and rising further to $126 million per year when 12% of the network is maintained annually. For the 65 in/mile scenario, as expected, the cost savings are lower, starting at approximately $34 million per year when 3% of the roughest sections are maintained, increasing to about $50 million per year for 6%, and reaching $69 million per year when 12% of the roughest sections are maintained. These results prove the significance of roadway roughness for reducing road user costs. The results also show that research studies should be conducted to find methods to decrease "after construction

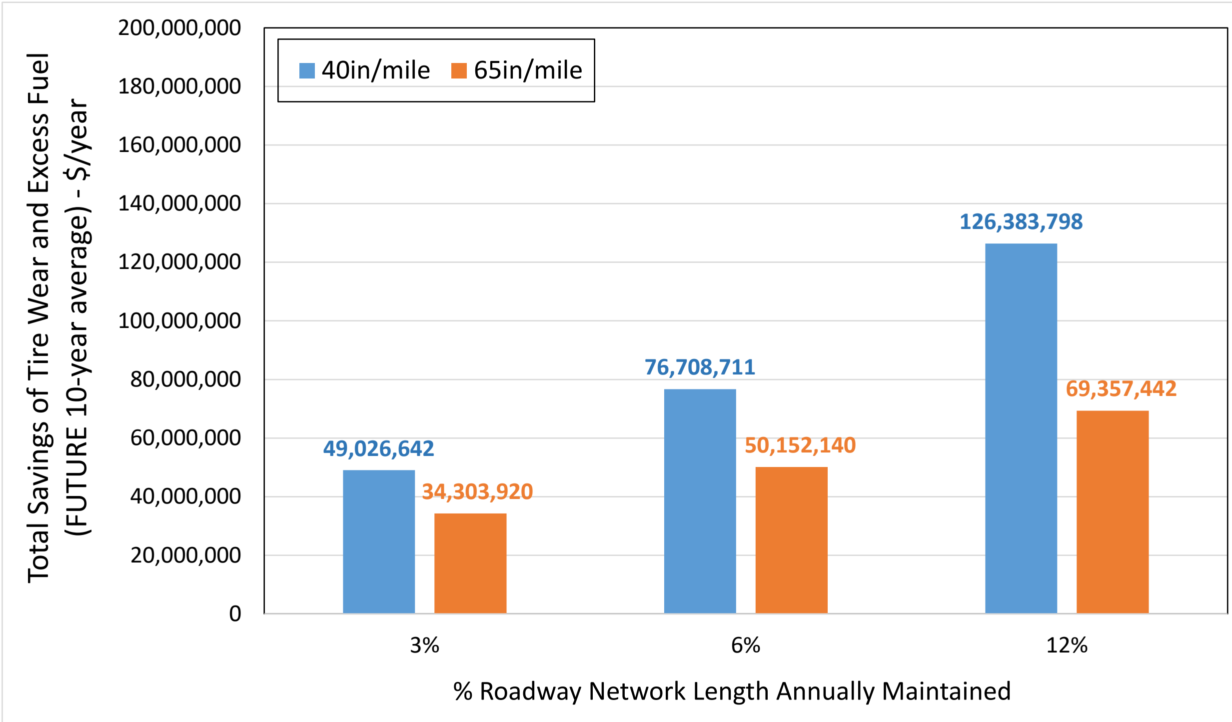
IRI levels” to 40 in/mile. Although the current ODOT target for “after construction IRI” is 60 in/mile, this roughness level can easily be reduced by modifying the asphalt mixture properties, improving the construction processes by increasing material uniformity (avoiding aggregate or thermal segregation), and reducing the excessive compaction effort during construction. In addition, the roughness levels of existing roads can also be reduced by monitoring roadway roughness using inertial profilers and reducing the high roughness sections by maintenance or diamond grinding to remove high-profile areas that increase vertical axle movements. It should be noted that reduced roughness will also improve pavement performance by reducing the vertical dynamic truck loads (see Table 1.1). Those performance benefits are not simulated in this research study.

In Figure 4.16(b), the analysis shifts to annually maintaining the top 3%, 6%, and 12% of road sections with the highest traffic volumes. Cost savings for the 40 in/mile scenarios are notably higher compared to Figure 4.16(a) due to greater reductions in tire wear and fuel consumption in heavily trafficked areas. In the 40 in/mile scenario, cost savings amount to approximately $99 million per year when the top 3% of high-traffic sections are maintained, rising to about $140 million per year when 6% of the network is maintained, and reaching nearly $159 million per year when 12% of the network is maintained.

For the 65 in/mile scenario, cost savings are significantly lower, starting at around $11 million per year for the top 3% of sections, increasing to $18 million per year for 6%, and remaining at $18 million per year for 12% of the network. The notable reduction in savings when increasing the post-maintenance IRI levels from 40 in/mile to 65 in/mile reflects the relatively low roughness of high-traffic volume roadway sections in Oregon. These sections typically undergo more frequent maintenance, so reducing their IRI levels to 65 in/mile offers limited additional benefits.

For high-traffic volume roadways, the most effective strategy would be to reduce IRI levels below the current 60 in/mile target. Alternatively, decision-making based on IRI rankings, as shown in Figure 4.16(a), rather than traffic volume, might yield greater benefits.

Investing in smoother roads offers substantial long-term financial benefits for road users. Reduced dynamic truckloads due to reduced pavement roughness are also expected to improve pavement longevity, reduce agency costs, and improve the overall roadway network condition in Oregon. While the initial costs of maintaining smoother roads are higher, the savings from reduced excess fuel consumption and tire wear, especially in high-traffic areas, more than compensate for these upfront expenses. Moreover, smoother roads result in higher performance and longer pavement lifespan, reducing the need for frequent and extensive repairs over time (see Table 1.1). Prioritizing high-traffic sections for smoother pavement maximizes cost savings and improves road durability, making it a cost-effective strategy for both vehicle operations and infrastructure maintenance. However, if it is not feasible to reach roughness levels of 40 in/mile in some high-traffic locations in the short term, using the IRI criteria for maintenance decision-making might be a better alternative [See Figure 4.16(a)].



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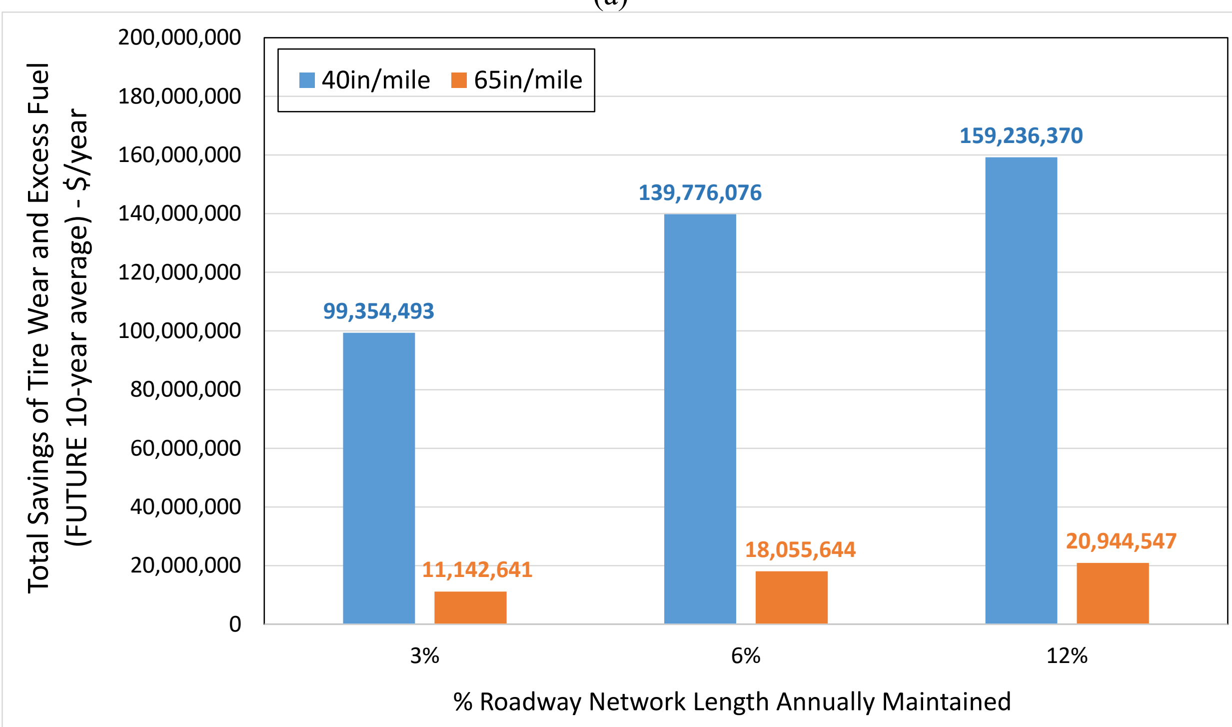


(b)

Figure 4.16: Annual cost savings of tire wear and excess fuel consumption averaged for a 10-year period (a) Cost savings when the top 3%, 6%, and 12% of the roughest road sections (highest IRI) are maintained annually, reducing road roughness to either 40 in/mile or 65 in/mile. (b) Costs when the top 3%, 6%, and 12% of the most heavily

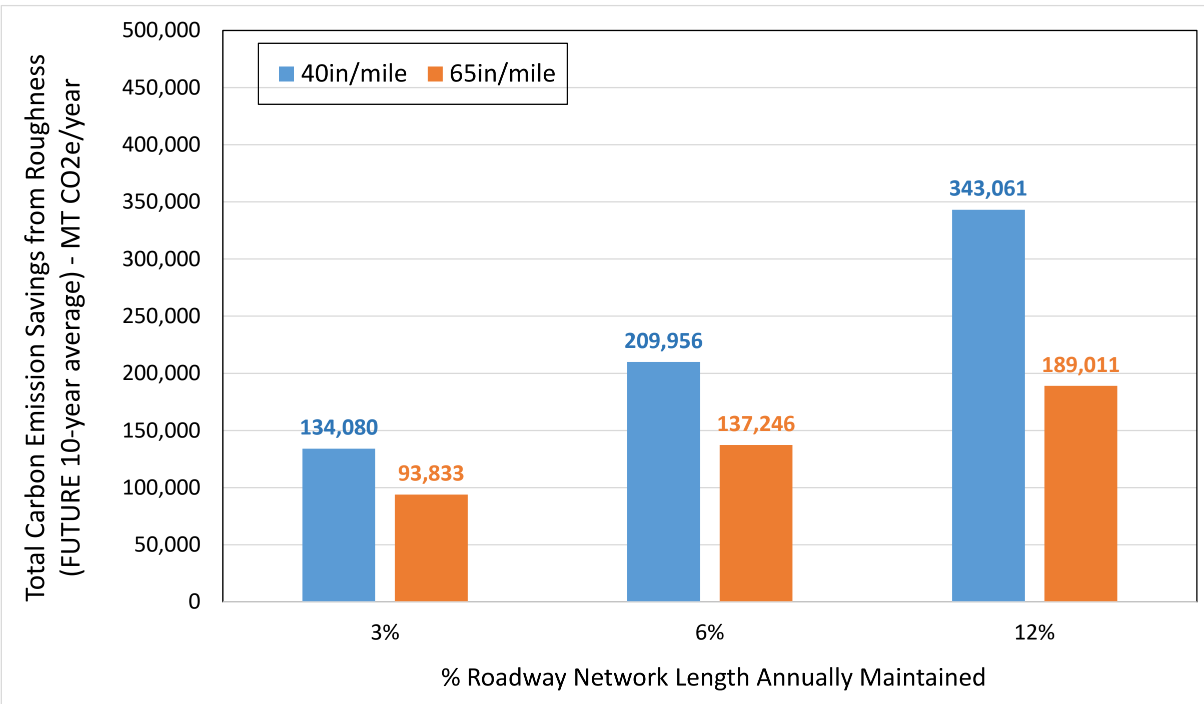
trafficked road sections are maintained, reducing road roughness to 40 in/mile or 65 in/mile.

Figure 4.17 presents the projected total carbon emission savings of roughness-related tire wear and excess fuel consumption over a 10-year period under different roadway maintenance scenarios. The charts compare how maintaining either the roughest sections of the network first (top 3%, 6%, and 12% by IRI) or the most heavily trafficked sections first (top 3%, 6%, and 12% by traffic volume) influences the potential emission savings, based on the smoothness achieved by the maintenance—either reducing road roughness to 40 inches per mile or 65 inches per mile. Since ODOT's average paving budget within the last 3 years allowed the maintenance of about 6% of the roadway network length annually, the impact of any increase (to pave 12%) or reductions (to pave 3%) in this budget on roughness related fuel and tire wear savings and the associated carbon emission savings were simulated. The baseline is "do nothing" for the next 10 years. It is important to note that these analyses were conducted with future increases in electric vehicle adoption taken into account based on Oregon EV projections for the next 10 years. For simplicity, simulations without electric vehicle adoption are not shown, but they are available upon request.

In Figure 4.17 (a), the excess CO_2 emissions are shown for maintaining the top 3%, 6%, and 12% of the road sections with the highest IRI. In the 40 in/mile scenario, the potential reduced emissions increase with an increasing percentage of the sections maintained, as expected. When 3% of the network is maintained, the potential emission savings are 134,080 MT CO_2/year, increasing to 209,956 MT CO_2/year when 6% of the network is maintained and reaching 343,061 MT CO_2/year for the scenario with 12% of the roadway network was maintained. This significant 133,105 MT CO_2/year increase in CO_2 emissions by increasing the length of the annually maintained roads from 6% to 12% proves the importance of increasing the paving budgets and its potential impact on the environment. It should be remembered that ODOT's total annual emissions from all operations was calculated to be 182,592 MT CO_2/year (Proudfoot and Toneys 2022). This significant reduction in emissions due to paving more can reduce ODOT's carbon footprint to significantly lower levels. However, more detailed LCA must be conducted to derive more reliable conclusions by also considering the performance impact of smoother roads (significant improvement in performance~reduction in emissions) and the impact of more frequent construction and maintenance (higher emissions due to more frequent paving) on emissions.

In the 65 in/mile scenarios, emission savings reduce to 93,833 MT CO_2/year for 3% of the roughest sections, 137,246 MT CO_2/year for 6%, and about 189,011 MT CO_2/year for 12% of the roughest sections annually maintained. Although these numbers are less significant than the 40 in/mile results, they are still substantial.

Figure 4.17(b) shows the scenarios when the top 3%, 6%, and 12% of roads with the highest traffic volumes were maintained to IRI levels of 40 in/mile and 65 in/mile annually. In the 40 in/mile scenario, the excess emission savings are much higher compared to Figure 4.17(a), reflecting the greater fuel consumption associated with high-traffic areas. When 3% of the network is maintained, annual excess emission savings are 262,082 MT CO_2/year, rising to 371,244 MT CO_2/year for 6%, and reaching nearly 427,829 MT CO_2/year when 12% of the highest traffic routes of the network are annually maintained. Excess emissions are lower for the 65 in/mile scenario, starting at approximately 30,009 MT CO_2/year for 3%, increasing to 49,648 MT CO_2/year for 6%, and reaching 51,953 MT CO_2/year for 12% of the network. This significant reduction in emission savings due to increasing the "after construction IRI levels" from 40 in/mile to 65 in/mile is a result of the lower roughness of the high-traffic volume roadway sections in Oregon. Since more maintenance is generally performed in those areas, reducing their IRI levels to 65in/mile creates less significant benefits. For this reason, for the high-traffic volume roadways, the best strategy would be to reduce the IRI levels to lower than the current 60 in/mile target. Another strategy might be to make the decisions based on IRI ranking [as shown in Figure 4.17(a)] rather than traffic levels if reducing the IRI levels to 40 in/mile is not feasible for any particular reason.



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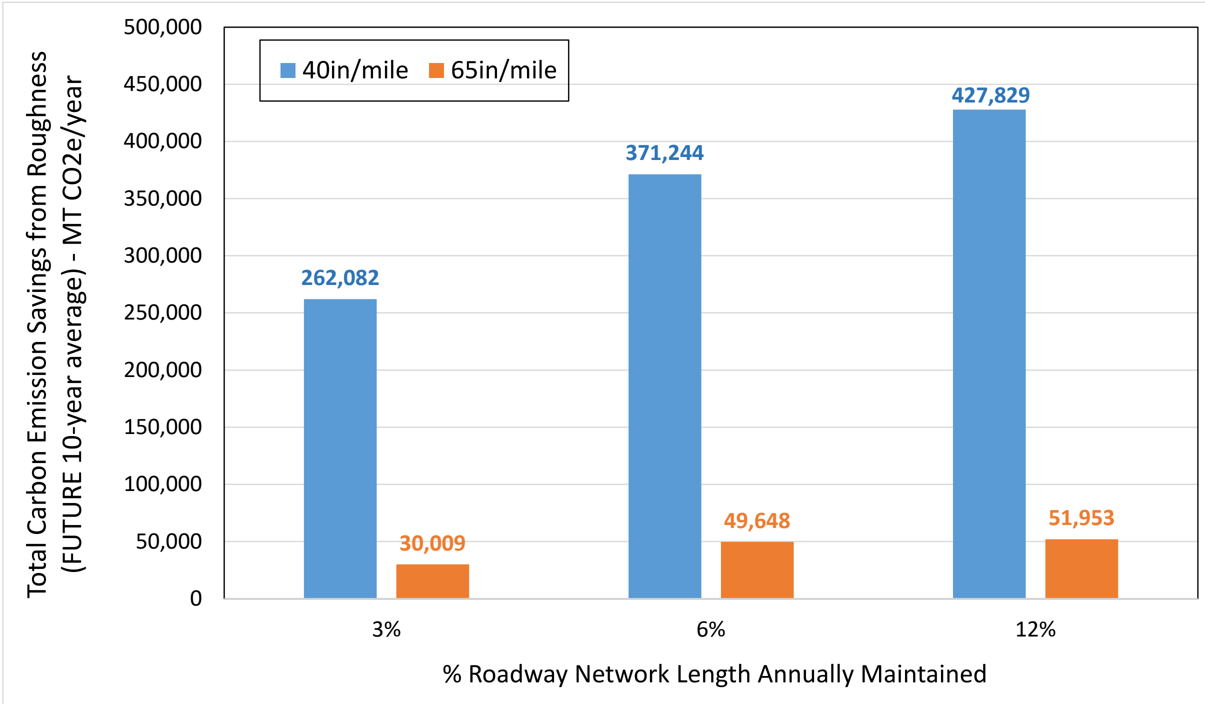

(b)

Figure 4.17: Annual CO_2 emission savings from road roughness over a 10-year period (a) Emission savings when the top 3%, 6%, and 12% of the roughest road sections (highest IRI) are maintained annually, reducing road roughness to either 40 in/mile or 65 in/mile. (b) Emission savings when the top 3%, 6%, and 12% of the most heavily trafficked road sections are maintained annually.

5.0 SUMMARY AND CONCLUSIONS

Most roadway emissions are generated during the roadway's use phase rather than solely from the material production and construction stages. Therefore, emission reduction strategies should address all stages of the pavement life cycle. A comprehensive analysis that includes the pavement use phase effects is crucial for achieving a comprehensive cradle-to-grave approach in the long term. To achieve this objective, this study focused on quantifying the impact of roadway roughness on vehicle fuel consumption, tire wear, and the associated CO_2 emissions.

The impact of roadway roughness on CO_2 emissions and vehicle operating costs was determined using the final network-level dataset. World Bank's Highway Development and Management Models (HDM4) calibrated for U.S. vehicles and pavement conditions (Chatti and Zaabar 2012a) were used to determine the effects of roughness reduction and increases in on-road users' vehicle operating costs and CO_2 emissions. The entire process was modeled by developing a computer code to process the PMS data and calculate the roughness-related excess fuel consumption, tire wear, and the associated CO_2 emissions. The results of a preliminary cradle-to-gate LCA conducted by Proudfoot and Toneys (2022) were also used to compare ODOT's total annual CO_2 emissions to the CO_2 emissions that can be saved by reducing the network-level pavement roughness.

5.1 MAJOR CONCLUSIONS

1. Based on the analysis conducted with the past 20 years of ODOT roadway network's IRI data, if the roads were maintained to achieve an IRI level of 40 in/mile, on average, approximately 142 million dollars would have been saved annually. This amount exceeds ODOT's approximate yearly paving budget of ≈$110 million (for the years 2021-2024) (Coplantz 2023). If the roads were maintained to achieve an IRI level of 65 in/mile, an estimated approximately $45 million would have been saved annually.

2. Maintaining smoother roads with lower IRI levels significantly reduces CO_2 emissions and enhances long-term pavement performance. For an IRI of 40 in/mile, total annual CO_2 savings amount to 423,462 metric tons (MT), which is **2.3 times higher than ODOT's total annual emissions of 182,592 MT CO2e from all operations, including construction and facility emissions.** At an IRI of 65 in/mile, emissions savings drop to 134,927 MT CO2e annually but remain close to ODOT's total emissions.

   Higher road roughness leads to substantially increased CO_2 emissions, emphasizing the importance of maintaining smoother roads. Smoother pavements reduce dynamic truckloads by minimizing vertical axle movement, enhancing road longevity. While the emission and cost savings calculated here are substantial, they do not account for the long-term performance benefits, which are expected to further amplify the savings. **These findings underscore the critical need to prioritize roadway network maintenance to achieve smoother pavements, benefiting both environmental and economic outcomes.**

3. When the impact of EVs is not simulated in the analysis, maintaining 6% of roads to an IRI of 40 in/mile is projected to save approximately $88 million per year, primarily from reduced fuel consumption and tire wear. However, at an IRI of 65 in/mile, savings drop to $58 million per year.

   When EVs are included, total cost savings decline slightly due to their reduced dependence on fuel. Under Federal EV adoption predictions, savings for roads maintained at 40 in/mile are approximately $83 million per year, and $54 million per year for 65 in/mile. With Oregon's higher EV adoption projections, savings further decrease to $77 million for 40 in/mile and $50 million for 65 in/mile.

4. In one simulated scenario, maintenance decisions were based on traffic levels rather than IRI levels. This approach yielded significantly higher cost savings at a 40 in/mile IRI target due to the larger number of vehicles and the resulting higher potential vehicle operating cost (VOC) savings. However, savings dropped sharply when roads were maintained to a 65 in/mile IRI level**. High-traffic roadways, such as the I-5 corridor, are typically prioritized for maintenance and already have average IRI levels close to the 65 in/mile target after maintenance. As a result, savings are lower when traffic levels dictate maintenance priorities.**

   These findings suggest that after-construction IRI targets for high-volume pavements should be set below the current standard of 60 in/mile. When achieving a 40 in/mile target is not feasible in the short term, maintenance decisions should focus on keeping IRI levels as low as possible, ideally below 65 in/mile. Similar conclusions apply when considering the associated reductions in CO_2 emissions, further emphasizing the benefits of smoother roadways.

5. For the Oregon-EV predictions scenario, annually maintaining 6% of roadways ranked by traffic levels and reducing the roughness from 65 in/mile to 40 in/mile is projected to generate approximately $122 million in yearly savings. However, reducing the roughness to 40 in/mile might be challenging for some of the cases and would increase the paving costs. **However, even when the roughness is reduced to 50in/mile and 55 in/mile, the savings (compared to 65 in/mile savings) will be around $73.2 million and $48.8 million, respectively. <u>Regardless of the specific level, targeting an IRI level lower than the current 60 in/mile will create significant savings even when it is not possible to achieve 40 in/mile during construction.</u>**

6. When maintaining 6% of roadways with the highest IRI levels over 10 years, reducing roughness to 40 in/mile yields annual CO_2 emission savings of 231,431 metric tons (MT), while a 65 in/mile target reduces savings to 151,181 MT CO_2/year. These values are comparable to ODOT's annual emissions of 182,592 MT CO_2/year (Figure 4.11).

   Introducing Federal EV adoption projections slightly reduces these savings, with emissions savings at 220,985 MT CO_2/year for 40 in/mile and 144,416 MT CO_2/year for 65 in/mile.

Under Oregon's higher EV adoption predictions, savings decrease further to 209,956 MT CO_2/year and 137,246 MT CO_2/year, respectively.

These findings highlight that EV adoption slightly mitigates emissions from road roughness, but maintaining smoother roads at lower IRI levels remains critical for maximizing emission reductions.

7. Analyzing the annual maintenance of the top 6% of roads with the highest traffic levels reveals substantial potential emission savings. Without accounting for EVs, maintaining roads at an IRI of 40 in/mile results in annual savings of approximately 385,012 MT CO_2, significantly higher than the 54,410 MT CO2 saved at 65 in/mile. **Achieving a smoother roadway network by increasing ODOT's paving budgets could generate annual emission savings exceeding twice the emissions from ODOT's operations over the next decade.**

   As with previous analyses, the inclusion of EVs slightly reduces the potential emission savings from roughness-related fuel consumption and tire wear, while smoother roads remain a critical strategy for maximizing environmental benefits.

8. Although the wide adoption of electric vehicles brings environmental and financial benefits, it does not drastically affect the savings from roughness-induced costs and emissions since, within the next 10 years, the percentage of EVs will not be very high. In addition, EVs are also not carbon-free, and electricity production also has a carbon footprint. With the adoption of EVs, electricity usage will significantly increase worldwide, which will also make electricity savings important. Accordingly, improving the energy efficiency of vehicles through smoother pavements will always be critical.

9. The cost and emission savings for annually maintaining the top 3%, 6%, and 12% of the road sections with the highest IRI and highest traffic levels were also assessed.

   For the highest IRI ranking:
   When 3% of the network is annually maintained to reach an IRI level of 40 in/mile, the potential cost savings are reduced to around \$49 million per year, increasing to about \$77 million per year for 6% of the network and rising further to \$126 million per year when 12% of the network is maintained annually. For the 65 in/mile scenario, as expected, the cost savings are lower, starting at approximately \$34 million per year when 3% of the roughest sections are maintained, increasing to about \$50 million per year for 6%, and reaching \$69 million per year when 12% of the roughest sections are maintained.

   For the highest traffic level ranking:
   In the 40 in/mile scenario, the cost saving is at approximately \$99 million per year when the top 3% of high-traffic sections are maintained, rising to about \$140 million per year when 6% of the network is maintained and reaching nearly \$159 million per year for 12% of the network. For the 65 in/mile scenario, the costs are lower, starting at around \$11 million per year for 3%, increasing to \$18 million per year for 6%, and reaching \$18 million per year when 12% of the most heavily trafficked sections are maintained. This significant reduction

in savings due to increasing the “after construction IRI levels” from 40 in/mile to 65 in/mile is a result of the lower roughness of the high-traffic volume roadway sections in Oregon. Since more frequent maintenance is generally performed in those areas, reducing their IRI levels to 65in/mile is creating benefits that are less significant. For this reason, for the high-traffic volume roadways, the best strategy would be to reduce the IRI levels to lower than the current 60 in/mile target. Another strategy might be to make decisions based on IRI ranking rather than traffic levels.

Similar results were also obtained in terms of emissions savings and presented in 4.5.3.2. All these results prove the significance of roadway roughness for reducing road user costs and the associated emissions.

10. In Oregon, newly paved road sections are required to have a maximum IRI of 60 in/mile, according to current standards (ODOT Pavement Services Unit 2019). However, with continued investment in research and innovation, proper construction equipment, and high-quality and more uniform materials, achieving an IRI of 40 in/mile is feasible. By reaching this smoother surface standard, significant savings can be realized in terms of reduced fuel consumption and tire wear, both of which are directly impacted by pavement roughness. Achieving a smoother pavement surface also improves driving comfort and safety. As also stated in the Introduction section of this report, smoother pavements last longer due to lower dynamic truck loads (See Table 1.1). This results in improved overall performance, durability, emission levels, and safety (due to less frequent construction) for smoother pavements.

5.2 FUTURE WORK

Although the current ODOT target for “after construction IRI” is 60 in/mile, this roughness level can easily be reduced by modifying the asphalt mixture properties, improving the construction processes by increasing uniformity (avoiding aggregate or thermal segregation), and reducing the excessive compaction effort during construction. In addition, the roughness levels of existing roads can be reduced by monitoring roadway roughness using inertial profilers and reducing the high roughness of the roadway sections by maintenance or diamond grinding to remove high-profile areas that increase vertical axle movements.

Reduced roughness will also improve pavement performance by reducing the vertical dynamic truck loads (see Table 1.1). Those performance benefits should be simulated in a future research study using Oregon's existing inertial profiler datasets, numerical modeling, and physical testing with different vehicle types on various pavement types. Using the quantified impact of roadway roughness on pavement durability, performance benefits should be evaluated. Using the quantified performance benefits, the cost and emission benefits from less frequent maintenance should be determined and included in the pavement LCA processes to achieve more realistic cradle-to-grave assessments.

Although smoother pavements provide significant cost and emission savings, it may be costly to reduce the pavement roughness to lower levels. For this reason, the additional cost and emissions associated with more paving and efforts to achieve smoother pavements should be quantified and incorporated into the analysis to improve the accuracy of the predictions.

The algorithm and the Python code developed in this study should also be applied to other roadways managed by counties and cities in Oregon to achieve a more comprehensive assessment of the roughness impact on Oregon road users and the environment.

This study used the conversation equations developed in the NCHRP 720 report (Chatti and Zaabar 2012a). Although those models were reliable and used by several other research studies in the literature, more unique models developed for Oregon roadways may provide more accurate results for cradle-to-grave pavement LCA processes. For this reason, a research study (with several vehicle types with installed fuel meters) should be conducted on Oregon roads to directly measure the impact of roughness on excess fuel consumption and tire wear and the associated CO_2 emissions.

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