OVERVIEW OF PAVEMENT-VEHICLE INTERACTION RELATED RESEARCH AT THE MIT CONCRETE SUSTAINABILITY HUB

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ABSTRACT

In 2009, the US cement and concrete industries established the Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT). A primary thrust of MIT's pavement activities has been improving the Life Cycle Assessment (LCA) practices to better quantify the environmental impacts over the life of a pavement. In doing their research, the MIT CSHub determined that the "use phase" can often dominate the materials, construction and maintenance phases of a pavement LCA. They also found that most of a pavement's use-phase impacts come from emissions by vehicles using the pavement due to excess rolling resistance between the pavement and the vehicle. The study of assessing how much fuel or energy is used by vehicles when using a pavement is called pavement-vehicle interaction or PVI. This paper will summarize the CSHub PVI research findings to date. Specific items covered will be:

- An overview of the different mechanisms of PVI (texture, roughness/smoothness, and deflection/dissipation)
- The development of a PVI model and Desk Top experiments to account for the excess fuel usage due to pavement deflection
- The application of PVI at the project level to compare the relative importance of each mechanism and show how PVI can be used to optimize designs.
- The application of PVI at the network level to manage the pavement system in order to minimize excess fuel usage and greenhouse gases.

KEY WORDS

PAVEMENT-VEHICLE INTERACTION / EXCESS FUEL / DEFLECTION / LIFE CYCLE ASSESSMENT / USE PHASE / GREENHOUSE GAS

1. INTRODUCTION

In 2009, the United States cement and concrete industries established the Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT) to carry out a multi-year research program to evaluate and improve the environmental and economic impact of concrete in pavements and buildings. The goal of the effort is to develop breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings by (1) providing scientific basis for informed decisions; (2) demonstrating the benefits of a life-cycle view; and (3) transferring research into practice.

With respect to pavements, one focus area of MIT's research has been on improving the Life Cycle Assessment (LCA) practices to better quantify the environmental impacts, energy consumption, material use, etc. throughout the life-time of a pavement. Some of the impacts a LCA can calculate include Carbon Dioxide (CO2) and Green House Gas (GHG) emissions, Global Warming Potential (GWP), nitrogen oxides (NOx), particulate matter ($PM_{2.5}$ and PM_{10}), energy consumption, water use, eutrophication potential, as well as many others.

While the mechanics of performing an LCA for a pavement are not terribly difficult, it is extremely data intensive. For this reason, it is essential that a standardized, but comprehensive, pavement LCA framework that includes the raw material production (extraction, processing, and manufacturing), to construction, use, maintenance, and finally disposal at the end of pavement's life be used. (Santero, Loijos, Akbarian, & Ochsendorf, 2011; Santero, Masanet, & Horvath, 2011)

This life cycle framework ensures that short term gains in the early stages do not come at the expense of long-term deficits at later stages. LCA's can be used to evaluate the environmental impact of a single product (e.g., a pavement) in order to reduce the impact of that product, or they can be used in a comparison mode between two different options for a product (e.g. a concrete and an asphalt pavement design) in much in the same way that a life cycle cost analysis (LCCA) is used to compare costs.

Figure 1 shows the comparative LCA results, expressed as GWP, for 32 pavement sections in different applications, traffic levels, and climate zones across the US. (Xu X., 2014) Overall, the LCA results vary based on the context for that given scenario and are dependent on the pavement structural design (thickness and materials); traffic that will use it; the anticipated performance of the pavement; and the maintenance and rehabilitation activities that will be applied to the pavement. In comparing the results, it can be seen that no specific pavement type is always the most "green" – sometimes concrete is lower, and sometimes asphalt is lower. However, the key item to note is that while the overall impact varies based on context, the "use phase" always plays a major role and is in same magnitude, and sometimes higher, than the materials, construction and / or maintenance phases (MIT, 2014).

MIT also found that most of a pavement's use-phase environmental impacts come from emissions by vehicles using the pavement due to excess rolling resistance between the pavement and the vehicle, which increases the fuel usage. The study of assessing how much excess fuel or energy is used by vehicles when using a pavement is called pavement-vehicle interaction or PVI. The goal of the paper is highlight the PVI research findings developed by the MIT CSHub over the last 7 years in order to increase understanding and to show how improving pavement designs can result in increased fuel efficiency and lower emissions.

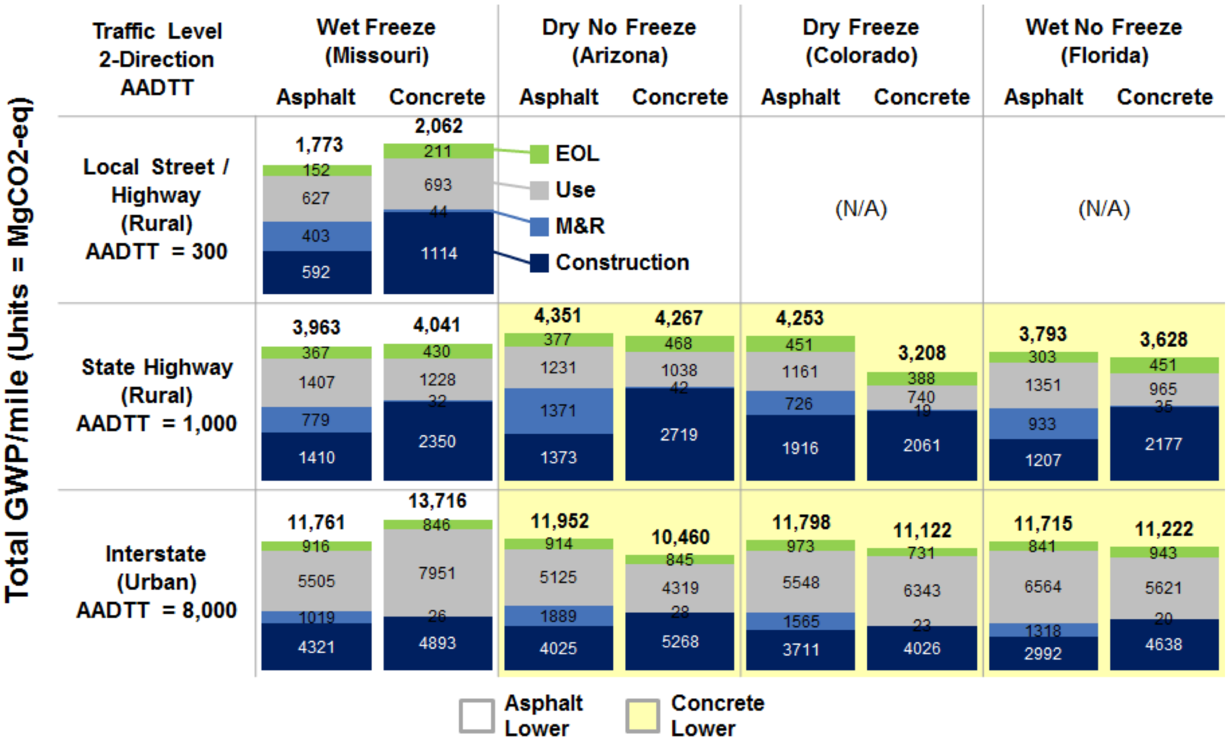
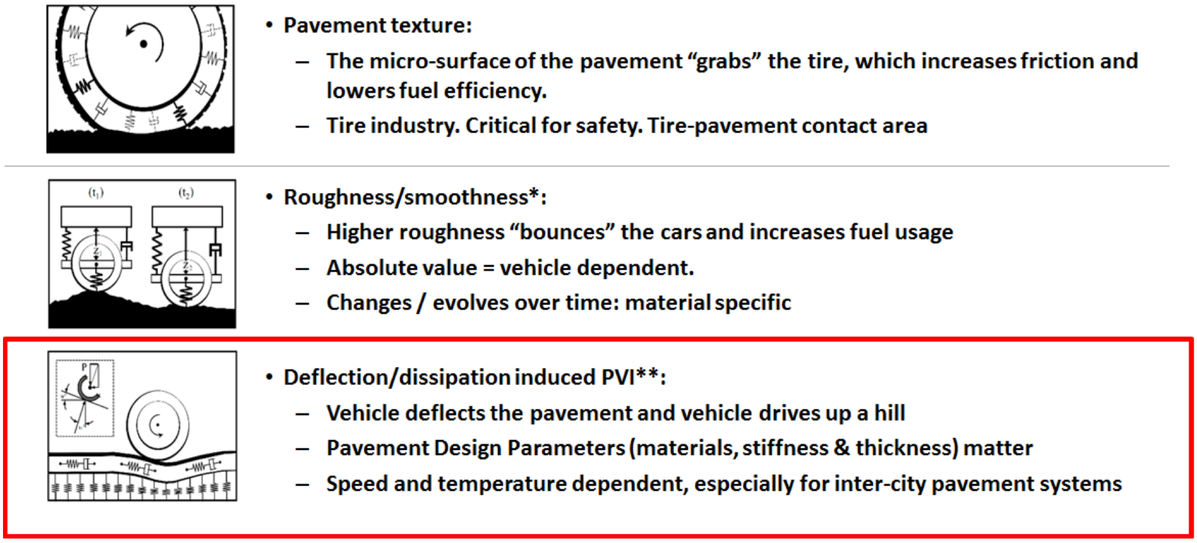


Figure 1 – Sample GWP results for different scenarios over a 50 year analysis period

2. OVERVIEW OF PAVEMENT-VEHICLE INTERACTION

The three pavement structural and surface property mechanisms that contribute to PVI are shown Figure 2. In the US, roughness and structure are considered the main contributors to pavement vehicle interaction. As there has been considerable study on roughness (I. Zaabar, 2010; M. W. Sayers, 1986; T. D. Gillespie, 1980; Chatti, 2012; Louhghalam, Tootkaboni, & Ulm, 2015; Louhghalam, Akbarian, & Ulm, 2015), the MIT CSHub research focused on the impact pavement structure and deflection on PVI's relation to fuel consumption and ultimately to GHG emissions



- **Pavement texture:**
  - **The micro-surface of the pavement "grabs" the tire, which increases friction and lowers fuel efficiency.**
  - **Tire industry. Critical for safety. Tire-pavement contact area**
- **Roughness/smoothness*:**
  - **Higher roughness "bounces" the cars and increases fuel usage**
  - **Absolute value = vehicle dependent.**
  - **Changes / evolves over time: material specific**
- **Deflection/dissipation induced PVI**:**
  - **Vehicle deflects the pavement and vehicle drives up a hill**
  - **Pavement Design Parameters (materials, stiffness & thickness) matter**
  - **Speed and temperature dependent, especially for inter-city pavement systems**

Figure 2: Factors that affect Pavement Vehicle Interaction (PVI) - Pavement Surface Texture, Roughness, & Pavement Structure (Stiffness)

While there have been previous empirical studies and the impact that pavement type can have on a vehicles fuel usage (see Figure 3 (Akbarian, 2012)), these studies had high variability and only looked at the behaviour of the pavements from asphalt versus concrete pavement view, with no consideration of the structural properties of the pavement or how they changed over time. Thus the missing element from these studies is a model that relates fuel consumption to the structural and material properties of the pavement so that it can be applied to specific scenarios and specific pavement parameters LCA.

3. PAVEMENT DEFLECTION PVI AND MODELLING ITS IMPACTS ON FUEL USAGE

Pavement deflection refers to the small dent that a car creates in the pavement as it drives on a roadway. This deflection creates a slight but perpetual uphill climb under the tire and results in a resisting force to the vehicle's motion. In order to maintain a constant speed, the vehicle has to compensate for the added resistance by consuming excess fuel, the magnitude of which depends on the steepness of the hill, which is a function of the condition and structure of the roadway and the weight of the vehicle. Note that excess fuel consumption (EFC) is defined as the additional fuel consumption compared with a pavement that is perfectly smooth, rigid, and does not bend (i.e. non-dissipative).

It is important to note is that even though the effect of PVI on an individual vehicle is small, its impact within a full pavement life cycle can be significant due to the large number of vehicles that travel over pavements. This is especially true for high volume traffic roadways where PVI can easily surpass the energy consumption and emissions due to the materials, construction and maintenance phases of the roadway over its lifetime.

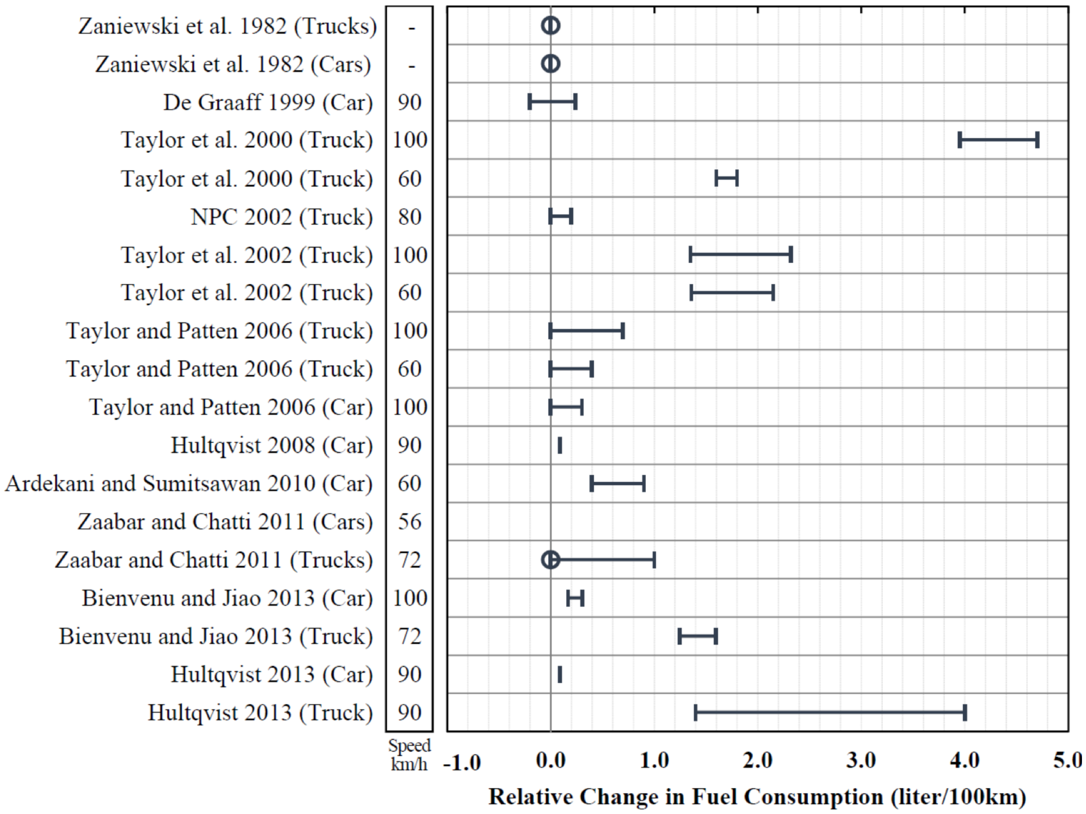
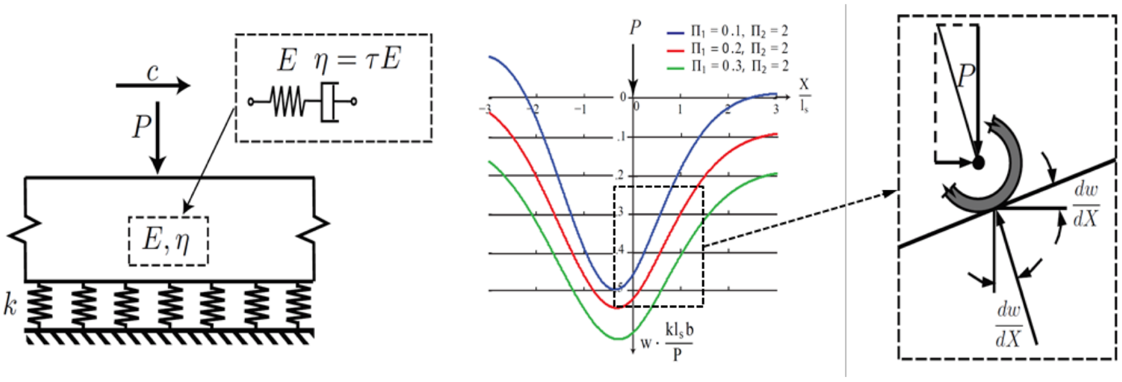


Figure 3: Summary of Deflection-induced PVI: empirical studies

MIT's PVI research shows that the dissipated energy in a viscoelastic pavement is directly related to the slope under the moving wheel (Louhghalam, Akbarian, & Ulm, 2013). In 2012, MIT published its first simplified model for estimating the excess fuel consumption (EFC) based on an elastic Euler-Bernoulli beam on a viscoelastic subgrade (Akbarian M., 2012). While this model provided a good approximation of EFC, it was insensitive to the viscoelastic response of asphalt and concrete top-layer materials to speed and temperature.

To address these shortcomings, MIT revised their model to incorporate the temperature and speed dependent mechanical properties of asphalt and concrete materials. (A. Louhghalam, 2014; Louhghalam, Akbarian, & Ulm, 2013). This second generation PVI model is conceptually a 2-step model. The first part determines the slope of a pavement system based on its structure and material properties (the *stiffness* of the system) and the second part relates the rolling resistance (i.e. dissipated energy) needed to drive up this slope to excess fuel consumption. To quantify the slope under a moving wheel, the pavement is modelled through an infinite viscoelastic beam over an elastic foundation, shown in Figure 4 (a). A Maxwell model is used to describe the viscoelastic material's stress and strain relationship where E is the Young's modulus, τ is the relaxation time of



(a) (b) (c)

Figure 4: Overview of MIT Deflection-induced PVI Excess Fuel Consumption Model.

the viscoelastic top layer that accounts time of loading and temperature dependencies (i.e. cool vs hot, slow vs fast), and η is the material viscosity. Figure 4 (b) shows the pavement deflection basin, where the maximum deflection is behind the moving wheel due to the delayed viscoelastic response. This results in a slope under the wheel and resistance to motion shown in Figure 4 (c).

The average slope under the tire, dw/dX, and ultimately the dissipated energy within the pavement, $\delta E = -P\, dw/dX$, are evaluated through a combination of dimensional analysis and numerical simulations of the beam's response (see (Louhghalam, Akbarian, & Ulm, 2013)). To simplify this complex procedure for LCA and LCCA, the PVI model is reduced from an eight-parameter function of subgrade stiffness *k*, pavement stiffness *E*, thickness *h*, width *b*, relaxation time τ, temperature *T*, vehicle axle load *P,* and speed *c* to a two-parameter relationship between the dimensionless dissipation Π and dimensionless speed Π_1 and relaxation time Π_2:

$$\delta E = \frac{c_{cr}}{c} \times \frac{P^2}{bk\ell_s^2} F\left(\Pi_1 = \frac{c}{c_{cr}}; \Pi_2 = \frac{\tau(T)c_{cr}}{\ell_s}\right) \qquad \text{Eqn 1.}$$

Where $c_{cr} = \ell_s(k/m)^{1/2}$ is the critical speed, $\ell_s = (\frac{Eh^3}{12}/k)^{1/4}$ is the Winkler length, $m = \rho h$ is the surface mass density, and ρ is the volume mass density of the top layer material. The functional relation F in Equation 1 is numerically simulated for a wide range of dimensionless variables Π_1 and Π_2 and is fit to the numerical solution to expedite the calculations and make the model much more computationally efficient.

The temperature sensitivity of the viscoelastic material is captured through its impact on the relaxation time τ using the time-temperature superposition principal via the Arrhenius law and the William-Landel-Ferry relationship for asphalt and concrete, respectively. Finally, the dissipated energy calculated from equation 1 is related to the instantaneous change in fuel consumption for passenger cars and trucks. For further details of model development, calibration, and validation see (Louhghalam, Akbarian, & Ulm, 2013).

The use of a mechanistic model allows for identifying the key design parameters that impact fuel consumption due to PVI from Equation 1. This scaling relationship is established between the dissipated energy in the pavement δE and the input parameters of speed *c*; relaxation time τ; vehicle load *P*; top layer modulus *E*; top layer thickness *h*; and subgrade modulus *k*; such that:

$$\delta E \propto (c\tau)^{-1}\mathrm{P}^2\mathrm{E}^{-1/4}\mathrm{k}^{-1/4}\mathrm{h}^{-3/4} \qquad \text{Eqn 2.}$$

Ultimately, the model is used to calculate the fuel consumption impact of deflection induced PVI for passenger cars and trucks. Figure 5 shows the model sensitivity to temperature and speed by comparing the EFC over a 12 month period for sample asphalt and concrete pavement sections in California and for an HS20-44 truck. As can be seen, temperature and speed have an impact on the EFC for both asphalt and concrete pavement, but they are much smaller for concrete pavements. For example, the excess fuel consumption on asphalt pavements is highly sensitive to temperature fluctuations and is an order of magnitude higher in the summer months compared to the low temperature winter months. Similarly, it is shown that an increase in speed results in reduction of the excess fuel consumption.

4. "DESK TOP" EXPERIMENTS TO VALIDATE THE PVI-DEFLECTION MODEL

While the above model is theoretically sound, some researchers still expressed concern that the model had not been empirically calibrated and validated against comprehensive field data that accounted for the pavement layer structure and material properties. However, the problem with empirical field studies, besides being costly and time consuming, is that they can have high variability in reported results due to inaccuracies in fuel consumption measurements, changing field conditions (wind speed, air temperature, grade, etc.), and the difficulty of separating the three elements that impact PVI (texture, roughness, and deflection).

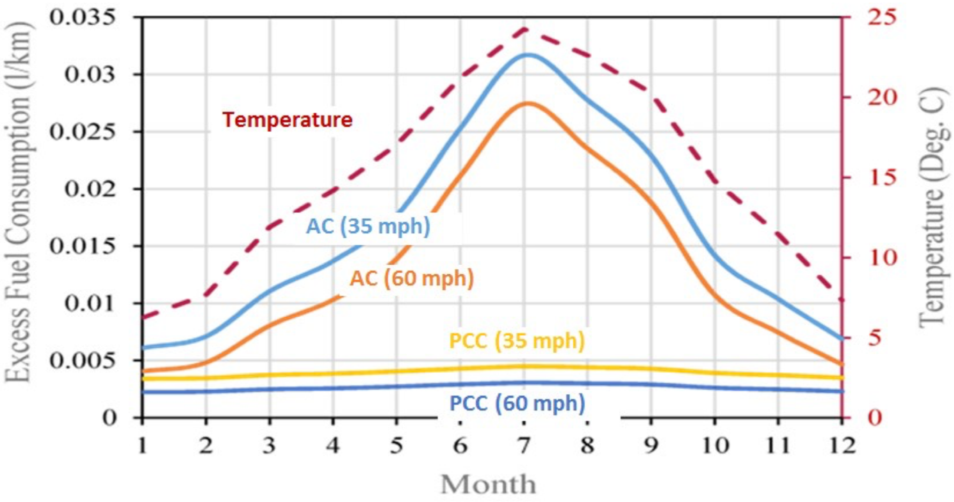


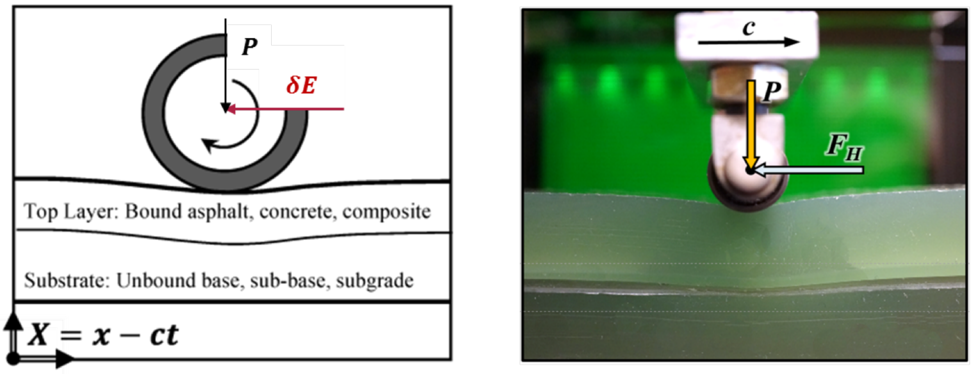
Figure 5: Sensitivity of MIT Gen II model to temperature and speed for a HS20-44 truck in California's roadway system

To address these issues, MIT developed a novel small-scale, desk-top experiment that allowed them to isolate the interaction of the wheel and the pavement structure. The pavement system, a two-layered viscoelastic beam on an elastic subgrade (Figure 6 (a)) was experimentally represented through a two-layered silicone elastomer pavement shown in Figure 6 (b). This experimental setup allowed for a range of top layer thicknesses, elastic moduli, and viscoelastic properties to be tested, and the pavements' response to a moving wheel of varying loads and speeds to be observed both through the resulting horizontal force resisting its motion and visually using a technique called photoelasticity. Figure 7 shows an example of the desk-top model's photoelasticity response to a moving wheel load. The asymmetry of stresses inside the material shows that the wheel is always moving "up a hill."

In total, MIT ran nearly 200 experimental configurations, equivalent to 290 km (180 miles) of road testing, to investigate the impact of key PVI parameters on excess energy dissipation namely with varying loads, speeds, pavement modulus values, pavement thicknesses and viscoelasticities (relaxation time). Once the testing was completed, the scaling of the dissipation forces from PVI desk-top model was investigated against the vertical load *P*, wheel speed *c*, and top layer thickness *h*:

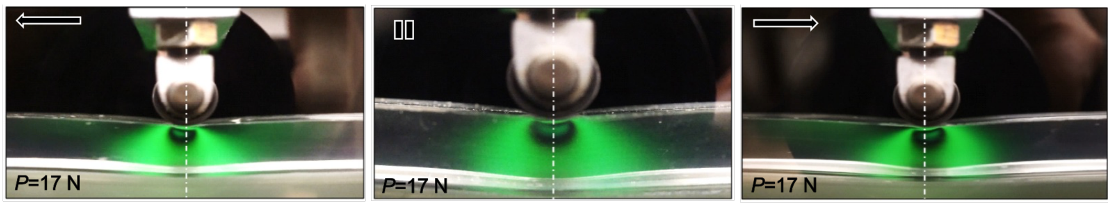
Experimental validation: $\delta\mathrm{E} \propto (\mathrm{c})^{-0.87}\mathrm{P}^{2.02}\mathrm{h}^{-0.63}$ Eqn 3.

The results of experimental scaling were found to be consistent with those in the theoretical deflection-induced PVI model of Equation 2 and confirmed the contribution of pavement structure to EFC. It was also determined that an increase in pavement stiffness minimizes the impact of deflection-induced PVI and verified that deflection-induced PVI impacts can be captured and can have a significant impact on life cycle energy use and emissions.



(a) (not to scale) (b)

Figure 6: Link between the (a) Theoretical Model and (b) Desktop Experiment



(a) (b) (c)

Figure 7: Desk-Top experiment of deflection-induced PVI showing the asymmetry of stresses inside the pavement using photoelasticity for (a) wheel moving left, (b) stationary wheel, and (c) wheel moving right

5. APPLICATION OF PVI AT THE PROJECT LEVEL

As shown for Figure 1, and as well as in other evaluations across a wide range of contexts, it is important to consider both roughness and deflection in analyses of EFC because the relative importance of each depends on the roughness conditions, traffic volumes and the specific pavement structures being evaluated. In general, improving the smoothness has a greater impact when the road is old and in need of repair while stiffness is fairly constant value and has a larger relative impact when the pavement is new or smooth, and there is a large amount of trucks.

As an example, Figure 8 and Figure 9 show the EFC for four pavement sections being evaluated for PVI impacts in the State of California (Coleri, Harvey, Zaabar, Louhghalam, & Chatti, January 2016; Harvey, Lea, & Kim, 2016). For this example, EFC, in liters/1000 km, for a concrete section, a composite section, full depth and a semi-rigid section are compared for 1000 vehicles per day for three different levels of roughness (smooth, medium and rough). The top graphs are for 5% trucks (50 trucks/day) and the bottom graphs are for 30% trucks (300 trucks/day). The EFC due to structure are computed using the MIT Generation II PVI Model and the roughness impacts are based on the Wold Bank's Highway Development Model HDM-4 model (I. Zaabar, 2010). Note that EFC results are based on trucks and light vehicles traveling at constant speed of 56 mph (90 km/hr) on a pavement with a surface temperature of 86° F (30° C). While not shown here, changing the vehicles speed or surface temperature does impact on the absolute values, but the overall trend remains. In reviewing the results, several items can be noted.

- Total EFC varies substantially and that variation can be over an order of magnitude from the best case to the worst case.
- Light vehicle EFC is impacted by roughness while truck EFC is a function of both roughness and structure. The reason structural EFC is important for trucks and not light vehicles is because the structural PVI affects scale with the load weight by the power of 2.
- When the truck levels are low, the relative importance of structural EFC to total EFC is relatively low, and as roughness increases, the relative importance of structural EFC

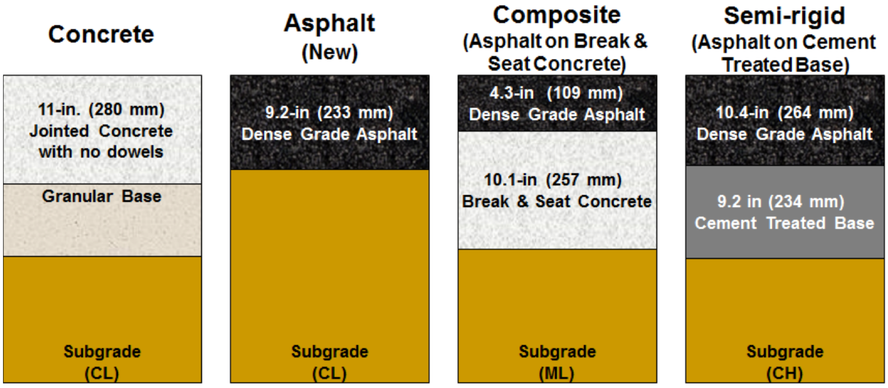


Figure 8: Pavement Sections used for EFC Comparisons

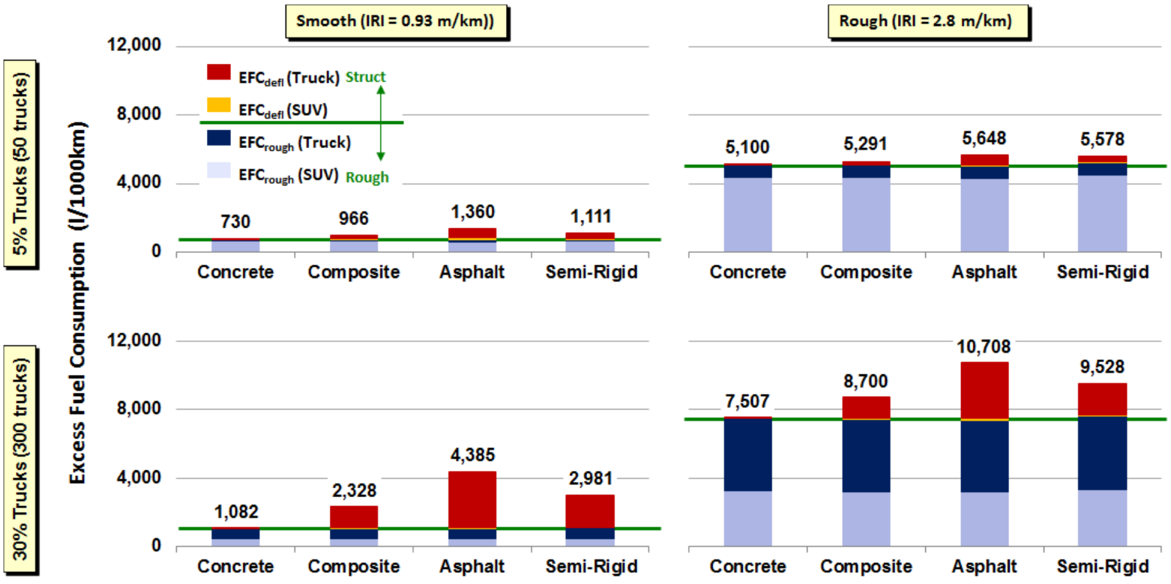


Figure 9: EFC results for 1000 vehicles on pavement structures, with different roughness conditions and truck levels (Units for EFC = L/1000km)
Note: Speed = 90 km/hr (56 mph), Temp = 30º C (86º F), Baseline IRI = 40 in/mi.

decreases even further (e.g. roughness contributes more)

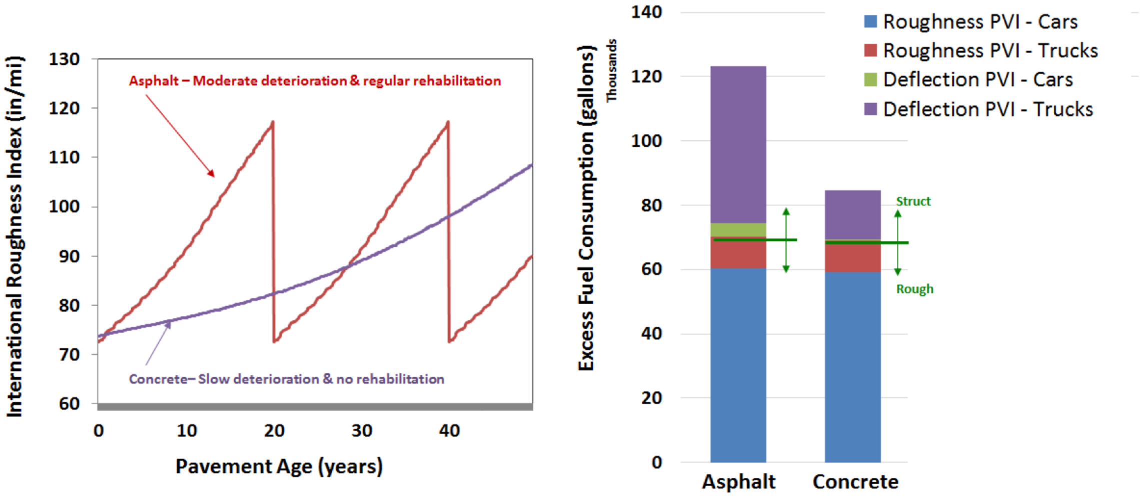
- Roughness PVI impacts are most important when the road is rough. If the roadway is maintained in a smooth condition, the relative importance of roughness EFC to total EFC is greatly reduced (e.g. structure contributes more).
- For any given traffic mix and IRI level, the roughness EFC is essentially the same for all pavement structures (light and dark blue sections) and is only a function of pavement type in respect to how slowly or quickly that specific pavement deteriorates.
- The structural / deflection based EFC is essentially constant for all IRI conditions (red and yellow sections) for the specific design / material properties; but changes based on the pavement type and truck traffic volumes.
- For concrete pavements, the structural / deflection EFC is low and is not a major contributor to total EFC for any traffic mix or pavement condition.
- The structural / deflection EFC for the other pavement structures is more than 2 orders of magnitude (100 times) higher than concrete for this case. However, it is important to note that the EFC for these pavements will increase or decrease as the visco-elastic properties of the material changes and while the magnitude may change, the trend will not.
- In general, when the road is rough, roughness EFC drive the results. However, if the roads are kept smooth, structural EFC begins to play a much more important role.
- Overall, it is the structural / deflection EFC component that differentiates pavements. It is greatest on the least stiff pavements and decrease as the pavement stiffness increases. The medium stiff pavements –composite and semi-rigid – are between the concrete and asphalt sections.

The end result is that both smoothness and structure play a major role in lowering EFC and if an agency or pavement designer wants to lower the EFC / GHG emissions of a pavement system at the project level, they have two primary strategies that can be used:

1. Build & Maintain Smoother Pavements either by improving the maintenance activities that keep a pavement smooth over its life time, or by building pavements that stay smoother longer
2. Build stiffer, or stiffen the existing pavement so that it deflects less

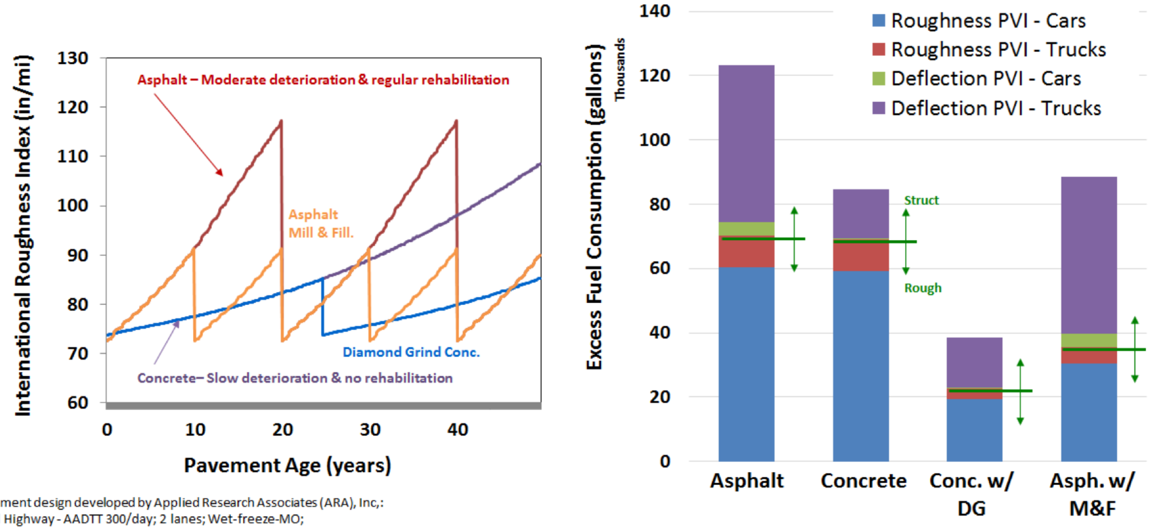
As an example of the impact these strategies can have, Figure 10 shows a comparison of two equivalent asphalt and concrete pavements alternates and the overall EFC for two different scenarios. The first scenario is a “typical smoothness scenario” and is shown in Figure 10 (a). On the left of this figure is the projected IRI for a local highway in Missouri using the AASHTO Pavement ME Design Procedure (MIT, 2014). As can be seen on this graph, the asphalt has moderate deterioration and is rehabilitated every 20 years to keep the road at a low level of roughness (red line). The concrete pavement has a slow rate of deterioration and provides a similar level of lifetime smoothness as the asphalt without rehabilitation (purple line). On the right is the projected EFC for each pavement based on the PVI source of the EFC (roughness from cars, roughness from trucks, deflection from cars, and deflection from trucks). If one looks only at roughness based PVI impacts, one can see that they are basically the same for both pavements. However, once PVI structural EFC is included, there is a dramatic difference in the overall EFC for the concrete and asphalt structures due to cioncrete’s increased stiffness.

The second scenario is an increased smoothness scenario Figure 10 (b). Often times, it is stated that if agencies just keep their pavements smooth, they will reduce EFC and have more



Pavement design developed by Applied Research Associates (ARA), Inc,:
Local Highway - AADTT 300/day; 2 lanes; Wet-freeze-MO;

(a) Scenario 1 - Contributions to Roughness and Structural Induced PVI on EFC.



Pavement design developed by Applied Research Associates (ARA), Inc,:
Local Highway - AADTT 300/day; 2 lanes; Wet-freeze-MO;

(a) Scenario 2 - Impact of reducing Roughness on overall EFC.

Figure 10: EFC from Roughness and Deflection based PV for Local highway in Missouri.
Equivalent Asphalt and Concrete Pavement Designs,
AADTT 300/day; 2 lanes; Wet-freeze.

sustainable pavements. While keeping the pavements smooth does help, structure / deflection also plays a major, if not dominant role when the pavement is already smooth. In this example, Figure 10 (b) shows the EFC if one were to apply a diamond grinding to the concrete pavement at year 25, or do a Mill and Fill to the asphalt pavement at year 10 in order to lower the IRI and maintain an even higher level of smoothness. As one can see, while the EFC from roughness PVI are decreased substantially, the EFC from the deflection PVI impacts are unaffected by the IRI changes. In fact, for this case, overall EFC emissions of the asphalt is still higher than the concrete without diamond grinding solely due to the structural PVI impacts.

The takeaway is that if one ignores the structural PVI impacts on EFC, the conclusions one would come to about the sustainability of the different scenarios would be flawed. Having said that, it is also important to note that while the EFC and PVI play an important role in the sustainability / environmental impacts of a pavement system, the only way to determine if such as strategy is beneficial for a given project is to perform a full LCA that takes account the PVI impacts as well as the impacts from construction, maintenance and end of life phases as shown in Figure 1. The reason for this is that one needs to determine if the trade-off between increased environmental burdens from the extra maintenance activities pay for themselves in reduced PVI burdens. Figure 11 shows the Full LCA results for the local highway designs in Missouri comparing the different scenarios. As can be seen for both concrete and asphalt, the roughness PVI impacts are greatly reduced and that lowers the overall LCA results. However, for the asphalt, the extra Mill and Fill operations have a much higher GWP burden than the diamond grinding and that extra burden eats at the savings from to decreasing the roughness. There is a decrease, but it is muted due to extra Mill and Fill operations. The end result is that the greatest EFC reductions come from addressing both the smoothness aspects and the stiffness aspects of the pavement system.

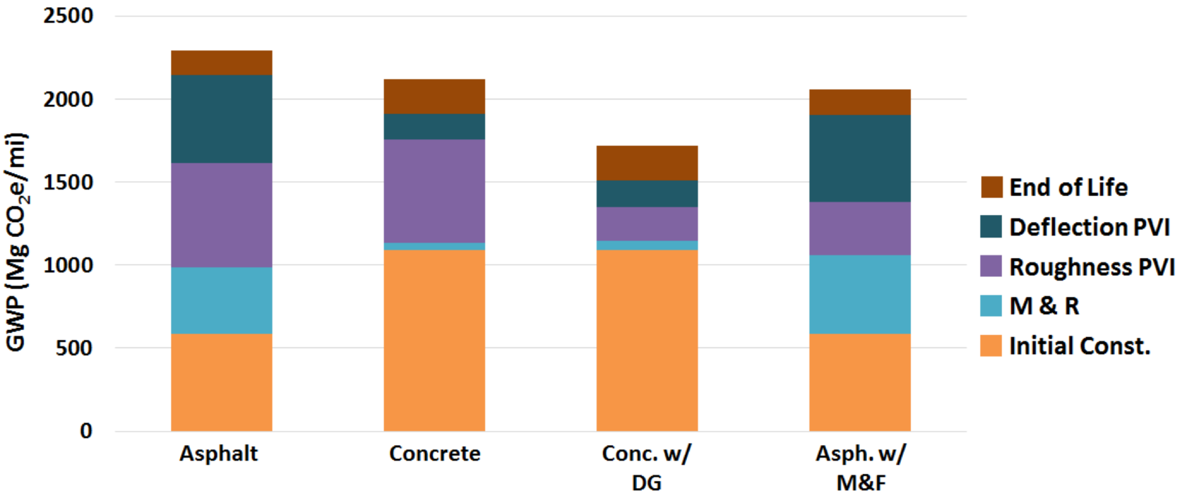


Figure 11: Full LCA Results for Local highway in Missouri. Equivalent Asphalt and Concrete Pavement Designs, AADTT 300/day; 2 lanes; Wet-freeze.

6. APPLICATION OF PVI AT THE NETWORK LEVEL.

One of MIT's goals in developing their PVI model was to have a computationally efficient model that could be incorporated into a network pavement management process. The idea was to create a quantitative link between pavement management and lifecycle energy use / GHG emissions by combining big data analytics to project level EFC and carbon dioxide (CO2) emissions. Then by integrating spatially and temporally for varying road conditions, pavement properties, traffic loads and climatic conditions; agencies could make better economic and environmentally sustainable decisions.

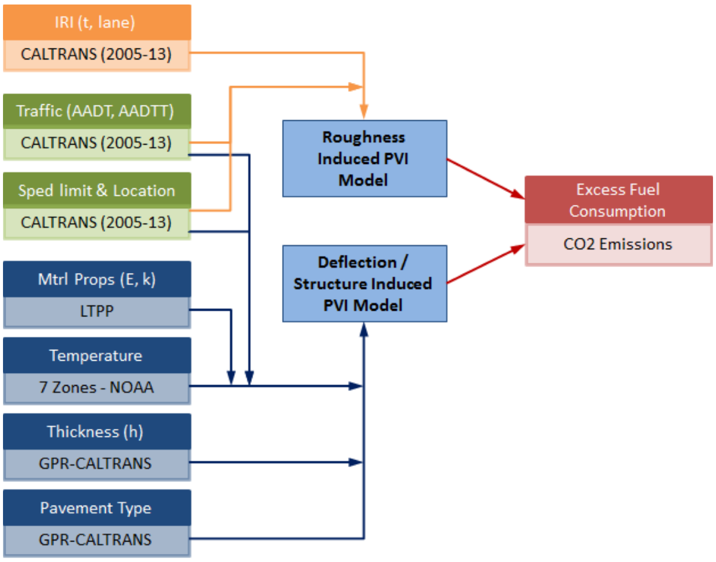


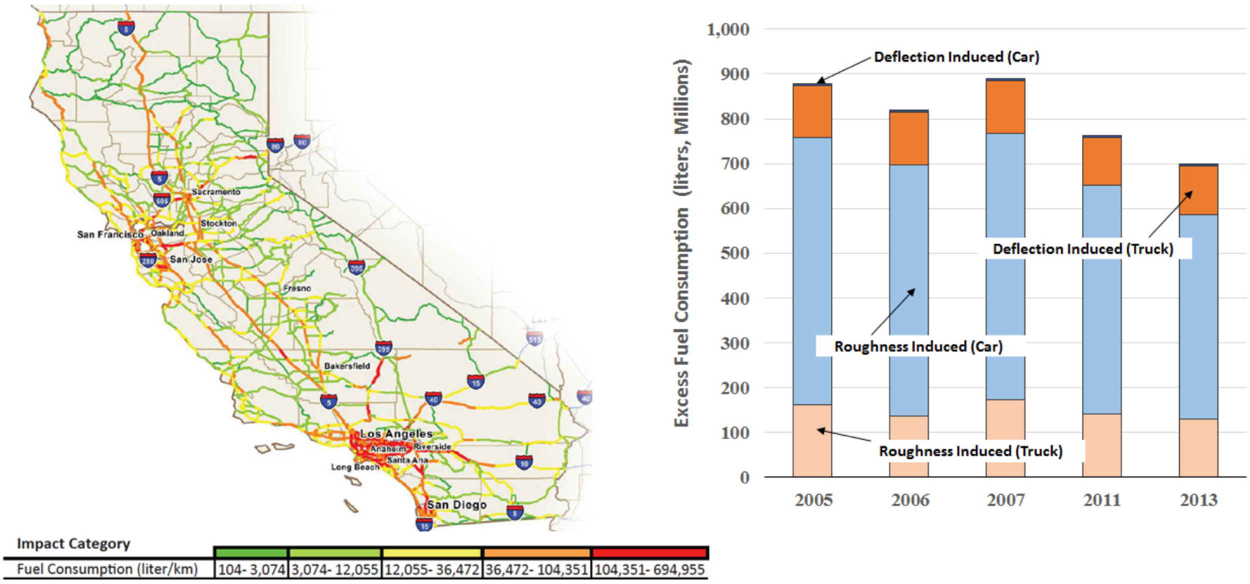
Figure 12: Flow of network analysis; the inputs and the output of deflection- and roughness-induced PVI models

To do this, MIT developed a novel ranking algorithm that allows for upscaling the project level EFC / CO2 emissions from to PVI so agencies can identify sections contributing significantly to CO2 emissions. They then applied it to the interstate highway systems in the State of Virginia Interstate System (Louhghalam, Akbarian, & Ulm, 2016) and the California Department of Transportation (CALTRANS) Highway Network as a proof of concept to show that significant improvement to both the network performance and environmental impacts could be made by maintaining a few lane miles. This paper will focus on the CALTRANS network analysis.

Figure 13 shows the flowchart of the network analysis, and the required data sets used by MIT. Information on pavement condition and design in the state of California were obtained from the Office of Pavement Management and Performance at CALTRANS, including data from five Pavement Condition Surveys (PCS) spanning 2005-2013 as well as Ground Penetrating Radar (GPR) data for the current pavement network. Also, average daily traffic data for passenger cars and trucks were extracted from the CALTRANS Traffic Census for the entire state highway system. Geographical Information System (GIS) base-maps were used to determine the speed limit of a pavement section and match its post-mile with its geographical location. Temperature data were obtained from datasets of the National Oceanic and Atmospheric Administration (NOAA) in the form of average monthly temperatures for seven climatic regions comprising the state of California. Lastly, the elastic moduli of pavement materials and subgrade were extracted from the LTPP database for the corresponding climate zone of the state. Pavement section identifiers and post-miles, provided separately within each data source, were homogenized for every 0.5 mile of the pavement section to match the data and the results of our analysis to their geographical locations via GIS base-maps.

The information from these data sets provided the inputs to the PVI models to estimate the EFC and related CO2 emissions. The pavement roughness (IRI) and vehicle speed are the inputs to the roughness-induced PVI model (Chatti, 2012), whereas pavement structural and material properties, temperature and vehicle speeds are used in the MIT PVI deflection model. To take into account the uncertainty associated with vehicle speed and its impact on the EFC due to pavement roughness and deflection, a Monte-Carlo Simulation was performed to generate 1000 samples of vehicle speed and material and structural properties.

Figure 13 (a) shows the distribution of the total EFC on the CALTRANS network by location in 2013. The results indicate high EFC around urban area, which correspond to roads with some poor pavement conditions, but more importantly with high traffic volumes. There is also a high concentration on the North-South Interstates through the central California valley where the roads are relatively smooth, but are composite pavements and have high truck volumes. Figure 13 (b)



(a) by location (2013)

(b) Total emissions by source (2007-2013)

Figure 13: Roughness and deflection induced annual excess CO2 emissions on VA interstates (tonnes of excess CO2)
Assumed speed= 100 km/h (62.6 mph); assumed temperature= 16 C/61 F

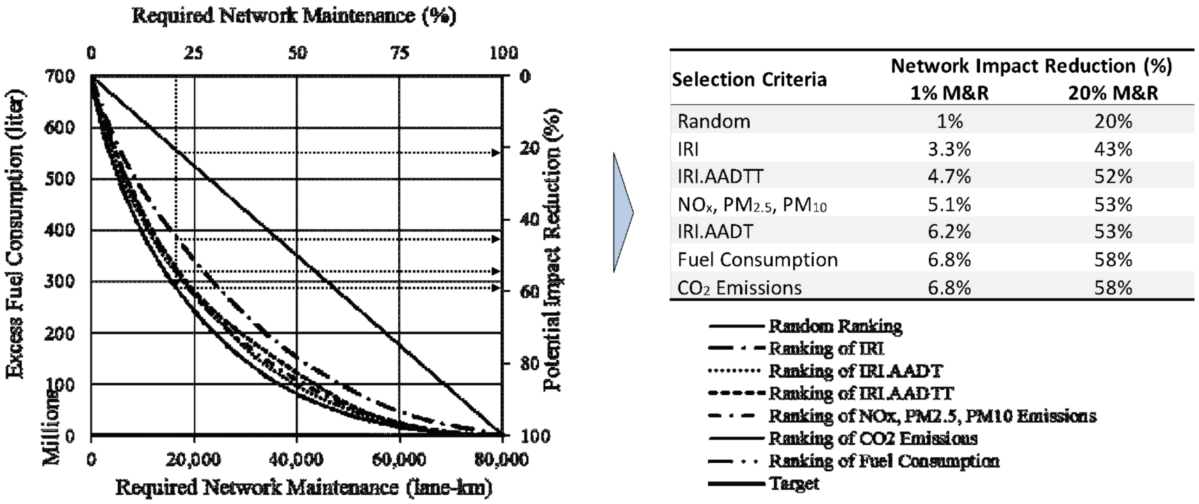
shows the yearly breakdown of EFC based on roughness- and deflection-induced PVI by vehicle type. As can be seen, most of the car induced PVI related emissions are due to roughness, while truck induced PVI emissions are due to both deflection and roughness.

Upscaling the EFC from pavement section to the network-scale provides a means for strategic rehabilitation planning when considering network-level carbon management. The challenge is to find the shortest path that results in maximum emissions reduction with minimum lane-mile of road maintenance. In reviewing potential ways that this could be done, MIT found that the rank-magnitude plot of the excess emissions exhibits a power-law behaviour akin to Zipf's law, i.e. a probability distribution, where the probability p(x) of measuring a particular value x varies inversely as a power function of that value, i.e. $p(x) = Cx^{-\alpha}$, with C a normalization constant, and α the power-law exponent. Power-law behaviour appears in a wide range of phenomena such as magnitudes of earthquakes, frequency of words, and citation of papers among others.

Given the underlying power-law distribution of emissions is applicable to the pavement network, MIT was able to rank and separate the few road sections with high EFC, from the many low impact ones and thus provide the shortest path for the network-level emission reduction for sustainability impact estimators such as CO2, NOx, $PM_{2.5}$ and PM_{10} emissions. This process provides an optimal framework for comparing a maintenance management strategy based CO2 emissions reductions to other strategies, such as randomly maintaining the roads, choosing the roads based on traffic volume, and the current practice of selecting roads based only on their IRI values.

Figure 14 presents the results of various ranking strategies evaluated in prioritizing the network pavement sections in need of rehabilitation throughout the network. These strategies included randomly ranking roads in need of rehabilitation (which is shown to be an upper bound to the optimization); ranking of roads with high roughness (IRI) values (a common pavement management practice in many states); ranking of roads based on a combination of road roughness IRI and the total truck traffic volume AADTT (IRI.AADTT); a ranking of diesel induced emissions (NO_x, $PM_{2.5}$, and PM_{10}) throughout California by ranking of pavements to minimize truck diesel consumption; a ranking of the impact of roughness on the total vehicular traffic, through IRI.AADT; and lastly and equally, by minimizing the EFC and CO_2 emissions..

As can be seen, the selection based on ranking EFC, which is an integration of road conditions, traffic loads and climatic conditions, leads to a maximum reduction rate of CO2 emissions per lane-



Selection Criteria	Network Impact Reduction (%)	
	1% M&R	20% M&R
Random	1%	20%
IRI	3.3%	43%
IRI.AADTT	4.7%	52%
NO_x, $PM_{2.5}$, PM_{10}	5.1%	53%
IRI.AADT	6.2%	53%
Fuel Consumption	6.8%	58%
CO_2 Emissions	6.8%	58%

Figure 14: Comparison of different road selection strategies for maintenance in terms of emission reduction potential

mile maintained. That is, by selecting which portions of CALTRANS network to rehabilitate using rankings based on PVI-induced emissions, CALTRANS can get a 58% reduction of total excess CO2 emissions by maintaining only 20% of the total lane-miles of the interstate network. The same result would require maintaining 58% of the lane-miles when using random selection, and approximately 27% of the lane-miles when selecting road sections based only on the IRI values.

It is important to note is that this network analysis only provides a snapshot of which sections of roadway are selected for rehabilitation and it assumes that all rehabilitation activities provide the same, one-time benefit. The optimal rehabilitation strategy for a given section should be based on a project level analysis that looks at both the long-term smoothness and stiffness EFC / PVI impacts of the different rehabilitation options, and a project level LCA that takes into account the environmental footprint of the different potential rehabilitation solutions, as described above to determine the solution(s) that results in the minimum impact over the life of the pavement. For example, on the North-South Interstates that run through the central California valley region, to get the greatest reductions, the chosen rehabilitation activities should both stiffen up the system and as well as smooth it (it is high truck volume route made up of a medium stiffness composite pavement system).

7. SUMMARY

In 2009, the US cement and concrete industries established the Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT) to develop and find breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings. With regards to pavements, MIT found that the “use phase” and in particular Pavement Vehicle Interaction almost always plays a substantial role in the environmental impact of given pavement design, and that these impacts are often higher than the impacts associated with the pavement materials and construction.

Based on this finding, MIT developed a mechanistic based PVI deflection model to determine excess fuel consumption of a pavement system based on its structure and material properties (the *stiffness* of the system). MIT then developed a small-scale, desk-top experiment that allowed them isolate the interaction of the wheel and the pavement structure to partially calibrate and validate the PVI-Deflection (structure) model. Finally, MIT showed how this model can be used at both the project level and network the level to reduce the PVI-related impacts and improve the decision-making process so that agencies can lead to reduced emissions in meaningful ways.

From this analysis, the major findings were:

- Excess Fuel Consumption is significant.
- Both roughness and structure impact EFC and the context of the specific circumstances will determine which (structure or roughness) is dominant.
- In general, light vehicles are primarily impacted by roughness-induced PVI while trucks are impacted by both roughness and deflection-induced PVI
- At the project level, EFC can be incorporated into the design process to improve pavement designs that save fuel, GHG, and money.
- At the network level, EFC can be used as a means to select the roadway sections for rehabilitation that will have the greatest impact on reducing the environmental impact of the network.
- By using both the information from the network analysis and project level specifics, decision-makers can make more informed decisions on which activities to invest in, in order to have the cost effective solution at lowering the environmental impact of the highway network.

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