



Pavement Roughness and Fuel Consumption

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EXECUTIVE SUMMARY

Problem

Rough roads are about more than just an uncomfortable ride. The roughness of a road is one indicator of how soon a road needs maintenance or reconstruction, which is tied to federal and state budget allocations. Furthermore, rougher roads can decrease the efficiency of a vehicle, increasing fuel use and greenhouse gas emissions. While roughness is a common measurement around the world, its impact on fuel efficiency is less understood.

Approach

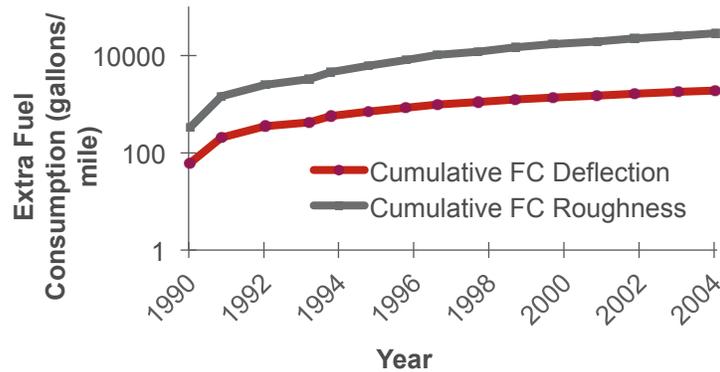
The roughness of U.S. roads is regularly measured by state and federal officials. Measurements are compared using a standard scale, known as the International Roughness Index (IRI), providing one metric in the set of criteria officials use to prioritize failing roads for maintenance and distribute budget funding appropriately. The consistency and regularity of roughness measurements has led to a robust database: the Federal Highway Administration (FHWA) Long Term Performance program (LTPP).

The CSHub leveraged LTPP data to understand the impact of roughness of fuel efficiency. To do so, roughness data was first linked to pavement materials and structure. Analyzing how roughness levels evolve on a given road segment over time sheds light on how different designs perform over time in terms of roughness. Secondly, data on traffic patterns can be connected to LTPP data, revealing the impact of traffic type and volume on pavement roughness over time. Finally, these analyses were combined and linked to the World Bank's commonly used fuel consumption model to estimate roughness-related fuel use over the lifetime of a road.

Findings

The LTPP data show that all common pavement types deteriorate at roughly the same rate, with the continuously reinforced concrete pavement displaying slightly lower deterioration rate. Adding the additional complexity of traffic volume, more significant differences emerge within the pavement types. Pavements with more structural support have the lowest deterioration rate, with continuously reinforced concrete again performing the best.

A case study was performed to relate fuel efficiency to roughness for one LTPP study area from 1990-2004. The CSHub found that roughness alone contributed to the consumption of an additional 30,000 gallons per mile for the representative road section over the study period, as shown in the figure. This equates to the cumulative release of 300 tons of CO₂ per mile of pavement. While this information points to the importance of maintaining roads to reduce roughness, additional work needs to be done to understand how representative this pavement section is of the U.S. roadway system. The impact of roughness, coupled with the pavement deterioration rate and road design, can help stakeholders understand ways to leverage road design and maintenance schemes in order to minimize fuel use and greenhouse gas emissions and maximize the use of limited road construction and maintenance funding.



Cumulative roughness-related fuel consumption for roughness and deflection for traffic traveling over a sample road over the course of 14 years.

Key Points:

- Roughness is a key metric used to monitor and maintain our nation's roadways.
- The Concrete Sustainability Hub developed a method to use existing roughness and traffic data to estimate roughness-related fuel consumption in relation to pavement material and structure.
- A sample case study shows a significant impact on fuel consumption due to roughness, with an increase in consumption of 30,000 gallons of fuel per mile over a 14-year test period.

1 INTRODUCTION

Most of us have experienced a bumpy ride at some point, whether on a backcountry road or an inner-city side street. In fact, roughness is probably one of the better-understood properties of pavements, both in a qualitative way by the average driver or passenger, and in a quantitative way by road engineers. Roughness simply means how bumpy or smooth a road is, which is an indicator of not only how comfortable your ride will be, but also the wear and tear on your vehicle, its fuel efficiency, and the maintenance needs of the road.



A road displaying rough and smooth pavement textures (Photo credit: Fernando Mafra).

Roughness is a metric associated with pavement-vehicle interaction (PVI), an umbrella term referring to the myriad resistive forces that a car experiences as it travels down a road. PVI is generally attributed to three primary factors: roughness (the focus of this report), surface texture, and deflection. In a previous CSHub report, *Where the Rubber Meets the Road: Estimating the Impact of Deflection-Induced Pavement-Vehicle Interaction on Fuel Consumption* (Akbarian 2013), deflection's effect on fuel efficiency is modeled by means of a road's materials and design. This novel approach provides a robust quantitative means for understanding deflection, which has the potential for incorporation into life cycle assessment (LCA) models used to quantify environmental impacts. Further, it allows for deflection-induced fuel consumption to be inferred rather than measured, since the actual physical presence is quite small and challenging to measure.

Roughness, on the other hand, is a well-established measurement. The U.S. National Cooperative Highway Research Program published overarching guidelines for measuring roughness in 1980 (Gillespie 1980) that were then built upon by the World Bank (Sayers 1986). Out of this work, the International Roughness Index (IRI) was developed and widely-adopted as the scale by which the roughness of a road can be defined. The IRI offers stakeholders a measurement that, when used alongside other metrics, a way to understand the state of a region's roadways as well as to prioritize roadways for maintenance or reconstruction. Further, because roughness is regularly measured throughout the US, it allows for a glimpse into how quickly or slowly a pavement degrades over time.

This report will provide a background on how roughness is quantified and interpreted, as well as insight into the limitations of our understanding of roughness. A CSHub analysis of the state of the US road network in terms of roughness will be presented. Along with how roughness changes over time for different pavement designs and traffic patterns. Finally, the report will discuss CSHub efforts to link roughness to fuel efficiency, similar to what has been done with deflection, estimating the aggregated impact of pavement roughness on fuel consumption in the US.

2 REALIZING ROUGHNESS

Roughness is an indicator of the state of a roadway, often used with other metrics to characterize the health of a road network as a whole as well as to prioritize road segments for maintenance and reconstruction. As such, roughness is frequently tied to road repair budget allocations and estimations for Departments of Transportation and the Federal Highway Administration (FHWA). NGOs often use the same data to make claims about the state of roadways. For example, in 2009, the American Association of State Highway and Transportation Officials (AASHTO) conducted an analysis of the American road system based on 2007 FHWA roughness data (2009). They found that 13% of US roads are in poor condition, most of which were located in urban areas that regularly experience high traffic levels. AASHTO then used roughness levels to predict upcoming maintenance costs, estimating, for example, that Oregon would need to spend \$200 million over the next 10 years to maintain the current condition of the road system.

It's clear that roughness measurements are a key metric for stakeholders to estimate upcoming costs. As such, understanding how roughness is measured is an important element to interpreting statistics published by AASHTO and other agencies. This section will provide an overview of the mechanics of the measurement itself as well as how it is used within the US.

2.1 Measuring Roughness

Potholes, ruts, and cracks are obvious symptoms of a rough road, however, roughness also exists on a micro-scale in terms of the smoothness or roughness of the pavement surface's texture. A driver's perception of roughness is subjective, depending on the type of vehicle, speed, and individual's sensitivity. The American Society for Testing and Materials (ASTM) defines pavement roughness as "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality"(American Society for Testing and Materials 2012). The FHWA follows the AASHTO Standard Practice for Determination of International Roughness Index for Quantifying Roughness of Pavements (American Society for Testing and Materials) as its standard method for measuring pavement surface conditions nationwide. Adopting this standard allows for a universal measurement throughout the country, enabling comparison of roadways on a national scale.

Roughness as a measurement refers to the amount of variation of a roadway's surface from a baseline profile. Typically, agencies deploy specialized devices, known as response-type road roughness measurement systems (RTRRMS), outfitted with sensors to measure a road's profile at prescribed intervals as the vehicle travels down the road at a constant speed, usually 50 mi/hr (80 km/hr). One example of an RTRRMS, shown in Figure 1, is equipped with five lasers for accurate measurement across the span of the road. Alternative measurement sensors include a profilograph, BPR Roughometer, or Dipstick.

The sensors record the depth of the dips and height of the humps along a road section, which are then aggregated to produce a value for roughness. The resulting measurement is typically expressed as in/mi or m/km. The value is considered as a “quarter-car simulation,” since most RTRMS devices are based on the movement of a single wheel.

While the standard for measurement of IRI is clearly defined, the actual practice of measurement is often challenged by real world conditions. For example, it’s not always possible to maintain a constant speed on a roadway; naturally, traffic lights, road accidents, and unpredicted traffic can slow down the measurement vehicles. Also, it’s common that a road section is comprised of multiple materials, e.g., a roadway may be primarily asphalt but the intersection is concrete. In response, the FHWA provides a series of recommendations to address these issues and attempt to ensure data compatibility. For example, for multi-lane roads, only data for the outermost lane is reported. Further, data should be gathered only under good weather conditions and in minimal winds, and ideally at times of minimal traffic. Finally, only pavement surfaces should be considered, therefore measurements from bridges or railroad crossings should be excluded from a roadway’s score. These specifications help to minimize uncertainty within measurements, however the inherent variability of real-world data should be considered when analyzing IRI data.



Figure 1. An example of a vehicle fitted with roughness measurement equipment (Photo credit: Grupo Inzamac)

2.2 The International Roughness Index

Roughness values gathered by the industry standard can be compared using the International Roughness Index. The Index was initially proposed by the World Bank in an effort to standardize the characterization of road conditions globally (Sayers 1986). The scale originated from the International Road Roughness Experiment, a research collaboration that took place in Brazil in 1982. Researchers took controlled measurements by various means and under various conditions. The resulting scale, shown in Figure 2, is still in use around the world. The IRI scale has received some criticism because of its development in Brazil, where the road conditions may or may not align with other region’s road conditions. Some efforts have been made to calibrate the IRI scale to US conditions, such as in Zabaar and Chatti IRI scale-based fuel efficiency model. Regardless, the internationally accepted IRI scale is still the de facto scale for most agencies, including the FHWA and state DOTs.

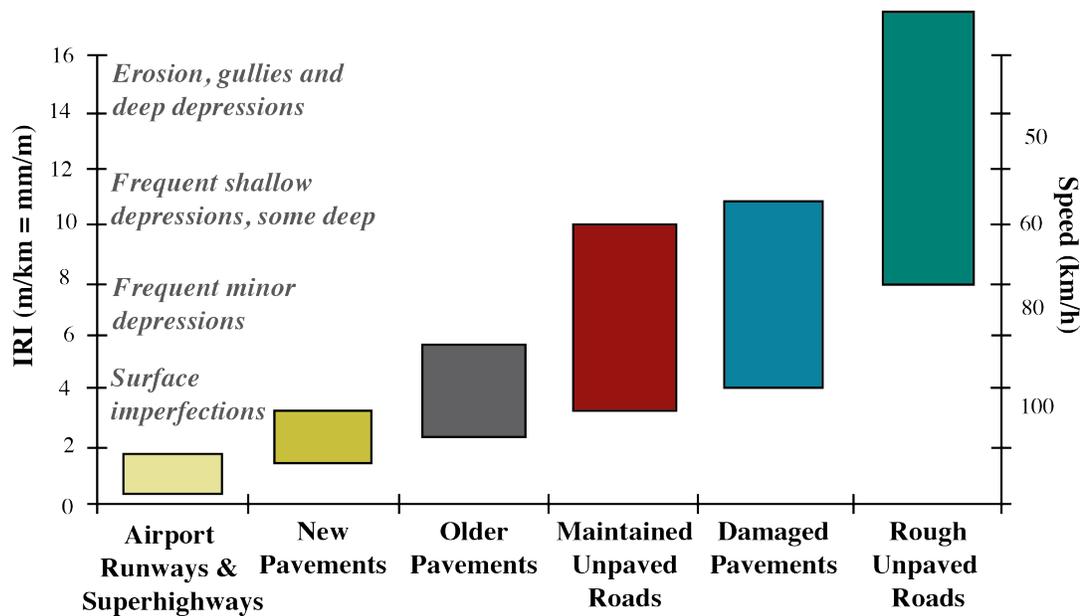


Figure 2. The International Roughness Index scale (Adapted from Sayers, et al (Sayers 1986))

2.3 IRI in the USA

In 1998, the FHWA first adopted a strategic plan to improve the rideability of U.S. roadways, such that 93% of roads were of an acceptable quality within 10 years (Federal Highway Administration 1998). The IRI was adopted as the metric, with the FHWA defining a ‘good’ value as less than 95 inches per mile and ‘acceptable’ as less than 170 inches per mile. Since that time, the program’s goals have been scaled back, with the primary focus shifting to maintaining smoother high traffic roads as well as good to acceptable IRI values for the highway network as a whole (Federal Highway Administration 2011).

On a federal level, data on pavement roughness are regularly gathered as part of the Long Term Pavement Performance program (LTPP), which was initiated by the federal government in 1986. LTPP monitors over 2500 test sections throughout North America, as shown in Figure 3. The wide range of data is stored in a database that can be accessed by the general public (Long Term Pavement Performance Program 2003).

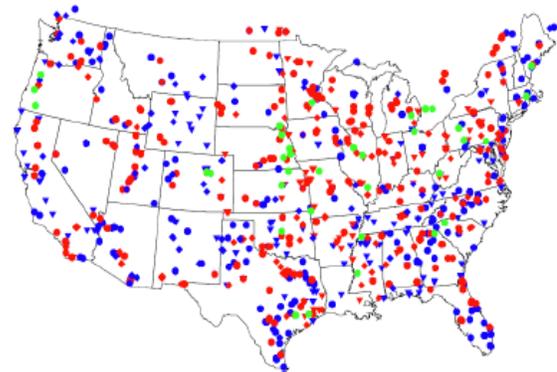


Figure 3. LTPP study sections: red dots denote asphalt study sections, blue dots are concrete, and green are composite pavements.

LTPP conducts their pavement monitoring on General Pavement Studies (GPS) sections and Specific Pavement Studies (SPS) sections. The CSHub uses the GPS sections as a representation of the US roadway network conditions. These sections are layered structures of asphalt, concrete, or composite, which is a combination of the two materials. Table 1 shows a description of each section.

Pavement Type	Section Name	Description
Asphalt Concrete (AC)	GPS-1	Asphalt Concrete on Granular Base
	GPS-2	Asphalt Concrete on Bound Base
Portland Cement Concrete (PCC)	GPS-3	Jointed Plain Concrete Pavement (JPCP)
	GPS-4	Jointed Reinforced Concrete Pavement (JRCP)
	GPS-5	Continuously Reinforced Concrete Pavement (CRCP)
Composite	GPS-6	Asphalt Concrete Overlay of Asphalt Concrete
	GPS-7	Asphalt Concrete Overlay of Concrete Pavement
	GPS-9	Unbound Concrete Overlay of Concrete Pavement

3 IRI AND PAVEMENT DETERIORATION

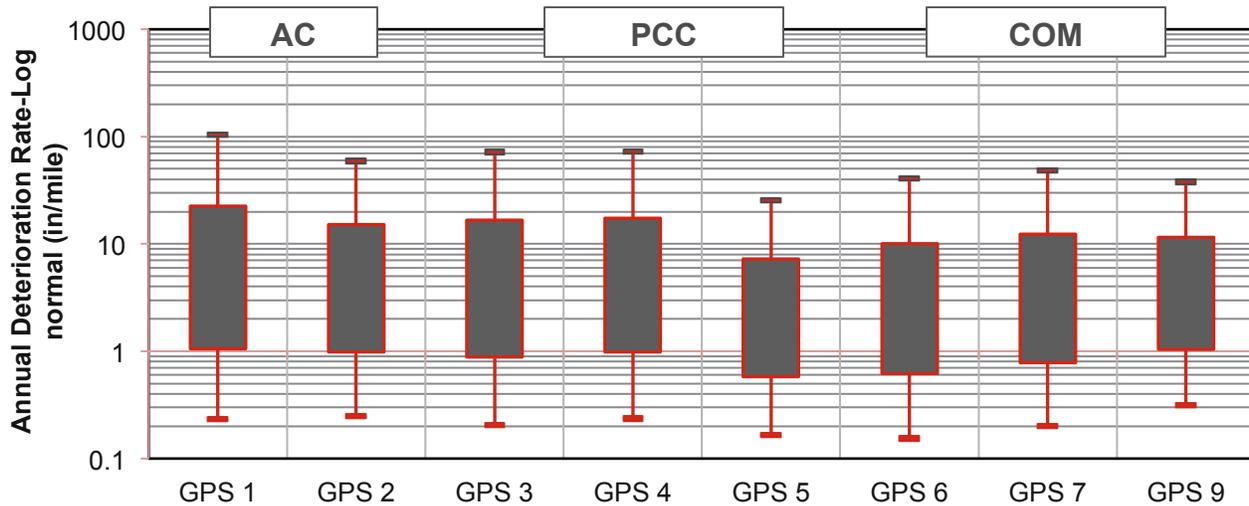
While roughness is a direct, on-the-ground measurement, a more important factor for many who use these data is the rate of change in roughness over time. Monitoring how roughness values change over the life of a roadway gives practitioners valuable insight into how a particular pavement design holds up to unique climatic and traffic conditions. This understanding has the potential to improve roadway design by selecting designs and design features that deteriorate more slowly in order to decrease maintenance needs over the life of a pavement. Simply put, roads that deteriorate more slowly will decrease maintenance needs -- reducing costs for already cash-strapped state and federal transportation agencies.

So why do some roads deteriorate faster than others? Because roads are complex structures that are exposed to the elements and battered by traffic; there are numerous influences that can cause pavement to become rougher. This section will highlight two factors that can be connected directly to an increase in roughness, and thus, deterioration in the pavement's quality: pavement design and traffic.

3.1 Pavement Design

Pavement roughness begins to surface as soon as a road is installed and increases as traffic

and climatic effects take their toll, eventually reaching a point where the pavement has deteriorated so much that it needs maintenance. While pavement roughness gives you an idea of current pavement conditions, a potentially more interesting story forms when you observe the rate of change in roughness over time, or the pavement deterioration rate, for different types of roads.



GPS 1: AC on Granular Base; GPS 2: AC on Bound Base; GPS 3: Jointed Plain CP; GPS 4: Jointed Reinforced CP; GPS 5: Continuously Reinforced CP; GPS 6: AC over AC; GPS 7: AC Over PCC; GPS 9: PCC Over PCC

Figure 4. Log-normal distribution of the annual roughness progression rate for the eight pavement types listed in table 1. Data extracted from the LTPP database release #25. Data show one (box) and two (bars) standard deviation from the mean.

LTPP GPS sections include information on pavement material and design, allowing a combined study of pavement type and its deterioration rate. Figure 4 shows the annual deterioration rates of three different pavement designs: asphalt, Portland cement concrete, and composite designs. The results show that the pavement deterioration rate of all pavement types are on the same order of magnitude, with continuously reinforced concrete pavements (GPS-5) having the lowest deterioration rate at the 95% confidence bounds.

3.2 Traffic

The US road system is made up of a mix of road types, ranging from multilane highways to rural roads. The volume of traffic on roadways is estimated by individual states as part of the FHWA’s Highway Performance Monitoring System (Federal Highway Administration). States gather data on traffic volume for various road types according to federal standards, which can be aggregated into useful traffic volume metrics like annual average daily traffic (AADT) and annual average daily truck traffic (AADTT). These measurements are used by the federal government to dole out federal highway funding, but, in terms of this report’s objectives, can

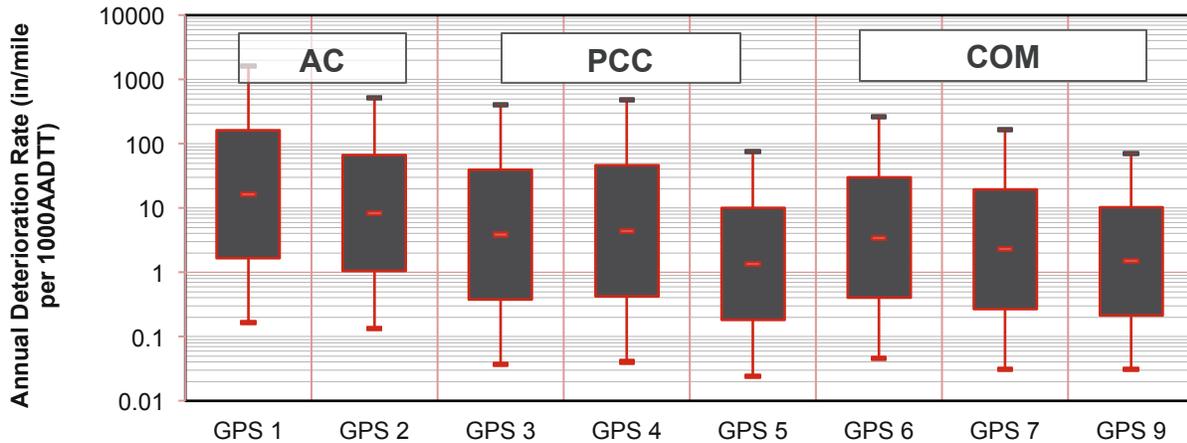
also be used to understand how traffic volumes impact the rate of pavement deterioration in terms of roughness.

The impact of traffic goes beyond simply the amount of cars traveling on a road – the type of traffic also influences pavement deterioration. The fact is, heavy vehicles, such as trucks and buses, are harder on roads than cars. For example, a fully loaded tractor-trailer is roughly 20 times heavier than a passenger car, but its impact on the roadway is disproportionately larger. A 1979 study by the General Accounting Office asserted that the pavement damage of one truck is equivalent to 9600 cars (U.S. Comptroller General 1979). The level of damage depends on each vehicle's weight. With AASHTO's prediction that the volume of freight carried by trucks will increase by 62% by 2020 (2003), the impact of truck traffic on pavement deterioration will likely grow in significance.



Traffic congestion (Photo credit: Sobre Pelayonex)

In this study we normalize the pavement deterioration rate to the pavement's loading condition: truck traffic. The traffic volumes are extracted in the form of AADTT values for the GPS sections of the LTPP database. Results are shown in figure 5. The response of different pavement systems in terms of pavement deterioration rate is more distinct when normalized to the traffic loading. Pavements that deteriorate slower, are at the bottom of the distribution boundaries with lower deterioration rates. An order of magnitude difference in pavement deterioration rate is seen at lower and upper bounds between the pavement sections, especially in the case of the continuously reinforced concrete pavements (GPS-5) with lower normalized deterioration rates than other section types. This analysis is performed as a first order estimate by only accounting for the impact of truck traffic on the development of IRI. Further, accounting for other external factors can shed more light on the impact of pavement type on the normalized deterioration rate. Since such level analysis is only possible with a large set of sample data, state level analyses are being performed that represent a majority of highway conditions in the state.



GPS 1: AC on Granular Base; GPS 2: AC on Bound Base; GPS 3: Jointed Plain CP; GPS 4: Jointed Reinforced CP; GPS 5: Continuously Reinforced CP; GPS 6: AC over AC; GPS 7: AC Over PCC; GPS 9: PCC Over PCC.

Figure 5. Log-normal distribution of the annual progression rate for eight pavement types shown in table 1 normalized to AADTT. Data extracted from the LTPP database release #25. Data show one (box) and two (bars) standard deviation from the mean.

4 IRI AND FUEL CONSUMPTION

Bumpy roads increase the amount of resistance a vehicle experiences as it travels down the road, similar to how driving into a strong headwind requires additional fuel to maintain a certain speed, though on a smaller scale. Increased resistance translates to an increase in fuel consumption. The level at which fuel efficiency is affected is heavily tied to the condition of the roads, or the pavement-vehicle interaction. Roughness is the leading influence of PVI and, therefore, is a key indicator of fuel efficiency. This section will briefly provide an overview of how PVI-related fuel efficiency is calculated as well as the results related to roughness.

There are various models available for estimating fuel consumption of a vehicle under different operating, weather, and pavement conditions. One commonly used model, the World Bank's Highway Design and Maintenance Standards Model (HDM) versions HDM-3 and HDM-4, accounts for the impact of PVI as part of the rolling resistance forces. In 2010, Zaabar and Chatti calibrated the mechanistic HDM-IV model for vehicles currently used in the United States. They investigated the impact of pavement condition on vehicle fuel consumption, namely the impact of pavement roughness for five different vehicle classes (medium car, SUV, van, light truck, articulated truck) under different operating, weather, and pavement conditions.

(Zaabar 2010). Figure 6 shows a clear trend in the increase of IRI with an increase in fuel consumption.

For this report, a case study was conducted to determine the effect of PVI on fuel consumption for one section of road using the HDM-4 model and the CSHub deflection model. While this case study only addresses a small section of road, it demonstrates the impact of IRI and also the method for connecting IRI with fuel consumption.

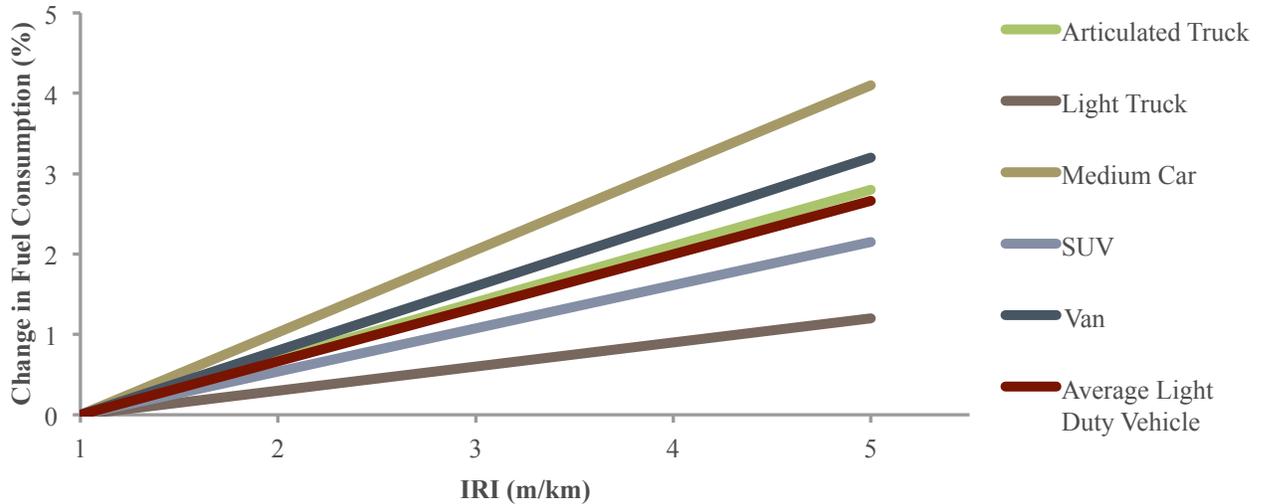


Figure 6. Effect of pavement roughness of fuel consumption (Adapted from Zaabar and Chatti (Zaabar 2010))

4.1 Case Study: Fuel Consumption, IRI, and Deflection

A section from the LTPP database was selected to estimate the impacts of PVI on vehicle fuel consumption throughout its lifetime, 1990-2004 in this case. Table 2 shows the information extracted from the LTPP database on this section.

Table 1 LTPP data used for case study

Section ID	31-3018
Experiment Number	GPS-3 (JPCP)
Lifetime	1990-2004
Deflection Data	- Layer thicknesses - Layer moduli
Roughness Data	- Annual roughness: IRI
Traffic Data	- AADT - AADTT - Number of lanes

Figure 7 shows the change in IRI between 1990-2004. The pavement deterioration rate is calculated from this figure based on the slope of the line. The annual deterioration rate is then normalized to the AADTT volumes, shown in Figure 8.

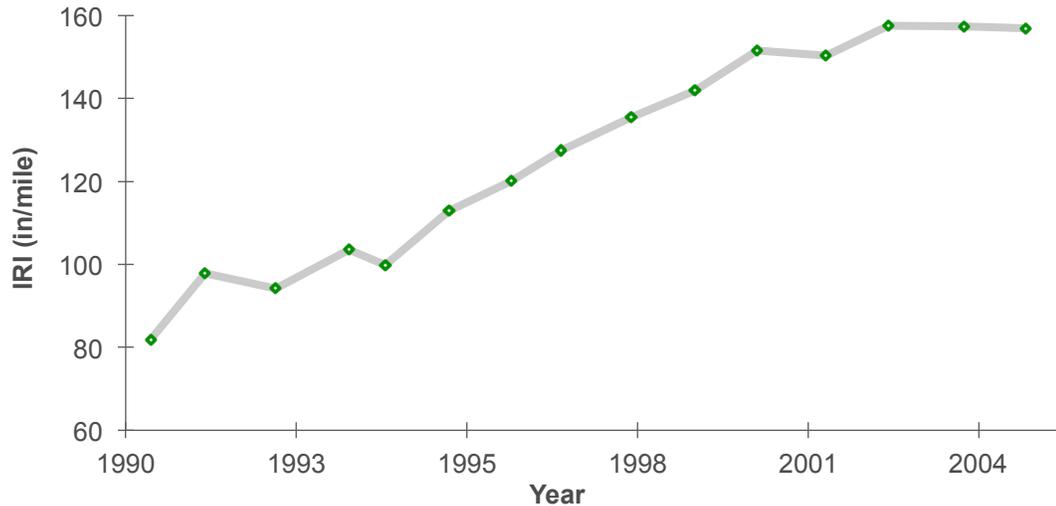


Figure 7. Evolution of IRI from 1990-2004 for GPS-3 section number 31-3018 of the LTPP database.

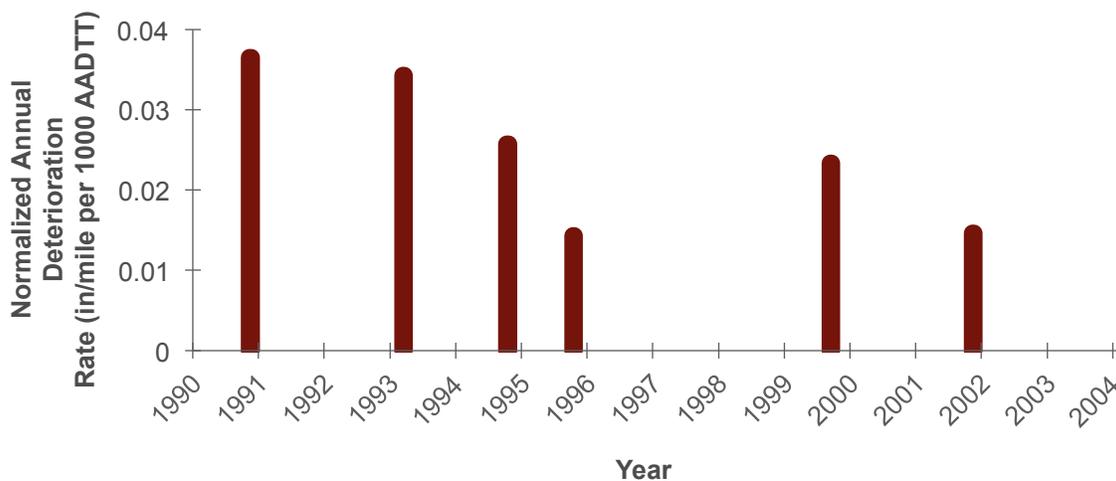


Figure 8. Pavement deterioration rate normalized to the annual average daily truck traffic (AADTT) for GPS-3 Section number 31-3018 of the LTPP database

Figure 9 shows the cumulative excess fuel consumption (FC) due to PVI from 1990-2004 for the traffic using this section of road. Roughness dominates the PVI impact on fuel consumption and is an order of magnitude larger than the impact of deflection. The combined excess fuel

consumed over this period is over thirty thousand gallons per mile, accompanied by release of three hundred tons of CO₂ per mile of pavement. The greenhouse gas (GHG) impacts are shown in Figure 10.

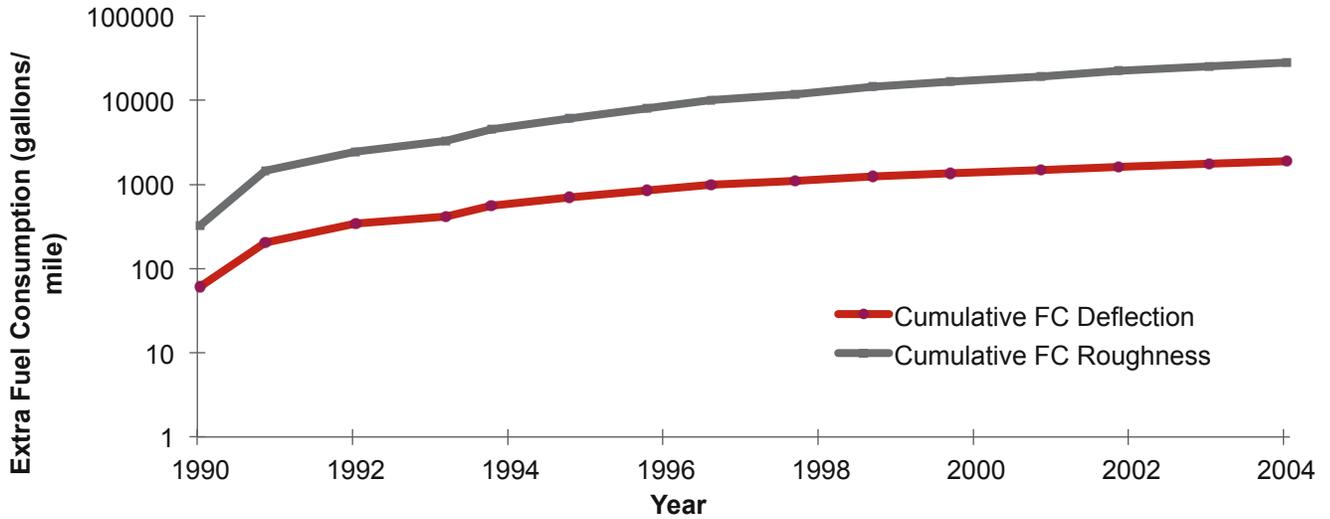


Figure 9. Cumulative fuel consumption due to deflection and roughness impacts of PVI from 1990-2004 at the 95% confidence intervals, for GPS-3 section number 31-3018 of the LTPP database.

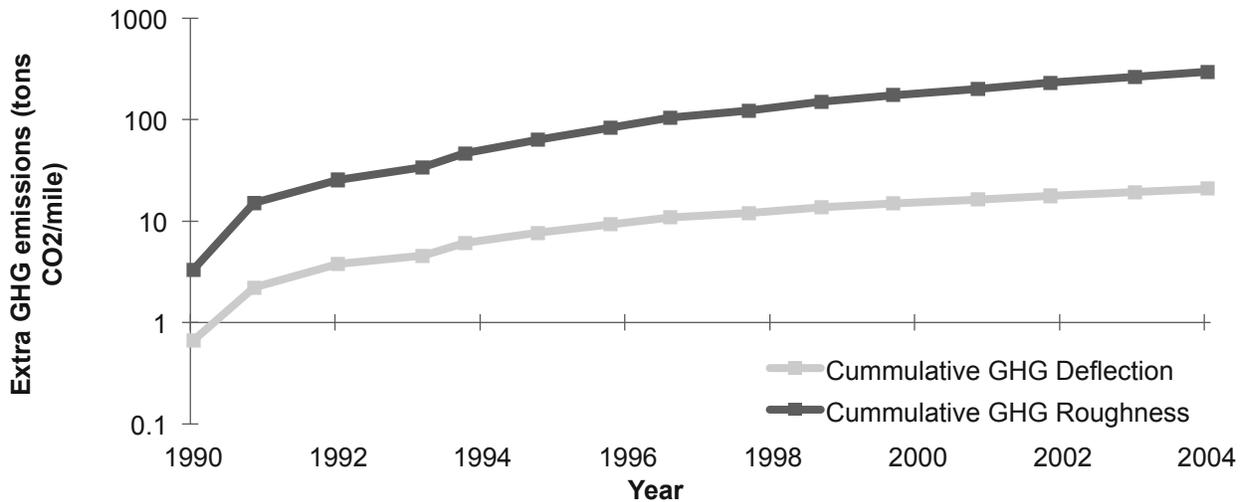


Figure 10. Cumulative GHG emissions due to deflection and roughness impacts of PVI from 1990-2004 at the 95% confidence intervals, for GPS-3 section number 31-3018 of the LTPP database.

5 CONCLUSION

Roughness is an important measurement of a road's health. Roughness and its associated IRI index are commonly used around the world, thus providing a standard platform for comparison of road networks. In the US, state and federal agencies gather roughness values every year, using the data to help prioritize road maintenance and reconstruction, often coupled with other factors like traffic volume. In this way, roughness can dictate, at least partially, the federal funds to a certain state for highway maintenance. Other organizations, like the World Bank, use the values to understand road conditions in areas in order to, for example, understand the state of local roads when making business or infrastructure investments or to judge a country or area's road conditions. Because of the seemingly far-reaching impact of roughness measurements, it's important to understand where the numbers are coming from and the limitations on what you can practically understand from the measurements.

The wealth of data on road roughness allows for additional analysis. Evaluating the change in roughness levels over time in terms of pavement design and traffic volume can allow practitioners to understand how pavement designs hold up under real-world conditions. Understanding the rate of pavement deterioration can allow stakeholders to predict upcoming maintenance schedules on existing roads, as well as to select the best road design for new construction based on the specific needs of the location.

Finally, it is possible to use roughness and traffic data to understand how rough roads affect fuel efficiency and greenhouse gas emissions. Results show that rougher roads lead to a greater fuel consumption in the sample shown here, having a potentially huge impact when aggregated throughout the US road system. The impact of roughness, coupled with the pavement deterioration rate and road design, can help stakeholders understand ways to leverage road design and maintenance schemes in order to minimize fuel use and greenhouse gas emissions and maximize the use of limited road construction and maintenance funding.

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