Where the Rubber Meets the Road:
Estimating the Impact of Deflection-Induced Pavement-Vehicle Interaction on Fuel Consumption

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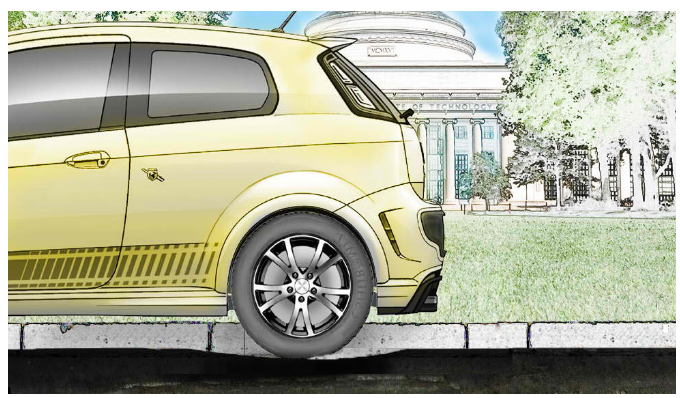
1 EXECUTIVE SUMMARY

Reducing fuel consumption is an important aspect of climate change mitigation. The US transportation sector burns over 174 billion gallons of fuel each year, making up 27% of total greenhouse gas (GHG) emissions, as well as contributing to human health concerns like smog, particulate matter, and NO_x. Common strategies for improving fuel efficiency include upgrading to higher efficiency vehicles or maintaining engine efficiency and proper tire inflation – all of which are difficult to regulate from a policy perspective. This report highlights the potential to improve efficiency through the design and maintenance of roadways, a lever that can be controlled by governmental agencies.

This study focuses on the dynamic interplay between a moving vehicle and the road, known as pavement-vehicle interaction, or PVI. PVI is tied to the vehicle and the road, as well as environmental forces like temperature and wind speed, which together influence the fuel consumption of a vehicle. There are three primary aspects of PVI related to the conditions of the road: pavement roughness, surface texture, and deflection.

Roughness is simply how bumpy or smooth a road is, and as you might imagine, rougher roads lead to higher fuel consumption. Road maintenance departments around the world measure roughness to determine when maintenance is needed on a roadbed. There is also an impact on PVI from pavement surface texture. Texture is most easily understood as is the abrasiveness of the road surface as you drag your hand across the surface. There are current efforts in relating surface roughness and texture to their impact on fuel consumption, although there is limited information on determining the impact of PVI texture. The focus of this report is on estimating the impact of the less understood phenomenon of deflection.

Deflection refers to the cumulative impact of the small dent in the pavement that a car creates as it drives down a roadway. This effect creates a slight, but perpetual uphill climb that can be more or less significant depending on the condition and structure of the roadway and the weight of the vehicle. Because the amount of pavement deflection is very small, it is challenging to physically measure. This report aims to fill this gap in understanding by proposing a method for quantifying deflection by modeling the properties of the roadbed, which is then used to estimate the impact of deflection on fuel consumption.



The model for deflection-induced PVI, developed by the Concrete Sustainability Hub (CSHub), estimates PVI through understanding the individual components that influence the deformation of the roadbed. Known as a beam on viscoelastic foundation model, the deflection-induced PVI model captures properties of the road's surface and substrate and the characteristics of the vehicle in order to quantify PVI. By examining each item individually, there is an opportunity to quantify the uncertainty related to each item, which provides an end result that is credible and transparent.

In order to ensure the model is delivering reasonable results, it was calibrated and validated using the Federal Highway Administration's Long Term Pavement Performance (LTPP) Database, which is robust set of data on road structures. The deflection predictions of the model show an acceptable level of accuracy when compared to field data and other real-world studies. However, there are a number of characteristics that are not yet included in the CSHub model. For example, cracking, rutting or joints in a road are not included.

To relate deflection to fuel consumption, a relationship was developed that characterizes the relative importance of a pavement's structural and material parameters along with vehicle weight (which defines the deflection) to external forces like slope and gravity which impacts the fuel usage. The scaling relationship shows that the thickness of the pavement has the most influence on fuel consumption, and both flexible and rigid pavements can be designed to reach similar fuel efficiency ratings. Using field data from the Federal Highway Administration, estimates on the impact of deflection on fuel consumption were created for passenger cars and trucks on concrete and asphalt roads. While these numbers are small, they become significant when aggregated to the US transportation fleet.

	Concrete	**Asphalt**
	Mean (Std. Deviation) [liters/100km]	Mean (Std. Deviation) [liters/100km]
Passenger Car	0.002 (0.0016)	0.012 (0.009)
Truck	0.013 (0.012)	0.077 (0.06)

This framework for understanding deflection allows for more precise estimates of environmental impact of roadways. This information fills a gap in understanding of pavement-vehicle interaction that has a potential to improve pavement design. The scaling relationship allows practitioner to toggle values for each pavement characteristic in a design setting, giving road designers a functional tool for optimizing road designs for fuel efficiency. Furthermore, it has been difficult to accurately model the impacts of the use phase of a roadway without this information, creating difficulties in life cycle assessment (LCA) studies. Enabling PVI estimation through LCA will provide a pathway for environmentally friendly road design and maintenance decisions. Additionally, understanding the impact of a roadway's design on fuel consumption gives policymakers a tool for mandating design and maintenance schedules that meet today's fuel efficiency goals as well as other environmental concerns, such as water conservation and air pollution.

Key Points:

Deflection-induced pavement-vehicle interaction is challenging to measure directly.

The Concrete Sustainability Hub’s deflection model allows for credible estimation of deflection based on a pavement’s materials and structure.

The model can be used to estimate fuel consumption of various vehicle types, providing a framework for environmentally friendly design and maintenance decisions.

2 INTRODUCTION

The US road system carries a huge volume of traffic. Each day, US vehicles drive a collective 8 billion miles. At this volume, it's easy to see how transportation is responsible for 27% of US greenhouse gas (GHG) emissions and the combustion of 174 billion gallons of fuel per year (Environmental Protection Agency 2009). While the use of fossil fuel-based transportation may be inevitable, improving fuel efficiency can create big change – for example, a 1% reduction in fuel consumption could cut GHG emissions by up to 15,500,000 tons of carbon dioxide per year. Upgrading to more fuel-efficient vehicles and maintaining vehicle engines and proper tire pressure are common tactics for improving fuel economy, however there is a further opportunity to reduce vehicle fuel consumption by improving the road itself.

The interplay between the road and the car is known as pavement-vehicle interaction, or PVI. There are three chief types of road-related PVI: roughness, texture, and deflection. Pavement surface texture and roughness refer to the conditions of the pavement's surface. Roughness is a common measurement of pavement conditions and work is ongoing to quantify its impact on fuel consumption. Texture is less understood though additional research is underway to determine its effect on PVI. The focus of this report is on PVI related to deflection.

Deflection is a similar phenomenon to what we experience when walking down a sandy beach. With each step, your foot sinks into the sand, creating an indentation that you then have to push out of to take your next step. Anyone who has tried running on the beach can attest that it is a much harder workout than running on pavement! This same effect, though less dramatic, takes place between a car and the road, as demonstrated by Figure 1.

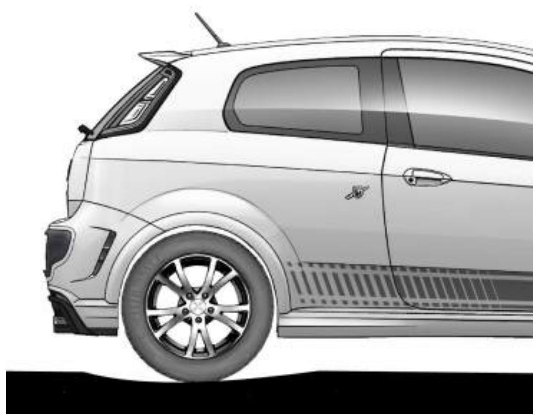


Figure 1 An illustration of pavement deflection.

While the impact of deflection-induced PVI on the fuel efficiency of an individual car is small, the cumulative impact can be quite significant when considering all of the vehicles on the road. Relating fuel consumption with pavement conditions and design properties can provide engineers and policymakers with a planning tool to optimize a road network's fuel efficiency. One potential assessment tool is life cycle assessment (LCA). When applied accurately, LCA can provide direction for investment strategies in pavement design, maintenance, rehabilitation, and reconstruction. This report investigates the causes and effects of pavement-vehicle interaction and offers methods for modeling deflection-related PVI that has the potential for inclusion into an LCA framework, a topic that will be covered in future reports.

3 PAVEMENT-VEHICLE INTERACTION

3.1 What is PVI?

Pavement-vehicle interaction, or PVI, refers to the effect of the road's condition and design properties on a vehicle. The main contributors to PVI are pavement roughness, texture, and deflection. As a pavement ages, its conditions deteriorate and roughness increases at rates depending on its design properties. There is a well-established metric for roughness, the International Roughness Index (IRI), which is used to make decisions regarding the maintenance of roadways, i.e. a bumpier road may be resurfaced sooner than a smooth road. Surface texture, such as how smooth or rough the pavement surface is, does affect fuel consumption, though there is not yet a way to account for this phenomenon. Surface texture, however, competes with safety concerns – smoother roads may lead to lower fuel consumption but can also increase accidents due to skidding.

Deflection-related PVI measures the cumulative impact of the small dent the car creates as it travels down a road. Because of the way energy is dissipated, the maximum deflection of the load is behind the path of travel, creating a small, but perpetual, uphill climb as the car moves forward. Deflection rates are related to the materials and structural properties of the road and the vehicle.

3.2 Where is PVI?

While the effect of PVI on individual vehicle fuel consumption may be small, its impact can become significant when considering the large number of vehicles that travel over a road during its lifetime. In fact, the increase in fuel consumption due to PVI for high traffic volume roadways, in some cases, can surpass the GHG impact of the road's construction and maintenance. Understanding the conditions that lead to increased PVI can help prioritize maintenance schedules and improve design decisions. The main factors that affect PVI are pavement design properties, conditions, vehicle type, and climate.

The US road network is made up of a combination of asphalt, concrete, and composite pavements. Pavement layers starting from the subgrade (ground), sub-base, base, and the top layer material include asphalt, concrete, aggregate, and stabilized (stiffened) aggregate layers. The choice of pavement type, asphalt or concrete, has an effect on PVI, however optimizing

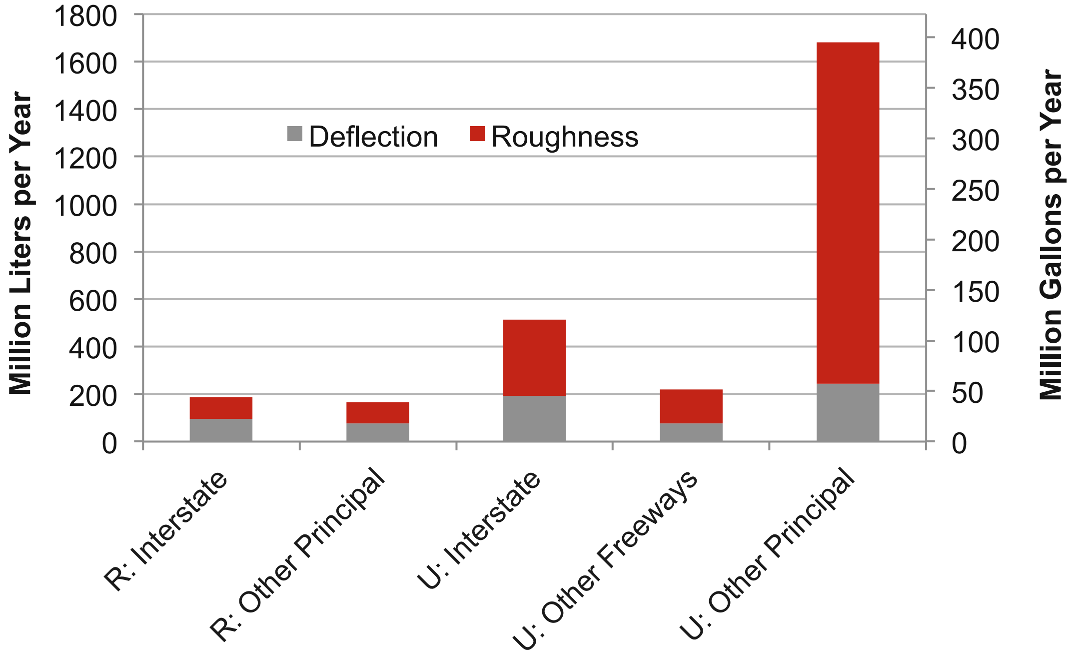


Figure 2 The impact of deflection and roughness of various types of US roadways.

for PVI is not as simple as selecting one material over another. The thickness and rigidity of the selected material and the substrate used beneath also have a significant impact on PVI.

The condition of the pavement, whether it's asphalt or concrete, and the traffic volume of roadway has an influence on fuel consumption of a road over its lifetime. As shown in Figure 2, the impact of roughness and deflection are on the same order of magnitude, except for Urban Other Principal Arterials where apparent higher roughness levels magnify the fuel consumption impact. In contrast, Interstates are generally better maintained, translating to higher gas mileage. This points to the potential for improved pavement management as a technique to improve fuel consumption of roadways, as well as a pathway to prioritize roads for improvement.

3.2.1 What affects PVI?

In general, roughness and deflection of a pavement are considered as the main contributors to pavement-vehicle interaction, however external factors such as local temperatures (tire, surface, air), tire pressure, vehicle suspension and others also have an influence on vehicle fuel consumption. In order to account for the impact of PVI in pavement LCA, all internal and external factors affecting fuel consumption are assumed constant and only the impact of the deflection-related interaction between pavements and vehicles is allocated to their life cycle.

To that end, the level to which PVI affects fuel consumption can vary considerably for different types of vehicles. As you might predict, a heavier vehicle creates a larger dent in the pavement as it rolls down the road. As such, trucks and vans will experience a larger change in fuel consumption than passenger vehicles due to deflection. The same is true for roughness; rougher roads have a larger impact on the fuel consumption of trucks over passenger cars. Figure 3 shows a summary of the impact of PVI on fuel consumption determined by previous research efforts. Considering that 60% of US shipments are delivered by truck, optimizing fuel efficiency of large vehicles will have significant environmental and economic impacts.

Climate also contributes to PVI-related road conditions. Temperature variations between cold and warm, and climatic conditions like wet or arid, affect how a road performs and how often it needs to be maintained to keep PVI rates reasonable (an effort inevitably balanced with state and federal funding). For example, temperature fluctuations can change the stiffness and roughness of a pavement's surface. Hot temperatures reduce asphalt pavement's stiffness, increasing the deflection. On the other hand, freezing temperatures stiffen asphalt pavements and its substructure, decreasing deflection.

4 CHALLENGES WITH QUANTIFYING PVI

While experiments have made measurements of the impact of PVI on fuel consumption, there are challenges with quantifying the deflection-induced impact, as well as determining how to scale it for vehicle traffic over the lifetime of a road. One of the core issues is simply the difficulty in obtaining a precise measurement of the change in fuel consumption caused by PVI for a vehicle and road type. The measurements are very small and the interplay of PVI-related effects are endless; this section will highlight challenges in measuring PVI for both roads and vehicles.

The existing literature has established that a link exists between pavement type and quality with fuel consumption. For instance, Zaniewski et al. suggested the extreme example that it would require much more fuel to drive at the same speed over a gravel road than over a newly paved road (Zaniewski, Butler et al. 1982). An overview of existing studies on the PVI impact of asphalt pavements compared to concrete pavements is shown in Figure 2. A major limitation of these studies is that they do not consider the pavement structure and materials beyond simply surface type: concrete versus asphalt.

In terms of the road's effect on PVI, past studies have focused on the impact of the pavement's

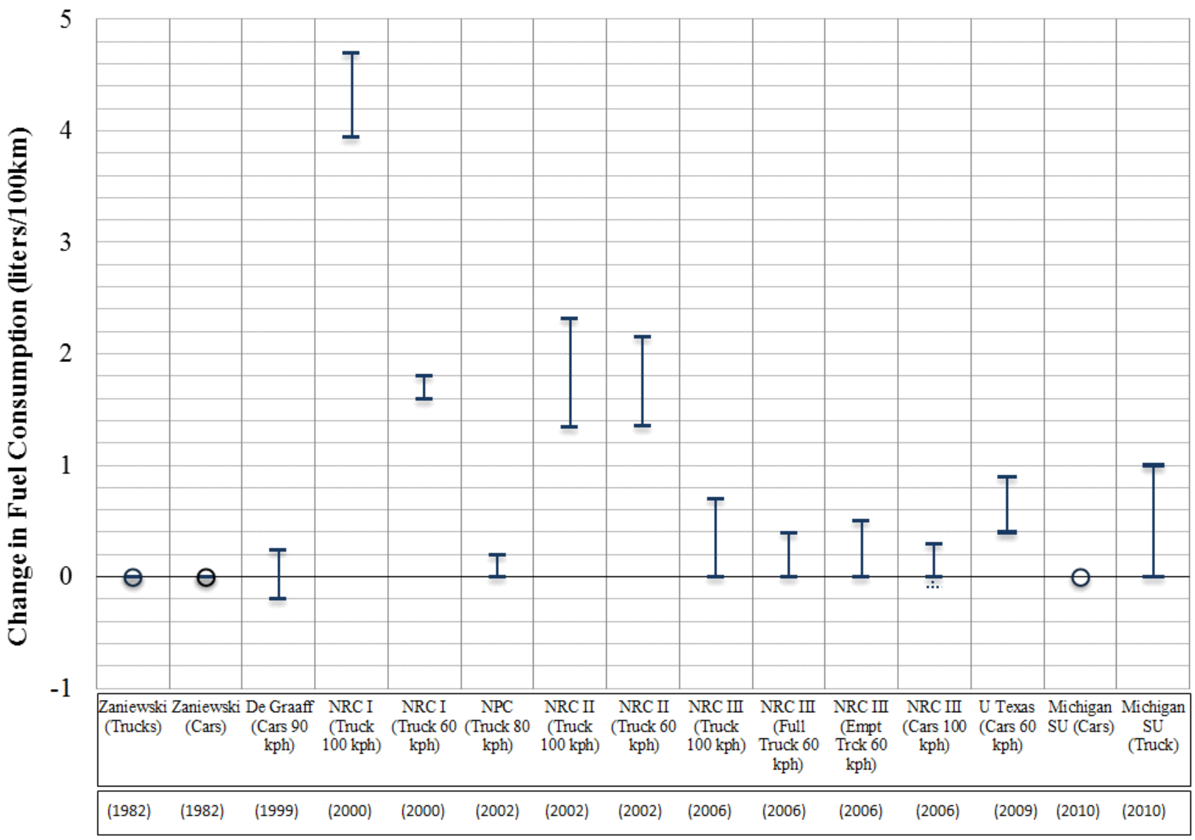


Figure 2 Values reported by previous studies on the effect of pavement type on fuel consumption of vehicles in liters/100 km (gal/100 mi). The change in fuel consumption is based on an asphalt (flexible) pavement compared to a concrete (rigid) pavement (Akbarian 2012).

surface, often focusing on the roughness. While this is certainly one key aspect of a roadbed, the pavement's structural and materials properties also have a significant impact on the pavement deflection, as well as the longevity of the pavement. For example, both the substrate underneath the pavement and the thickness of the pavement layer have an effect on PVI but none of the current empirical studies have accounted for such impacts. This has made it challenging to connect PVI with pavement design and has also added uncertainty to the results from studies conducted to date.

Measurements on PVI for vehicles are often taken under test conditions, either on a test track or in an outdoor setting with limited control over conditions. When thinking about PVI over a large scale, such as a state's road network, real life situations are incredibly variable. Vehicles experience an array of conditions that interact to affect fuel consumption, such as wind resistance, tire pressure, fuel type, or ambient temperature, that are challenging to differentiate and track. And, of course, there are myriad types of vehicles of varying sizes, weights, engine speeds, and so on. Accounting for these differences and allocating changes in fuel consumption to each one is complicated.

The available studies on fuel consumption related to PVI show a level of uncertainty of up to 10 times. Also, the results from these studies are scenario dependent that can translate into potentially large inaccuracies when applied to other conditions. For these reasons, it is difficult to reliably make an estimate of PVI that accounts for all of these issues. To that end, a quantitative model is needed that relates fuel consumption to the structure and material properties and their effect on deflection.

5 DEFLECTION-INDUCED PVI ESTIMATION

In order to understand the impact of PVI on fuel efficiency, the level of roughness and deflection must be estimated. The science around roughness is more advanced, therefore existing best practices are employed in our fuel consumption estimation. The gap in understanding around deflection estimation is more significant. Understanding that there are many ways in which PVI can affect fuel consumption, this report focuses on the impact of pavement deflection on vehicle fuel consumption. This report proposes an innovative approach to modeling deflection taking a road's materials and structure into account.

5.1 Modeling Deflection

This section provides a brief overview of a model developed by the Concrete Sustainability Hub to predict pavement-related deflection mechanistically, including the quantification of uncertainty, and describes the efforts undertaken to calibrate and validate the model[1]. A mechanistic model is typically employed to understand and predict the behavior of a complicated system through its individual components. Making use of a mechanistic PVI model can close the uncertainty gap present in existing models as well as incorporate physical elements of road design to make predictions. The model has two components: 1) modeling the deflection of any pavement systems, and 2) relating deflection to fuel use.

This model employs a novel approach to quantifying the impact of PVI deflection using a beam on viscoelastic foundation model. This method focuses on quantifying the many factors that influence the deformation of pavement. This includes the properties of the pavement surface and substrate as well as the mass and inertia of the vehicle in order to represent the dynamic

[1] For detailed information on the model, please see the following report: Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements at http://web.mit.edu/cshub/news/pdf/PVI_Report-2012.pdf.

interaction of pavement and vehicles. The resulting estimates of deflection can be linked with fuel consumption, as discussed in the subsequent section.

By building a mechanistic model, which allows for a detailed understanding of the pavement design properties, PVI can be effectively quantified in a way that has a potential to be integrated into existing LCA models. This model provides the ability to tweak individual design parameters to see how the results change. For example, one could vary the thickness of the pavement layer or include different materials in the substrate to see how deflection is affected. In this way, the relative importance of different pavement characteristics can be realized, giving road designers a tool for optimizing road designs to minimize deflection.

5.1.1 Model Calibration

In order to ensure that the deflection model reports accurate results, the model was calibrated against an existing set of data. The Long-Term Pavement Performance program, a part of the US Federal Highway Administration, has been collecting data on pavements since 1987 with a goal of improving pavement prediction and design models (Office of Infrastructure Research and Development 2000). The program uses a device known as a Falling Weight Deflectometer (FWD) to measure pavement deflection in response to a known weight, providing an indication of the behavior of a pavement's structural capacity and material properties. The program has routinely monitored 2,500 road sections since its inception.

The LTPP FWD test datasets provide a robust set of information on pavement characteristics and performance. The detailed level of time-history data allowed CSHub researchers to "see" a ripple effect in the pavement caused by a weight impacting the pavement, an effect known as wave propagation. These ripples, or waves, move through the roadbed at different speeds depending on the condition of the pavement. This information was related to material properties of each pavement section, which were then used to calculate pavement deflection compared to those measured with FWD experiments.

5.1.2 Model Validation

Once the model was calibrated and the material properties were calculated, the next step was to validate the model's results against FWD deflection measurements. Figure 4 shows a

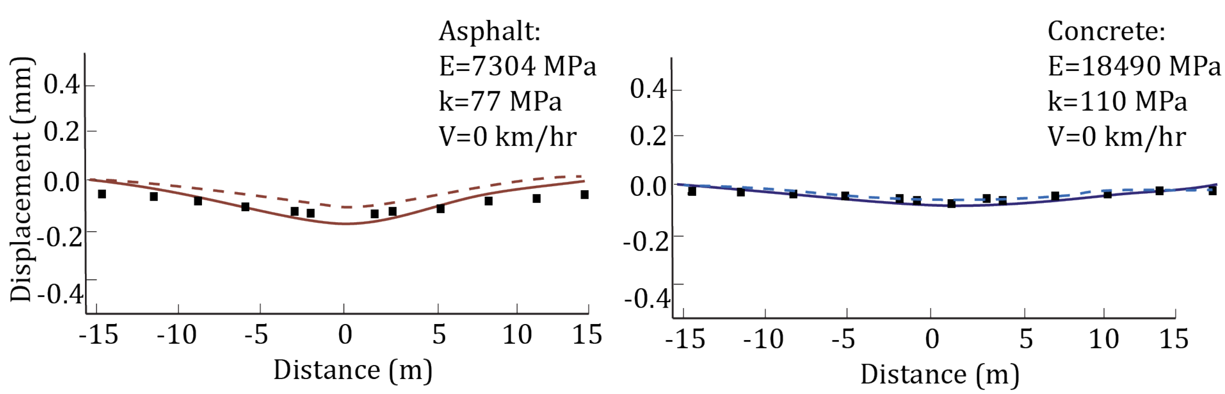


Figure 4 A comparison between the experiment tests, shown as dots, and the model results, shown as damped (dashed line) and undamped (solid line).

comparison between model prediction and the FWD field measurements for concrete and asphalt pavements. The solid and dashed lines represent the model's output under damped and undamped conditions. For a moving vehicle, damping of the subgrade results in the maximum deflection occurring behind the wheel, creating an uphill slope under the vehicle wheel. Damping also has an impact on the maximum deflection and is used to improve the model's estimation of deflection. In both damped and undamped cases, the model predictions match the field measurements to an acceptable level of accuracy. Figure 5 shows the FWD experimental deflection values versus the predicted model deflection values for the damped and un-damped cases for all datasets representing the entire US.

5.1.3 Limitations of the model

While this model is currently providing a reasonably accurate estimate of deflection-induced PVI, there are many important factors that are not yet included in the model. For example, viscoelasticity of the top layer and multilayered response are to be integrated to further test the pavement's response. Further, not all phenomena of roadways are included. For example, the model assumes that all pavements are continuous, thus impacts of joints in the pavement, as well as cracking or rutting on deflection are not taken into account. That said, the values produced by the model are similar to those found in recent studies, confirming the ability of the model to provide a realistic summary of the relationship between pavement materials and structures and fuel consumption.

6 RELATING PVI TO FUEL CONSUMPTION

The PVI deflection model quantifies the pavement deflection for a specific road design and condition. In order to relate this value with fuel consumption, it is necessary to understand the relative importance of different structural and material parameters. For example, to what degree does the pavement type (concrete or asphalt), the weight of the vehicle, or the thickness of the structure affect fuel consumption? Understanding these relationships allows for the comparison of different pavement designs in terms of PVI – a technique that can be used to guide efficient pavement design.

Once the deflection model was calibrated and validated, the importance of different parameters that affect fuel consumption due to the deflection was obtained. To achieve this goal, scaling relationships were developed between the structural and material parameters that affect pavement deflection to fuel usage. The relationships are based on the structural and material properties of the pavement, the vehicle load, as well as some of the basic forces that impact a vehicle fuel usage, namely slope and gravity. Other forces, such as wind resistance or inertia, are left out of this equation; our attention is on the interaction of pavements and vehicles. The effect of the vehicle's weight on pavement deflection along with the scaling factors for the subgrade and top layer materials, and the thickness of the pavement, lead to the following relationships:

$$IFC \sim GR\ x\ q\ x\ g = q^2\ x\ E^{-1/2}k^{-1/2}h^{-3/2}$$

$$GR \sim q\ x\ E^{-1/2}k^{-1/2}h^{-3/2}$$

where *IFC* represents Instantaneous Fuel Consumption, *GR* represents gradient caused by pavement deflection, *q* the external load, *g* represents gravity, *E* the top layer modulus, *k* the subgrade modulus, and *h* the top layer thickness. The exponents represent the scaling coefficients, or the degree of each items relationship on fuel consumption. In this case, the thickness of the top layer of the pavement, *h*, is the most important factor in terms of pavement design.

The fuel consumption estimates determined by the scaling relationships are consistent with similar studies on PVI-related fuel consumption. Figures 5 and 6 show the CSHub's results compared with several recent studies.

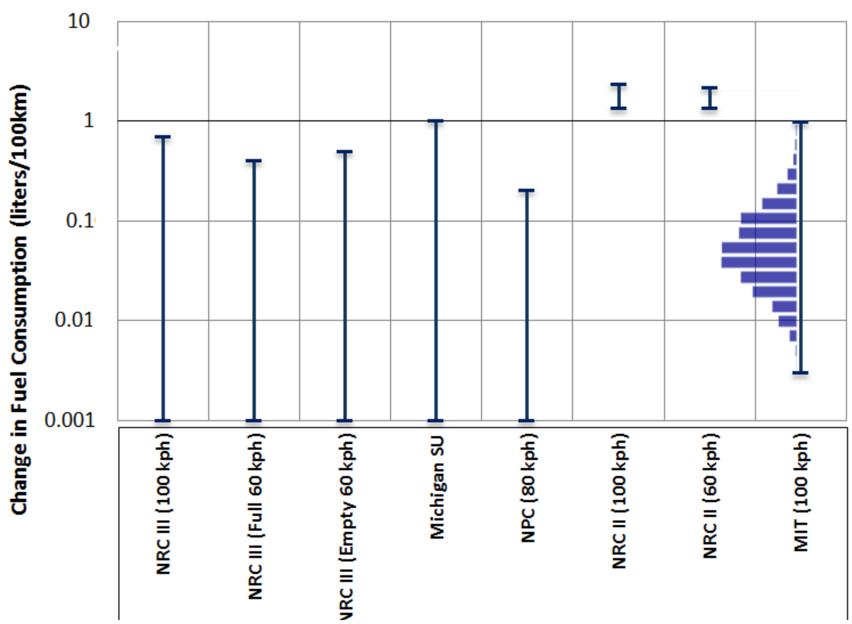


Figure 5 Truck fuel consumption estimates of MIT model compared to other studies (Akbarian 2012).

7 RESULTS

The scaling relationship shows that both rigid and flexible pavements can be optimized for fuel consumption due to deflection through variations in design. In other words, one material is not necessarily better or worse, it's simply a matter of how a road is designed.

These results can be further analyzed to see the point at which different designs would be more advantageous under various scenarios. While any parameter can be examined in detail, here we show the results for thickness because it is the dominant influence on fuel consumption. For example, if you consider a range of potential thicknesses of the top layer of either material, you can obtain a more nuanced look at the degree to which material type and thickness affect fuel consumption. As shown in Table 1, for a range of thickness and modulus ratios there are numerous cases where either concrete or asphalt pavements can have lower fuel consumption.

Table 1 The relationship between the thickness (h_c and h_a) of a pavement modulus (E_c and E_a) and its effect on fuel consumption, as represented by a fuel consumption ratio (asphalt/concrete). Fuel consumption ratio values greater than one (shown in gray) represent cases where fuel consumption is higher on asphalt pavement compared to that concrete pavement.

		Thickness Range (h_c/h_a)					
	Fuel Consumption Ratio (Asphalt/Concrete)	**1.0**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**
Modulus Range (E_c/E_a)	**9**	3.0	2.6	2.1	1.8	1.4	1.1
	8	2.8	2.4	2.0	1.7	1.3	1.0
	7	2.6	2.3	1.9	1.5	1.2	0.9
	6	2.4	2.1	1.8	1.4	1.1	0.9
	5	2.2	1.9	1.6	1.3	1.0	0.8
	4	2.0	1.7	1.4	1.2	0.9	0.7
	3	1.7	1.5	1.2	1.0	0.8	0.6
	2	1.4	1.2	1.0	0.8	0.7	0.5

In order to test the model and scaling scenarios under real-world conditions, data from the FWD tests were used to calculate pavement deflection for concrete and asphalt roads. The deflection values are calculated from distributions in pavement materials and structural properties found throughout the US roadway network, information available from the Long Term Pavement Performance (LTTP) database (Long Term Pavement Performance Program 2003). The mean and standard deviations shown in Table 2 represent 1,079 concrete sections and 4,564 asphalt sections; these values are used to represent the grade of the road. Because of the mechanics of the road (the effect of damping) the maximum deflection is behind the wheel of a moving car, resulting in a slight slope. We use this slope GR to calculate the effect of deflection on fuel consumption. Although this impact is small, its aggregated effect through the network can be significant. The vehicle's weight appears to have a clear impact, with trucks showing significantly larger changes in fuel consumption compared to passenger cars.

Table 2 The impact of deflection compared to a rigid (non deflecting) surface on fuel consumption applying the deflection distributions to real world road conditions from the LTPP database.

	Concrete	Asphalt
	Mean (Std. Deviation) [liters/100km]	Mean (Std. Deviation) [liters/100km]
Passenger Cars	0.002 (0.0016)	0.012 (0.009)
Trucks	0.013 (0.012)	0.077 (0.06)

8 CONCLUSION

This document presents a solution to a gap in understanding of the environmental impact of roads – how does the interaction between the road and the vehicle affect fuel consumption? While there have been many efforts to quantify PVI in the past, the inability to reliably quantify deflection-induced PVI has limited the ability to fully understand a roadway's materials and structure's influence on fuel consumption.

The report describes a mechanistic model developed by the Concrete Sustainability Hub that defines the impact of deflection on PVI through the pavement's design, such as the thickness and make-up of the pavement and substrate. The model was calibrated and validated using real-word data collected by the FHWA. The resulting information was analyzed to develop an understanding of the degree to which changes in different pavement characteristics affect fuel consumption at a road network level. The results are similar to other estimates for PVI on fuel consumption, demonstrating that this model is capable of producing reasonable results.

The resulting information provides a functional framework to guide pavement design for reduction of PVI-related emissions. Further, the model can be used to better understand the use phase of pavement within life cycle assessment, a current gap that inhibits the reliability of such techniques. This allows designers to evaluate the impact of the use phase in relation to the materials, manufacturing, and maintenance, providing a clear pathway towards environmentally friendly decision making.

The CSHub is continuing to refine and build upon the research presented here. Work is ongoing to create a model to estimate roughness, similar to the deflection model. Further, future work will describe how PVI estimations can be incorporated into LCA in order to improve life cycle impact characterizations.

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10 GLOSSARY OF TERMS

Scaling Coefficient	A scaling coefficient, or scale factor, is a number that multiples some quantity at a constant rate.
Pavement-Vehicle Interaction	Pavement-Vehicle Interaction, or PVI, refers to the resisting forces that take place between a vehicle and the road.
Life Cycle Assessment	A technique for estimating the environmental impact of a product or service.
Pavement Modulus	The pavement modulus refers to the material properties of a pavement material, such as stiffness or flexibility.
Environmental impact	The consequence of pollution, such as eutrophication of waterways or ocean acidification.
Embodied energy	Embodied energy is the total energy required to produce a product or material.
Use phase	Use phase is the period after a product's manufacture when it is in use by a consumer. Use phases vary considerably with products and can have a high impact on the total life cycle impact.