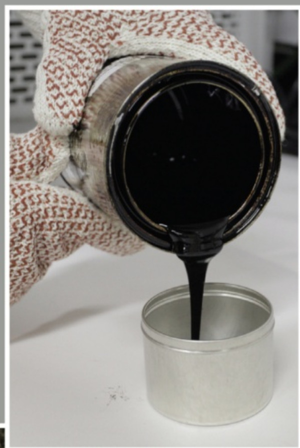

NCAT Report 16-03

A SYNTHESIS REPORT: VALUE OF PAVEMENT SMOOTHNESS AND RIDE QUALITY TO ROADWAY USERS AND THE IMPACT OF PAVEMENT ROUGHNESS ON VEHICLE OPERATING COSTS

By
Dr. Mary M. Robbins
Dr. Nam H. Tran, P.E.

April 2016

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

A SYNTHESIS REPORT: VALUE OF PAVEMENT SMOOTHNESS AND RIDE QUALITY TO ROADWAY USERS AND THE IMPACT OF PAVEMENT ROUGHNESS ON VEHICLE OPERATING COSTS

NCAT Report 16-03

By
Mary M. Robbins, Ph.D.
Nam H. Tran, Ph.D., P.E.

National Center for Asphalt Technology
Auburn University, Auburn, Alabama

Sponsored by
National Asphalt Pavement Association
The State Asphalt Pavement Associations

April 2016

ACKNOWLEDGEMENTS

This authors wish to thank the National Asphalt Pavement Association (NAPA) and the State Asphalt Pavement Associations for sponsoring this research as part of the Determining Service Life Based on Comparable IRI research project and for providing technical review of this document.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the sponsoring agencies, the National Center for Asphalt Technology, or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this report related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

1.1 Background

Ride quality is generally associated with users' level of comfort relative to the traveled roadway, which, in turn, is affected by pavement smoothness or roughness. Pavement roughness describes the irregularities in the surface of the pavement. As Hveem stated, "Ever since roads and highways have been constructed, the people who use them have been keenly aware of the relative degrees of comfort or discomfort experienced in traveling" (*1*). Hveem goes on to write, "There is no doubt that mankind has long thought of road smoothness or roughness as being synonymous with pleasant or unpleasant" (*1*).

Recognizing the importance of ride quality to the traveling public, transportation agencies have used this as a key performance indicator in the pavement maintenance and rehabilitation process, conducted periodically to extend pavement service life and, more importantly, to improve motorist safety and satisfaction. The importance of pavement ride quality is recognized by the Federal Highway Administration (FHWA) through its requirements for the Highway Performance Monitoring System (HPMS). Agencies are required to report pavement roughness in terms of International Roughness Index (IRI) or Present Serviceability Rating (PSR) where IRI is not reported (some non-National Highway System routes) as part of the HPMS. According to the HPMS Field Guide, IRI is utilized in a number of analyses, including modeling pavement deterioration and for use in cost allocation studies (*2*).

As Swanlund points out in *Public Roads*, research has shown that smooth roads cost transportation agencies less over the life of the pavement and result in decreased highway user operating costs, delayed costs, decreased fuel consumption and decreased maintenance costs (*3*). Thus, "not only do our customers want smooth roads for comfort, smooth roads cost less for both the owner/agency and the user" (*3*). Therefore, there is a need to review previous research efforts to fully understand the implications of pavement roughness. The purpose of this synthesis report was to search, review, and synthesize available information on the importance of ride quality and pavement smoothness to the traveling public. As part of this report, the impact of pavement roughness on vehicle operating costs was also examined as it likely influences the public's perception of pavement roughness.

2. RIDE QUALITY AND PAVEMENT ROUGHNESS

Pavement roughness measurement in terms of pavement serviceability was first introduced by the American Association of State Highway Officials (AASHO) at the completion of the AASHO Road Test in the late 1950s (*4*). In this measurement, the serviceability of a pavement is expressed as PSR. PSR is the mean roughness rating on a scale from 0 to 5 assigned by a panel of passengers driving over the pavement in a vehicle. The relationship between the panel-rated PSR and other non-panel pavement performance measurements is represented by a mathematical model known as the Present Serviceability Index (PSI).

Several studies were conducted after the AASHO Road Test to evaluate various non-panel measurement systems. Of those studies, the International Road Roughness Experiment (IRRE) commissioned by the Work Bank and conducted in the early 1980s in Brazil was essential to the development of the ride quality measure commonly used today across the United States. This experiment was conducted in 1982 by research teams from Brazil, England, France and the United States (*5*). As a result of the IRRE, the International Roughness Index (IRI) was established (*6*). IRI is an objective measurement of pavement roughness and can be obtained using vehicle-mounted high-speed inertial profilers. Inertial profilers determine the distance between a reference point on the profiler and the pavement surface while accounting for vertical movement of the vehicle to capture the true relative profile (*7*). A mathematical model is then applied to the measured relative surface profile to calculate IRI as the suspension displacement per unit of distance traveled, expressed as m/km or in/mile (*8*). IRI is a widely used method for measuring pavement roughness. IRI was found to be the most significant factor associated with changes in drivers' perception of road roughness in Washington State (*9*).

2.1 Importance of Ride Quality to Traveling Public

The importance of ride quality to the traveling public has been illustrated through national, regional, and state surveys. In a nationwide survey conducted in 2000 by the FHWA, respondents were asked which highway characteristics should receive the most attention and resources for improvement. Twenty-one percent selected pavement surface conditions including quiet ride, surface appearance, durability, and smoothness of ride, which was rated just lower than traffic flow (28%) and safety (26%), as shown in Figure 2.1 (*10*). A more recent national survey conducted by Edelman Berland for the Asphalt Pavement Alliance in 2014 asked respondents to identify the road attributes they believed were of greatest importance (*11*). Of the 3,000-plus drivers surveyed, "69% said they were willing to accept periodic maintenance delays if it means they get to enjoy a smooth driving experience" (*11*).

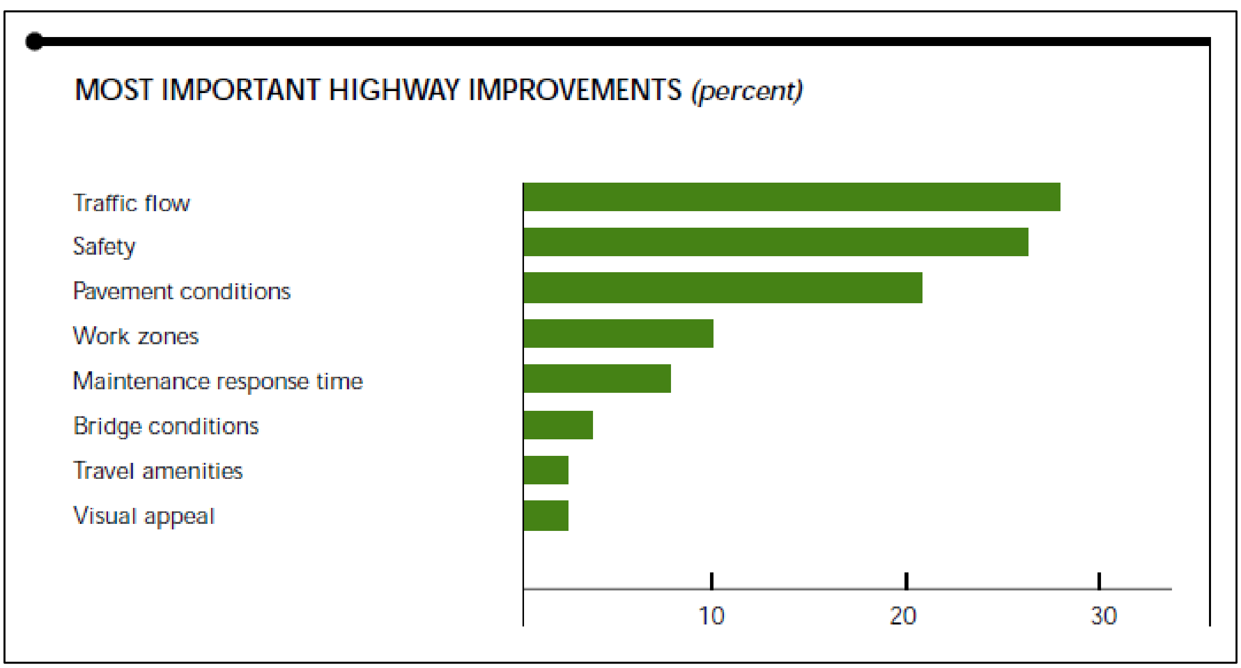

FIGURE 2.1 Pavement Condition Ranked Third Most Important (*10*)

A five-year multi-phase regional survey of public perceptions of two-lane highway pavements was conducted to establish policies and thresholds for pavement improvement in Wisconsin, Iowa, and Minnesota (*12*). One of the key findings in the first phase of the regional survey was that most survey participants "believed the resurfacing should only occur when the ride deteriorated". It can be inferred from this finding that roadway-users relate the need for intervention most with ride quality.

In a statewide survey conducted for an audit of the Washington State Department of Transportation (WSDOT) in 1997, respondents indicated that "poor road surface" ranked second as the state's biggest transportation problem (*9*). Authors reported that recommendations from the audit included "a need for greater recognition of customer perceptions of pavement conditions" and WSDOT "should consider including pavement roughness in addition to Pavement Structural Condition and rutting, in its candidate pavement project thresholds" (*9*).

2.2 Factors Related to Perceived Ride Quality

As a result of the 1997 audit, WSDOT conducted an experiment to determine the issues associated with drivers' perception of surface roughness and actual measured roughness. The study identified the most significant factor associated with drivers' perception of road roughness was measured IRI, although other factors also affect drivers' perception (see Table 2.1) (*9*).

TABLE 2.1 Factors Associated with Drivers' Perception of Road Roughness on Urban Highways (*9*)

Variables Associated with More Roughness	Variables Associated with Less Roughness
Measured IRI	Older individuals
Observable "maintenance"	Sport utility test vehicles
Presence of joints/abutments	Minivan test vehicles
Age of surface	Female users
In-vehicle noise	Frequent users of SR 520
Vehicle speed	
High income users	
Male users	
Frequent users of I-405	

As part of the five-year multi-phase regional study, a survey was conducted where participants were asked to travel to designated stretches of roadway and indicate the level to which they were satisfied with the pavement, felt it was better than most, or should be improved (*12*). Relationships drawn between driver satisfaction and pavement roughness revealed that when respondents in Wisconsin were satisfied, the values of IRI ranged from as low as 0.7 m/km (44.3 in/mile) to 3.3 m/km (209 in/mile). Although it was concluded that "the pavement indices do not explain satisfaction to any great degree," the IRI values at which 70% of the respondents were satisfied were 1.7 m/km (108 in/mile), and 1.2 m/km for Wisconsin and Iowa, respectively. Furthermore, in both states, 70% of the respondents agreed that of the roadways driven, those with an IRI of 2.8 m/km (177 in/mile) should be improved.

A similar study completed in 2014 for North Carolina Department of Transportation (NCDOT) asked 241 participants to rate the smoothness of the pavements in each region of the state (*13*). Participants rated the pavement by both categorical (acceptable or unacceptable) and numerical (0 – 5) scales. Similar to the 1997 audit conducted in Washington, perceived ride quality was influenced most by measured IRI values, speed limit, and seating location within the survey vehicle. Relationships between measured IRI value and categorical ratings indicated that pavements with IRI of 103 in/mile or less were most likely rated as acceptable, and roadways with IRI greater than 151 in/mile were most likely to be rated as unacceptable.

FHWA recognized the importance of ride quality with their Mobility Goal, established as part of the 1998 FHWA National Strategic Plan to increase the percentage of miles on the National Highway System (NHS) with acceptable ride quality to 93% within 10 years (*14*). Acceptable ride quality for Interstates and the NHS was defined as IRI less than or equal to 170 in/mile, and thus IRI greater than 170 in/mile was considered unacceptable. In 2002, the primary performance goal was revised to a goal of 95% of vehicle miles traveled on the NHS, and a secondary performance goal was also established to set a goal for vehicle miles traveled on roadways with good ride quality. Good ride quality was defined by an IRI of 95 in/mile or less and thus refining the IRI categories as good (≤ 95 in/mile), acceptable (> 95 in/mile and ≤ 170 in/mile), and an implied category of unacceptable (> 170 in/mile). These categories were revised again in 2015 when FHWA proposed criteria for determining good, fair, and poor ratings for the proposed national performance measures required under Moving Ahead for Progress in the 21st Century (MAP-21) (*15*). Proposed categories for IRI are separated by urban and non-urban areas. For non-urban areas, IRI is defined as good (< 95 in/mile), fair (95 to 170 in/mile), and poor (> 170 in/mile). For urban areas (defined by a population of 1,000,000), IRI is defined as good (< 95 in/mile), fair (95 – 220 in/mile), and poor (> 220 in/mile).

Although thresholds and goals were established at the national level, not all agencies have adopted them. For example, WSDOT considers an IRI greater than 221 in/mile unacceptable (*16*). Louisiana responded to a survey issued as part of a 2009 study on pavement ratings and scores across the nation, with limits defining acceptable IRI for different classifications of roadways (*17*). These values were reported as IRI less than 171 in/mile, 201 in/mile, 226, in/mile, and 226 in/mile for Interstate highways, NHS, state highways, and regional highways, respectively. While these thresholds may be higher than those established by FHWA, several agencies have set internal goals that are tighter than the national goals. As part of the same survey, agencies were asked to report any specific state legislation or internal goals. Several agencies reported goals or legislation that specifically pertained to IRI, and they are summarized from the 2009 study (*17*) as follows:

- The goal reported for Arkansas was to rehabilitate all pavements with IRI > 96 in/mile.
- Maine aimed to keep IRI on their roadways less than 168 in/mile.
- Maryland reported separate goals for interstate and secondary routes as IRI less than 119 in/mile and 171 in/mile, respectively.

- The internal goal set for Montana was reported as having less than 5% of the miles with IRI greater than 148 in/mile.
- At the time of the survey, Vermont's proposed goal was to have a "minimum ride index of 50% or IRI of 171 in/mile". It can be inferred from this that Vermont intends to achieve roadways with IRI *less* than 171 in/mile.
- Virginia's internal goal was reported as achieving less than 15% of their roadways with IRI greater than 139 in/mile.

Referring back to the 1997 audit of WSDOT, it was recommended that WSDOT "consider including pavement roughness in addition to Pavement Structural Condition and rutting, in its candidate pavement project thresholds" (*9*). A WSDOT report on the state's pavement roughness in 2010 reveals that WSDOT currently considers an IRI-based roughness index for programming projects and a cracking index and rutting index to determine when resurfacing should be conducted (*16*). However, because roughness is generally considered a "lagging" indicator that increases when other problems such as cracking and rutting have become severe, rehabilitations for asphalt pavements in Washington are typically triggered by cracking or rutting indices. IRI as a lagging indicator may be explained by WSDOT's unacceptable IRI value of 221 in/mile. It should be noted, however, that WSDOT reports that only 9.1% of their pavement network was unacceptable in 2012 by FHWA's criteria (*18*). WSDOT also points out that the FHWA categories for IRI were developed for Interstate Highways for the purpose of comparing relative performance from state-to-state (*16*).

Aside from thresholds for defining acceptable roughness, WSDOT, like many agencies, assigned qualitative descriptions to ranges of IRI for assessment of the ride quality of their pavements. Table 2.2 shows WSDOT's comparison of the IRI categories with those of FHWA. The IRI categories for FHWA shown in WSDOT's comparison were developed by FHWA in earlier years and presented in the 1999 Conditions and Performance Report when the use of IRI measurements were not as widespread (*19*). These categories, listed in Table 2.2, were intended for translation between PSR and IRI. To put these categories in context, the recently proposed categories for MAP-21 have also been shown. IRI categories for other agencies have been reported in a comparison of pavement condition performance measures originally conducted in 2008 and presented in the 2009 study on pavement scores (*17*). Those agencies' established categories of roughness are also listed in Table 2.2. It is evident that many state agencies are using IRI to describe ride quality, and the values within each category vary to some degree from state-to-state.

TABLE 2.2 IRI Categories (*after 15, 16, 17, 19*)

	IRI Categories of Roughness (in/mile)				
Agency	Very Good	Good	Fair	Poor	Very Poor
FHWA (1999)	< 60	61 – 95	96 – 120	121 – 170	> 170
FHWA (2015) Non-urban Urban*		 < 95 < 95	 95 – 170 95 – 220	 > 170 > 220	
WSDOT	≤ 95	96 – 170	171 – 220	221 – 320	> 320
Arkansas		1 – 95	96 – 170	> 170	
Indiana		< 101	101 – 169	≥ 170	
Nebraska	< 55	55 – 157	158 – 211	212 – 267	> 268
Nevada Interstate Non-interstate	 1 – 59	 60 – 94	 95 – 119 95 - 170		
North Dakota	< 80	81 – 129	130 – 177	> 177	

*Urban has population ≥ 1,000,000

3. IMPACT OF PAVEMENT ROUGHNESS ON VEHICLE OPERATING COSTS

Ride quality affects not only users' level of comfort but also their costs. According to Biehler, a former president of the American Association of State and Highway Transportation Officials (AASHTO), "The American public pays for poor road conditions twice—first through additional vehicle operating costs and then in higher repair and reconstruction costs" (*20)*. He goes on to elaborate, "Driving on rough roads accelerates vehicle depreciation, reduces fuel efficiency, and damages tires and suspension" (*20*).

According to a 2015 factsheet on surface transportation published by national transportation research group TRIP, 88% of person miles of travel are conducted in private vehicles (*21)*. Given this large percentage, the public is likely to notice rough pavements. TRIP used IRI as reported by the FHWA in 2013 to surmise that 28% of the "nation's major urban roads" (interstates, freeways, and other major routes in urban areas) were in poor condition (IRI > 170 in/mile) and 41% were in mediocre or fair condition (IRI = 120 – 170 in/mile) (*22*). TRIP also found that "driving on roads in need of repair costs the average driver $516 annually in extra vehicle operating costs," with additional vehicle operating costs ranging between $549 and $1,044 annually for urban areas (populations > 250,000). These costs were estimated by applying the recent Highway Development and Management (HDM) model, HDM-4, and results from a 1994 Texas Transportation Institute (TTI) report to the average number of miles driven on roads in need of repair, determined from the FHWA IRI data reported in 2013, and current vehicle operating costs reported by AAA in 2012 (*22*).

Vehicle operating costs (VOC) generally consists of fuel, tire wear, maintenance and repair, oil consumption costs, and can also include vehicle depreciation costs. It has long been thought that VOC is influenced by pavement condition, pavement type, roadway geometry, and operating speed in addition to vehicle type and vehicle technology. A number of studies have been completed on such topics, including an investigation dating back to 1877 (*23*). Since then, numerous studies have also been completed on the effect of pavement condition, specifically on components of VOC. Focus has been placed on the effect of roughness on the components of VOC (excluding the frequently changing vehicle technology and type): fuel consumption, tire wear, repair and maintenance, and oil consumption costs. The following sections include a synthesis of the relevant literature.

3.1 Impact of Pavement Roughness on Fuel Consumption Costs

Extensive work has been conducted in the area of fuel consumption relative to pavement roughness. Although not all studies evaluated the additional costs due to increased fuel consumption on rough pavements, it can be inferred that an increase in fuel consumption would result in increased costs. Much of the early studies were conducted in developing countries and/or on unpaved, gravel or earthen roadway surfaces and, in some cases, roughness levels were beyond those typically seen in the U.S. (*24-27*). For example, four primary cost studies were conducted between 1970 and 1982 in Kenya, the Caribbean, India, and Brazil. These studies indicated that there was an effect of pavement roughness on fuel consumption, although the effect was much more pronounced in the models developed in the Brazilian study than the other three (*25*). The range of IRI used for these experiments ranged from as low as 2.0 m/km (in the Caribbean) to as high as 22.1 m/km (in Kenya) (*26*). Applying the conversion factor of 1 m/km = 63.4 in/mile to these studies results in a range of 126.8 in/mile to 1401.1 in/mile, which falls into the category of poor on the low end and very poor on the high end according to the FHWA (see Table 2.2).

Four studies were published in ASTM's 1990 STP1031, in which an effect of pavement roughness on fuel consumption and/or rolling resistance was reported in four additional countries (Belgium, France, South Africa, and Sweden) (*28-31*). Later converted to IRI by other researchers, the percent change in fuel consumption per unit of IRI (m/km) for these four studies was reported for a car and ranged from 0.7% to 1.7% (*32*).

Results from a Wisconsin study revealed a nonlinear increase in fuel consumption with an increase in roughness (*33*). It was found that a 3% increase in fuel consumption resulted between the smoothest (serviceability index (SI) = 4.4) and roughest (SI = 0.9) pavements tested. A South African study found a strong correlation between roughness and rolling resistance (and thus, fuel consumption) (*34)*. Despite these reported correlations between fuel consumption and roughness, a separate U.S. study found no statistically significant differences at the 95% level in fuel consumption on paved sections (*35*). Therefore, it was concluded that for the range of conditions in the U.S., the type or condition of paved roads does not influence fuel consumption. The authors acknowledged that these findings conflict with previous studies (*36, 37*) that reported a correlation between roughness and fuel consumption, citing that the sections used in those experiments did not realistically represent operating conditions in the U.S. due to the potholes, patches, and badly broken portions of the roadway included in those studies. Later, Barnes and Langworthy elected to forgo the effect of pavement roughness on fuel consumption costs in developing per-mile costs for trucks and passenger cars in Minnesota (*38, 39*). The authors stated that previous studies were in developing countries and on roads with much worse conditions than in the U.S.; therefore, Barnes and Langworthy concluded that roughness effects on fuel consumption were not applicable.

Although Barnes and Langworthy chose not to include the effect of pavement roughness on fuel consumption, several recent studies in the U.S. have reported a positive correlation between pavement roughness and fuel consumption. Chatti and Zaabar conclude that the most important pavement condition factor relative to fuel consumption is surface roughness in terms of IRI (*40*). Additionally, studies at WesTrack (*41*), Florida (*42*), and Missouri (*43*) reveal that for roughness levels and conditions seen in the U.S., pavement roughness influences fuel consumption. These studies reported higher fuel efficiency on Florida pavements with lower IRI (*42*) and improvements in fuel consumption by up to 4.5% at WesTrack (*41*) and 2.461% in Missouri (*43*) on smoother pavements. It has also been shown at the National Center for Asphalt Technology's Pavement Test Track that fuel consumption increases with increased IRI (*44*). Furthermore, the widely adopted HDM-4 model for computing total transport costs was calibrated for U.S. conditions, reflecting roughness levels and improvements in vehicle technology (*40*). In evaluating the HDM-4 fuel consumption model and the effect of pavement roughness on fuel consumption, an analysis of covariance was conducted showing pavement roughness to be statistically significant. In calibrating the HDM-4 fuel consumption model, Chatti and Zaabar determined that a 1 m/km (63.4 in/mile) increase in IRI effects fuel consumption by approximately 2% (*40*). By decreasing IRI by 1 m/km, Chatti and Zaabar estimate as much as $24 billion could be saved in fuel costs per year in the U.S. based on a 3% reduction in fuel consumption for 255 million passenger cars and gas prices when the report was compiled in 2012.

3.2 Impact of Pavement Roughness on Tire Wear Costs

The influence of pavement condition, specifically pavement roughness, on tire wear costs has been an important part of vehicle operating cost studies. In 1985, Zaniewski and Butler stated "there is direct physical evidence being compiled around the world that shows that pavement roughness influences vehicle operating costs" (*45*). In developing countries, varying levels of influence were reported for roughness on tire wear, such that models developed for Kenya and the Caribbean had a rate of increase in tire wear due to pavement roughness of nearly two times higher than the rate utilized in models developed for Brazil and India (*27*). A tire wear prediction model was developed Watanatada, Dhareshwar, and Rezende-Lima (*27*), using data primarily from the Brazil study (*46*). Although limited data were available, the model for cars and utilities "was calibrated as a simple linear function of road roughness." It was also reported that based on this developed model, roughness had a small effect in tire wear for a constant load level on a level road and a much greater effect on steep roads.

In 1982, a U.S. study (*35*) developed adjustment factors based on relationships developed in the earlier cost study conducted in Brazil. Cost adjustment factors proportionate to the change in tire consumption as the surface changes from a baseline condition of a serviceability index (SI) of 3.5 were developed (*35*). These cost adjustment factors were such that the adjustment factors at SI = 3.5 were 1.00 and increased with decreasing SI, indicating that rougher pavements result in higher tire expense related to tire wear. In a similar fashion, in a Minnesota study an incremental increase of 10% for every decrease in PSI of 0.5 (starting at 5% for a PSI of 3.0 and down to 2.0) was used to account for the effect of pavement roughness on all vehicle operating costs, with the exception of fuel consumption costs (*38, 39*). For the most recent study in the U.S., in which the HDM-4 tire wear model was calibrated for U.S. conditions, increasing IRI by 1 m/km (63.4 in/mile) was found to increase tire wear by 1% at 88 km/h (55 mph) (*40*). In turn, decreasing IRI by 1 m/km could save $340 million per year in tire wear costs (*40*).

3.3 Impact of Pavement Roughness on Maintenance and Repair Costs

It has been shown through vehicle fatigue response testing that pavement roughness does influence the response of vehicle suspension and can result in accelerated fatigue at PSI less than 1.0 (*47*). Consistent with this finding, correlations between maintenance and repair costs and pavement roughness have been observed in several studies in the U.S. and abroad. Earlier studies in developing countries found a positive effect of roughness on vehicle maintenance costs (*25*). In all four countries, vehicle parts consumption was modeled by road roughness and vehicle age. The effect of roughness on vehicle parts consumption for cars and light goods vehicles was modeled by a linear relationship in the Caribbean and Kenya, while an exponential function for road roughness was used for the Brazilian and Indian models (*25*). While this exponential relationship results in very large increases in parts consumptions for rough roads, there are notable differences between the studies including surface type (paved, earthen, and gravel), and vehicle models and their inherent deterioration rate. Simple models correlating spare parts and mechanics' labor with road characteristics were developed using the Brazilian data (*27*). Spare parts consumption was found to be dependent on road roughness and vehicle age, and the effects combined "multiplicatively". When age was held constant, the relationship between parts consumption and roughness was found to be generally non-linear. Cost adjustment factors were developed for an early U.S. study (*35, 45*) as well as a more recent study in Minnesota (*38, 39*) to account for the effect of roughness. The Minnesota study suggests that a 1¢ per mile increase for maintenance and repair costs results when moving from the smoothest to the roughest pavement in the study. The calibrated HDM-4 repair and maintenance model revealed that decreasing IRI by 1 m/km (63.4 in/mile) could result in repair and maintenance savings between $24.5 billion and 73.5 billion per year (*40*). It should be noted that these estimates were based on estimated annual repair and maintenance costs for 255 million U.S. passenger cars totaling $244.8 billion and IRI greater than 3 m/km (190.2 in/mile).

3.4 Impact of Roughness on Oil Consumption Costs

It was reported early on that engine oil consumption costs were the least important cost component in the aggregate vehicle operating costs (*24*). Echoing this sentiment, Chesher and Harrison later stated "costs associated with the consumption of engine oils, other oils and grease, are a minor element of transport costs" (*25*). This may explain the limited research in the area of pavement roughness effects on oil consumption costs. Although limited, research has shown that the effect for engine oil consumption can be high for cars in India (*20*). Despite these results for Indian cars, Chesher and Harrison reported that "roughness was predicted to have a very small effect on Indian truck [engine] oil consumption" (*25*). Additionally, Zaniweski et al. updated adjustment factors originally developed by Winfrey (*48*). These updated adjustment factors indicated that rougher pavements increase engine oil consumption (*35, 45*). The adjustment factor for trucks an SI of 4.0 was reported as 0.82 and about 1.1 for an SI of 2.0, exhibiting an increase in oil consumption costs as SI decreases (or as roughness increases).

3.5 Impact of Pavement Roughness on Depreciation Costs

Depreciation was modeled in early international studies indirectly as a function of surface conditions and roughness by considering value-age relationships to calculate value due to age (*25*). The 1982 U.S. study considered the use-related expense portion of depreciation by approximating the reciprocal of the maximum vehicle life mileage and data from the previous Brazil study to adjust expenses for pavement conditions through cost adjustment factors as a function of serviceability index (*35, 45*). However, research on the effect of pavement roughness on depreciation costs is limited, with researchers making decisions on vehicle operating costs based on experience rather than observed causal effects of roughness on depreciation. This was the case in Minnesota, where researchers stated that "a car that is driven almost exclusively on smooth highways will last more miles than one that is driven mostly on rough pavements" (*38*).

4. SUMMARY

Through state, regional, and nationwide surveys, it has been established that ride quality and pavement smoothness are important to the traveling public. Pavement surface conditions were ranked third most important in the 2000 FHWA nationwide survey (*10*) and ranked as the second biggest transportation problem in the 1997 WSDOT statewide survey (*9*). Certain levels of pavement roughness are associated with not only a comfortable or an uncomfortable ride but also a need for maintenance or rehabilitation. A regional survey conducted in Wisconsin, Iowa, and Minnesota found most participants "believed the resurfacing should only occur when the ride deteriorated" (*12*). Studies in both Washington and North Carolina revealed that measured IRI was one of the most influential factors in drivers' perception of pavement roughness (*9, 13*).

Public perception is also likely to be influenced by increased vehicle operating costs due to rougher pavements, therefore, the effect of pavement roughness on components of vehicle operating costs were explored. Vehicle operating costs include fuel, tire wear, maintenance and repair, oil consumption, and depreciation costs. Extensive studies have been conducted on the topic of pavement roughness and its effects on fuel consumption costs. Much of the early studies, particularly those conducted in developing countries, included roadway surfaces and roughness levels that extend well beyond those considered unacceptable in the U.S. Citing these conditions, researchers elected to forgo the effect of pavement roughness on fuel consumption costs in developing per-mile costs for trucks and passenger cars in Minnesota (*38*). However, other studies conducted at WesTrack (*41*), Florida (*42*), and Missouri (*43*) in the 2000s reveal that for roughness levels seen in the U.S., pavement roughness influences fuel consumption and thus, influences fuel consumption costs. Additionally, the widely adopted HDM-4 model for computing total transport costs was calibrated for U.S. conditions, reflecting roughness levels and improvements in vehicle technology (*40*). The calibrated HDM-4 fuel consumption model was used to determine that 1 m/km (63.4 in/mile) increase in IRI effects fuel consumption by as much as 2%.

In addition to fuel consumption, costs associated with tire wear, maintenance and repair, oil consumption, and depreciation were also found to be influenced by pavement roughness. Research in the areas of oil consumption and depreciation costs are limited; however, of those early studies that included the effect of roughness on these cost components, it was found that in developing countries, an increase in oil consumption occurred with an increase in pavement roughness (*25*). Maintenance and repair costs were found to increase with increases in roughness, albeit the rate of increase varied from study to study; this was also the case with tire wear costs. Applying the calibrated HDM-4 model to 255 million vehicles, Chatti and Zaabar reported that by decreasing pavement roughness by 1 m/km (63.4 in/mile), as much as $73.5 billion in maintenance and repair costs could be saved annually in the U.S. (*40*). Chatti and Zaabar also reported that the same reduction in IRI could translate to a savings of $340 million per year in tire wear costs for passenger vehicles. Although the estimates conducted by Chatti and Zaabar for cost savings related to reduction in IRI are somewhat generalized and in some cases, based on roughness values at or above FHWA's failure criteria, they illustrate the potential for VOC savings with improved pavement roughness.

It is evident from the state, regional, and national surveys that ride quality is one of the key concerns of the traveling public. Furthermore, research dating back to the 1960s has shown the influence of pavement roughness on components of vehicle operating costs, indicating increased VOCs with increased roughness. The findings from literature reported here underscore Swanlund's sentiments that "not only do our customers want smooth roads for comfort, smooth roads cost less for both the owner/agency and the user" (*3*), as research suggests higher vehicle operating costs are associated with rough pavements.

REFERENCES

1. Hveem, F. Devices for Recording and Evaluating Pavement Roughness. California Division of Highways, 1960. http://www.dot.ca.gov/newtech/researchreports/1959-1960/60-09.pdf.
2. FHWA. *Highway Performance Monitoring System Field Manual*. Office of Highway Policy Information, Washington, D.C., 2014.
3. Swanlund, M. Enhancing Pavement Smoothness. *Public Roads,* Vol. 64, No. 2, Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 2000, pp. 20-22.
4. Carey Jr., W. N., and P. E. Irick. The Pavement Serviceability-Performance Concept. *Highway Research Board Bulletin 250,* National Research Council, Washington, D.C., 1960, pp. 40-58.
5. Sayers, M. W., T. D. Gillespie, and A. V. Queiroz. *The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements*. World Bank Technical Paper Number 45, World Bank, Washington, D.C., 1986.
6. Sayers, M. W., T. D. Gillespie, and C. A. V. Queiroz. The International Road Roughness Experiment: A Basis for Establishing a Standard Scale for Road Roughness Measurements. *Transportation Research Record 1084*, Presented at 65th Annual Meeting of the Transportation Research Board, Washington, D.C., 1986, pp. 76-85.
7. Sayers, M. W. and S. M. Karamihas. *The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles*. The Regent of the University of Michigan, Ann Arbor, MI, 1998.
8. Shahin, M. Y. *Pavement Management for Airports, Roads, and Parking Lots*, 2nd ed. Springer Science, New York, NY, 2005.
9. Shafizadeh, K., F. Mannering, and L. Pierce. *A Statistical Analysis of Factors Associated with Driver-Perceived Road Roughness on Urban Highways*. WSDOT Report No. WA-RD 538.1, Washington State Transportation Center, Seattle, WA, 2002.
10. Keever, D., K. Weiss, and R. Quarles. *Moving Ahead: The American Public Speaks on Roadways and Transportation in Communities*. Report No. FHWA-OP-01-017, FHWA, Washington, D.C., 2001. http://www.fhwa.dot.gov/reports/movingahead.htm.
11. Asphalt Pavement Alliance. *Ahead of the Summer Driving Season, a New Survey from the Asphalt Pavement Alliance (APA) Finds U.S. Drivers Increasingly Frustrated with the State of U.S. Roads*. APA News, Lanham, MD, May 21, 2014. http://www.asphaltroads.org/news/post/national-driver-survey-reveals-need-focus-drivability. Accessed August 1, 2014.
12. Kuemmel, D., R. Robinson, R. Sonntag, R. Griffin, and J. Giese. Public Perceptions of the Midwest's Pavements: Policies and Thresholds for Pavement Improvement on Rural Two-Lane Highways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1761*, Paper #01-0346, TRB, National Research Council, Washington, D.C., 2001, pp. 11–19.
13. Chen. D., J. Hildreth, X. Fang, V. O. Ogunro, and C. Laville. *Development of IRI Limits and Targets for Network Management and Construction Approval Purposes*. Report No. FHWA/NC/2013-02, North Carolina Department of Transportation, Raleigh, NC, 2014.

14. FHWA. *Smoothness*. http://www.fhwa.dot.gov/pavement/smoothness/index.cfm. Accessed November 8, 2015.
15. FHWA. *National Performance Management Measures; Assessing Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program*. 23 CFR Part 490, RIN 2125-AF33, U.S. Department of Transportation, Washington, D.C., 2015.
16. WSDOT Pavement Roughness (IRI) Report: 2010. Part of *WSDOT Pavement Notebook*, Washington State Department of Transportation, 2012.
17. Papagiannakis, A., N. Gharaibeh, J. Weissmann, and A. Wimsatt. *Pavement Scores Synthesis*. FHWA-TX-09-0-6386, Texas Department of Transportation, Austin, TX, 2009.
18. WSDOT. *The Gray Notebook*. Edition 52, Washington State Department of Transportation, 2014, p. 17. http://wsdot.wa.gov/publications/fulltext/graynotebook/Dec13.pdf. Accessed October 21, 2014.
19. U.S. Department of Transportation. *1999 Status of the Nation's Highways, Bridges and Transit: Conditions and Performance, Report to Congress*. Washington, D.C., 1999.
20. Biehler, A. *Rough Roads Ahead: Fix Them Now or Pay for Them Later*. AASHTO, Washington, D.C., 2009.
21. *Key Facts about America's Surface Transportation System and Federal Funding*, The Road Information Program (TRIP), Washington, D.C., April 2015. http://www.tripnet.org/docs/Fact_Sheet_National.pdf.
22. *Bumpy Roads Ahead: America's Roughest Rides and Strategies to Make our Roads Smoother*. The Road Information Program (TRIP), Washington, D.C., 2015.
23. Law, H. and D. Kinnear-Clark. *The Construction of Roads and Streets*. Crosby Lockwood & Co., London, 1877.
24. De Weille, J. *Quantification of Road User Savings.* World Bank Staff Occasional Papers Number Two, International Bank for Reconstruction and Development, The John Hopkins Press, Baltimore, MD, 1966.
25. Chesher, A. and R. Harrison. *Vehicle Operating Costs: Evidence from Developing Countries.* The Highway Design and Maintenance Standards Series, The Johns Hopkins University Press, Baltimore, MD, 1987.
26. Bennett, C. R. and I. D. Greenwood. *Modelling Road User and Environmental Effects in HDM-4*. Volume Seven, The Highway Development and Management Series, The World Road Association (PIARC), Paris, France, 2001.
27. Watanatada, T., A. M. Dhareshwar, and P. R. S. Rezende-Lima. *Vehicle Speeds and Operating Costs: Models for Road Planning and Management*. The Highway Design and Maintenance Standard Series, The Johns Hopkins University Press, Baltimore, MD, 1987.
28. Descornet, G. Road-surface Influence on Tire Rolling Resistance. In *Surface Characteristics of Roadways: International Research and Technologies,* ASTM STP 1031, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 401-415.
29. Laganier, R., and J. Lucas. The Influence of Pavement Evenness and Macrotexture on Fuel Consumption. In *Surface Characteristics of Roadways: International Research and Technologies,* ASTM STP 1031, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 454-459.

30. du Plessis, H. W., A. T. Visser, and P. C. Curtayne. Fuel Consumption of Vehicles as Affected by Road-Surface Characteristics. In *Surface Characteristics of Roadways: International Research and Technologies,* ASTM STP 1031, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 480-496.
31. Sandberg, U. S. Road Macro-and Megatexture Influence on Fuel Consumption. In *Surface Characteristics of Roadways: International Research and Technologies,* ASTM STP 1031, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 460-479.
32. McLean, J. and G. Foley. *Road Surface Characteristics and Condition: Effects on Road Users.* Research Report ARR 314, ARRB Transport Research, 1998.
33. Ross, F. R. Effect of Pavement Roughness on Vehicle Fuel Consumption. In *Transportation Research Record: Journal of the Transportation Research Board, No. 846*, TRB, National Research Council, Washington, D.C., 1982, pp. 1-6.
34. Bester, C. Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1000*, TRB, National Research Council, Washington, D.C., 1984, pp. 28-32.
35. Zaniewski, J.P, B.C. Butler, G. Cunningham, G.E. Elkins, M.S. Paggi, and R. Machemehl, Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors, *Report No. FHWA/PL/82/001*, Federal Highway Administration, Washington, D.C., 1982.
36. Claffey, P.J., and Associates, Running Costs of Motor Vehicles as Affected by Road Design and Traffic, *NCHRP Report 111*, Highway Research Board, National Research Council, Division of Engineering, 1971.
37. Zaniewski, J. P., B. K. Moser, P. J. de Morasis, and R. L. Kaesehagen. Fuel Consumption Related to Vehicle Type and Road Conditions. In *Transportation Research Record: Journal of the Transportation Research Board, No. 702,* TRB, National Research Council, Washington, D.C., 1979, pp. 328-334.
38. Barnes, G. and P. Langworthy. *The Per-Mile Costs of Operating Automobiles and Trucks.* Final Report MN/RC 2003-19, Minnesota Department of Transportation, St. Paul, MN, 2003.
39. Barnes, G. and P. Langworthy. Per Mile Costs of Operating Automobiles and Trucks. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1864,* TRB, National Research Council, Washington, D.C., 2004, pp. 71-77
40. Chatti, E. K. and I. Zaabar. *NCHRP Report 720: Estimating the Effects of Pavement Condition on Vehicle Operating Costs.* Transportation Research Board of the National Academies, Washington, D.C., 2012.
41. Epps, J. A., A. Hand, S. Seeds, T. Schulz, S. Alavi, C. Ashmore, J. A. Deacon, J. T. Harvey, and R. Leahy. *NCHRP Report 455: Recommended Performance-Related Specification for Hot-Mix Asphalt Construction: Results of the Westrack Project*. Transportation Research Board of the National Academies, Washington, D.C., 2002.
42. Jackson. N. M. *An Evaluation of the Relationship Between Fuel Consumption and Pavement Smoothness.* Preliminary Report, University of North Florida, Jacksonville, FL, 2004.

43. Amos, D. *Pavement Smoothness and Fuel Efficiency: An Analysis of the Economic Dimensions of the Missouri Smooth Road Initiative.* Final Report OR07-005, Missouri Department of Transportation, Jefferson City, Missouri, 2006.
44. Heffernan, M. E. *Simulation, Estimation, and Experimentation of Vehicle Longitudinal Dynamics That Effect Fuel Economy*. Master's Thesis, Auburn University, Auburn, AL, 2006.
45. Zaniewski, J. P. and B. C. Butler. Vehicle Operating Costs Related to Operating Mode, Road Design, and Pavement Condition. In *Measuring Road Roughness and Its Effects on User Cost and Comfort,* ASTM STP 884, American Society for Testing and Materials, Philadelphia, PA, 1985, pp. 127-142.
46. *Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilization: Final Report on Brazil-UNDP Highway Research Project.* Volume 5, Final Report, Empresa Brasileira de Planejamento de Transportes (GEIPOT), Brasilia, Brazil, 1982.
47. Poelman, M. A and R. P Weir. Vehicle Fatigue Induced by Road Surface Roughness. In *Vehicle, Tire, Pavement Interface* (J.J. Harvey and J.C. Wambold, eds.), ASTM STP 1164, American Society for Testing and Materials, Philadelphia, PA, 1992, pp. 97-111.
48. Winfrey, R. *Economic Analysis for Highways*. International Textbook Company, Scranton, PA, 1969.