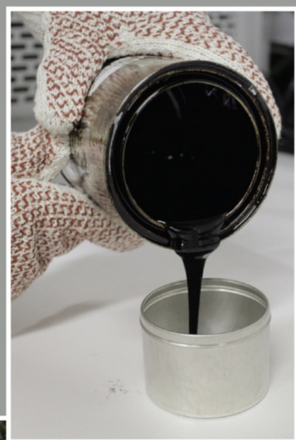

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1. INTRODUCTION
1.1 Background
Ride quality as a measure of pavement roughness plays an important role in users' level of comfort and operating costs. As Swanlund points out in *Public Roads* (*1*), smooth roads cost transportation agencies less over the life of the pavement and result in decreased highway user operating costs, delayed costs, decreased fuel consumption and decreased maintenance costs. Thus, "not only do our customers want smooth roads for comfort, smooth roads cost less for both the owner/agency and the user" (*1*).

This notion of increased user and agency costs was echoed almost a decade later by Biehler, then president of the American Association of State and Highway Transportation Officials (AASHTO). He stated, "The American public pays for poor road conditions twice—first through additional vehicle operating costs and then in higher repair and reconstruction costs" (*2*). He went on to elaborate, "Driving on rough roads accelerates vehicle depreciation, reduces fuel efficiency, and damages tires and suspension" (*2*).

More recently, The Road Information Program (TRIP) used the international roughness index (IRI) data reported in 2011 by the Federal Highway Administration (FHWA) to assess the roughness of the nation's roadways and its potential effects on highway user costs (*3*). TRIP concluded that 27% of the "nation's major urban roads" (interstates, freeways, and other major routes in urban areas) were in poor condition with IRI greater than 170 in/mile, and 42% were in mediocre or fair condition with IRI between 120 and 170 in/mile (*3*). TRIP also found that "driving on roads in need of repair costs the average driver $377 annually in extra vehicle operating costs," with additional vehicle operating costs ranging between $178 and $832 annually for urban areas with populations greater than 500,000.

It is evident that rough pavements result in increased users' costs through vehicle operating costs. This report is prepared based on a review of literature to further discuss the extent to which pavement roughness affects the various components of vehicle operating costs.

1.2 Pavement Roughness
According to the American Society of Testing and Materials (ASTM E867), pavement roughness is defined as "the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for longitudinal profile, transverse profile, and cross slope" (*4*). Pavement roughness measurement in terms of 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 (*5*). In this measurement, the serviceability of a pavement can be expressed as the Present Serviceability Rating (PSR), which is the mean roughness rating on a scale from 0 to 5 given by a panel of passengers in a vehicle. The relationship between the panel-rated PSR and non-panel pavement performance measurements is represented by a mathematical model known as the Present Serviceability Index (PSI). After the AASHO Road Test, several studies were conducted to evaluate various non-panel measurement systems, such as roughometers, profilometers, and ride meters, in order to replicate the results. In the early 1980s, an experiment was

commissioned by the World Bank in Brazil to determine how to best relate profile data to pavement quality. The International Road Roughness Experiment (IRRE) was conducted in 1982 by research teams from Brazil, England, France, the United States, and Belgium (*6*). Researchers found that surface profile was the best common ground between all the different technologies studied. As a result of this study, a roughness measurement standard, known as International Roughness Index (IRI), was established (*7*).

IRI is an objective means to assess pavement roughness "based on the response of a generic motor vehicle to the roughness of the road surface" (*8*). This is done through the quarter-car model, a mathematical model that simulates how a reference wheel traveling at 50 mph would respond to the deviations in the pavement surface (i.e. roughness) along the length of the pavement (*8*). By applying the quarter-car model to the measured profile, IRI is computed as the cumulative suspension displacement per unit of distance traveled and expressed as m/km or in/mile (*9*). In other words, IRI is a specified mathematical transform of a pavement surface profile (*10*). IRI can be modeled on pavement surface profiles determined by inertial profilers, which measure the distance between a reference point on the profiler and the pavement surface using lasers. The distance is then adjusted to account for vertical movement of the vehicle captured by accelerometers to determine the true relative profile of which the quarter car model is then applied to compute IRI.

While other indices (ride number, profile index, etc.) can be calculated from a surface profile, "IRI summarizes the roughness qualities that impact vehicle response and relates most to overall vehicle operating cost, overall ride quality, dynamic wheel loads (that is damage to the road from heavy trucks and braking and cornering safety limits available to passenger cars), and overall surface condition" (*10*). As a result, IRI ranges differ from one class of roadway to the next. The ranges of roughness, expressed as IRI, expected on various roadways, such as airfields, new and aged paved roadways, maintained, unpaved roadways and damaged roadways are shown in Figure 1. For paved roads (regardless of class), the expected IRI range is very broad with IRI from less than 100 in/mile on interstate pavements to as high as 700 in/mile on damaged pavements (*11*).

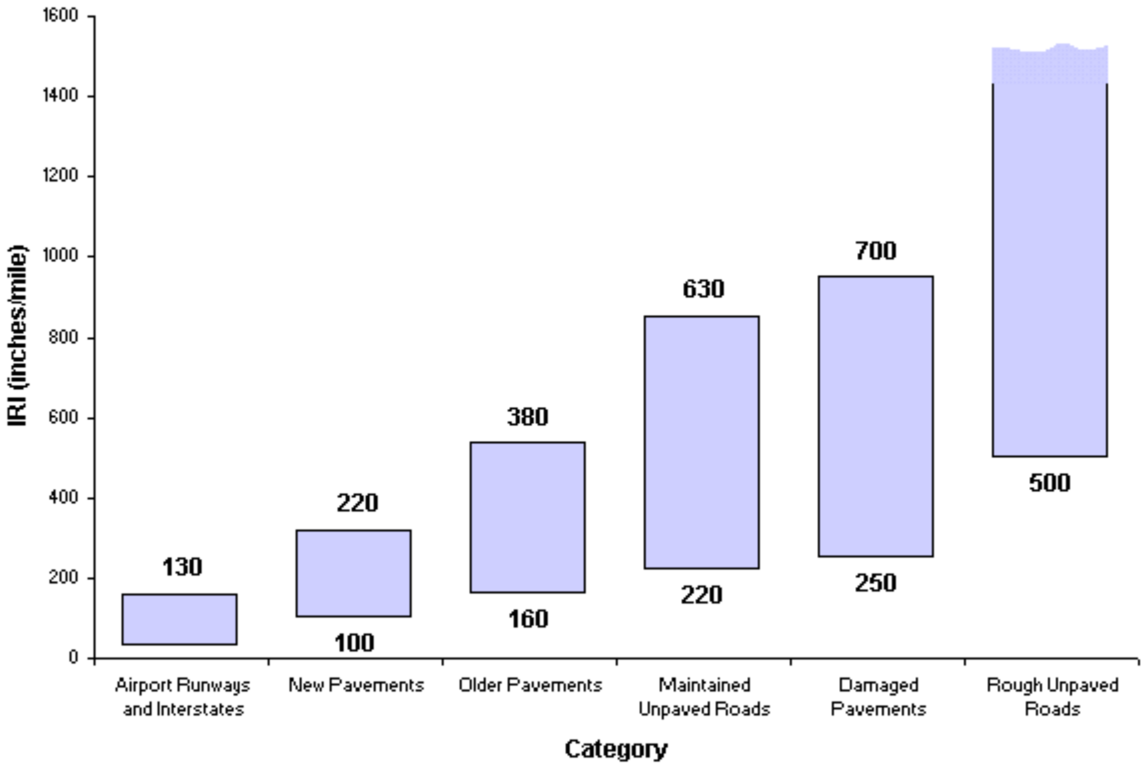

Figure 1 IRI Roughness Scale (*11*), *after* (*12*)

Although Figure 1 displays IRI values that may be experienced on different types of paved roadways, the IRI ranges that U.S. agencies consider for categorizing roadways in their network are much tighter. Table 1 below shows the ranges of IRI considered by FHWA and Washington State Department of Transportation (*13*). FHWA considers pavements that have a roughness measured by IRI greater than or equal to 170 in/mile as unacceptable, while Washington State Department of Transportation (DOT) considers pavements unacceptable when they have reached an IRI of 221 in/mile (*13*).

Table 1 IRI Categories of WSDOT and FHWA (*13*)

IRI Categories of Roughness (in/mile)		
	WSDOT	FHWA
Very Good	≤ 95	≤ 60
Good	96 - 170	61 - 95
Fair	171 - 220	96 - 120
Poor	221 - 320	121 - 170
Very Poor	> 320	> 170

2. EFFECT OF PAVEMENT ROUGHNESS ON VEHICLE OPERATING COSTS

In Volume 7 of the World Bank's manual for the Highway Development and Management (HDM-4) model, vehicle operating costs (VOC) is defined as the "total cost of road transport" and it takes into account fuel consumption, tire consumption, oil and lubricant consumption, parts consumption, labor hours, depreciation, interest, and overheads (*14*). It has been suggested 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 on rolling resistance on common roads (*15*). Much of the groundwork for vehicle operating costs used today was completed by Winfrey in 1969 (*16*), from which a comprehensive set of running cost tables was developed. Shortly thereafter, Claffey completed a comprehensive study of VOC in the U.S. in 1971 (*17*). Since then, numerous studies have been completed on the effect of pavement condition on VOC by studying the effect of pavement roughness on various components of VOC, including fuel consumption, tire wear, repair and maintenance, and oil consumption costs. The following sections discuss key findings of these studies. Some of the studies had been conducted before IRI was developed in the 1980s. Therefore, where the conversion is known or is indicated by the authors of the original work, an approximation of the equivalent IRI is provided as IRI measurements capture the roughness qualities most associated with ride quality and vehicle operating costs (*10*).

2.1 Impact of Pavement Roughness on Fuel Consumption Costs

Studies have shown increased fuel consumption on rough pavements, resulting in increased operating costs. The first major studies on the impact of pavement roughness on fuel consumption were conducted by the World Bank on unpaved, gravel, or earthen roadway surfaces in developing countries to develop and refine the widely-used Highway Design and Maintenance (HDM) model (*14, 18, 19*). Since the model was developed based on roughness data that were not typically seen in the U.S., it was later calibrated to U.S. roadway conditions. According to Chatti and Zaabar, IRI values on U.S. roadways typically range from 1 to 5 m/km (63.4 t0 317 in/mile) (*20*).

De Weille conducted one of the earliest studies in 1966. He used data from an earlier U.S. study to reveal that operating costs were higher for gravel and earthen roadways than for smoother paved roadways (*21*). Fuel consumption was reported to be 20% higher on a gravel road than a paved road and even higher (40%) on an earthen road relative to a paved road (*21*).

The World Bank conducted the first four primary cost studies between 1970 and 1982 in Kenya, the Caribbean, India, and Brazil. Table A2.2 of a 2001 World Bank report reveals that the range of IRI used for the fuel consumption experiments in these countries ranged from as low as 2.0 m/km (126.8 in/mile) in the Caribbean to as high as 22.1 m/km (1401.1 in/mile) in Kenya (*14*). This range falls into the category of poor on the low end and very poor on the high end according to the FHWA's criteria (*22*). The range included roughness data for various surface types, including paved, gravel, and earthen roads. According to Chester and Harrison (*18*), unpaved roadways could have IRI as low as 1.6 m/km (101.4 in/mile) if in excellent condition. The effect of roughness was built into both the fuel and speed equations for the Brazilian model (*18*). This model also showed a much more pronounced effect of roughness than those developed from the Indian, Caribbean, and Kenyan studies (*18*).

The World Bank developed the HDM model, which was later refined primarily using data from the earlier study in Brazil (*23*) to produce the HDM-III model (*19*). The effect of roadway characteristics (including roughness) was incorporated into the HDM-III model. For use in the fuel consumption model of the HDM-III model, data from the study in Brazil were analyzed to determine the effect of roughness on rolling resistance (*19*). In that study, rolling resistance for light and heavy vehicles was considered for four road sections, including paved and unpaved roadways with two levels of roughness: smooth and rough (*19*). Average roughness ranged between 29 (2.2 m/km, or 141 in/mile) for the smooth paved road and 178 (13.7 m/km or 868 in/mile) for the unpaved, rough road, expressed as quarter car index (QI) or counts/km, such that the authors approximated IRI by QI/13, where IRI is in m/km. Comparing these values with current FHWA IRI categories (see Table 1), it is evident that the lowest IRI values for paved roads in the Brazilian study would be considered poor. However, it should be noted that the authors identify a roughness range for paved roads as 25 to 125 QI and 50 to 250 QI for unpaved roads to be used with their predictive models if measurements are not available. For paved roads, very rough corresponds to a roadway exceeding 125 QI (roughly equivalent to an IRI of 9.6 m/km or 610 in/mile) and smooth corresponds to a QI of 25 (1.9 m/km or 122 in/mile). For unpaved roads, 50 QI (3.8 m/km or 244 in/mile) is considered smooth and 250 QI (19.2 m/km or 1219 in/mile) is classified as very rough. The key findings of this research effort include (*19*):

- Rolling resistance generally increased with road roughness.
- Two empirical models were developed for the coefficient of rolling resistance for light and heavy vehicles considering a linear relationship between roughness (QI) and the coefficient of rolling resistance. These interactions are important, as "increasing roughness (from very smooth paved to very rough unpaved) causes the vehicle power and fuel consumption to go up via an increase in the rolling resistance coefficient."
- Rolling resistance was also a function of vehicle weight, and due to this combination, the effect of roughness on fuel consumption was stronger for loaded trucks than unloaded ones.
- For paved roads that were level-tangent with roughness within the range of 50-150 QI (3.8 m/km or 241 in/mile), the effect of increasing roughness on rolling resistance was offset by the reduction in air resistance as a result of decreased speeds on rough surfaces.
- For roughness levels typical of unpaved roads (beyond 125 QI), the effect of rolling resistance on fuel consumption for level-tangent roadways dominated any reduction in air resistance due to reduced speed on a rougher surface.

Results from a Wisconsin study revealed a nonlinear increase in fuel consumption with an increase in roughness (*24*). Fuel consumption in passenger cars was measured with a fuel meter on five test sites featuring bituminous pavements ranging in roughness from a serviceability index (SI) of 0.9 to 4.4. The result was a 3% increase in fuel consumption between the smoothest (SI = 4.4) and roughest (SI = 0.9) pavements tested. Although this relationship was found to be non-linear, for pavement roughness typical of Wisconsin state trunk highways (SI from 4.5 to 1.5), the increase in fuel consumption could be estimated with a linear function, such that 1.5% more fuel would be consumed on a pavement with an SI of 1.5 than one with an SI of 4.5.

A South African study found a strong correlation between roughness and rolling resistance and thus, fuel consumption (*25*). It was reported that asphalt and concrete roads have lower rolling resistance than roads with surface treatments, and for a truck traveling at 80 km/h, 18% more fuel will be used on a gravel road than on a paved road in good condition.

Contrary to previous studies, including a 1979 report by the same author (*26*), Zaniewski et al. concluded in their 1982 report that "roughness does not have a measureable effect on real world fuel economy" (*27*). Zaniewski et al. conducted a comprehensive study to "determine the operating costs and fuel consumption of motor vehicles as a function of vehicle and roadway characteristics" as well as the effect of pavement condition and type on performance parameters and to develop adjustment factors based on pavement type and condition (*27*). Vehicle operating costs considered included fuel consumption, oil consumption, tire wear, maintenance and repair, and user-related depreciation. The goal of this research study was to determine the quantities of consumption as a function of roadway characteristics (grade, surface type, and roughness); thereby, the costs could be obtained by simply applying unit prices to consumption. Fuel consumption was measured for passenger vehicles, loaded single unit, and loaded semi (tractor trailer) trucks on test sections with a serviceability index ranging between 1.8 and 4.5. Fuel consumption was found to be slightly higher on the unpaved section than the paved sections. However, it was reported that at the 95% significance level, no statistically significant differences in fuel consumption were found on the paved sections. Therefore, it was concluded that for the range of conditions in the U.S., the type or condition of paved roads did not influence fuel consumption. The authors acknowledged that these findings conflict with previous studies by Claffey (*17*) and Zaniewski et al. (*26*), which reported that pavement roughness influences fuel consumption by 30% and 10%, respectively. However, it was pointed out by Zaniewski et al. that the sections used in those previous experiments did not realistically represent operating conditions in the U.S. due to potholes, patches, and badly broken portions of the roadway included in those studies (*27*).

Four different studies from Belgium, France, South Africa, and Sweden (*28-31*) on the topic of fuel consumption or rolling resistance and its relationship to roughness were presented at the International Symposium on Surface Characteristics in 1990. Not all of these studies directly measured fuel consumption, and their methods of measuring roughness were not consistent. However, they agreed with previous findings that a relationship between pavement roughness and fuel consumption exists. Descornet identified that the main influence on rolling resistance was surface profile irregularities in the wavelength range between macrotexture and unevenness (*28*). After converting rolling resistance to fuel consumption, it was reported that 9% fuel savings could be had on smooth pavements over rough pavements based on the range of surface characteristics tested. Laganier and Lucas measured fuel consumption directly and characterized road evenness with the longitudinal profile analyzer to determine the influence of pavement evenness and macrotexture on fuel consumption (*29*). They concluded that for the range of pavements tested, extra fuel consumption of 0 to 0.4 liters per 100 km resulted for surfaces with evenness rating from excellent to poor. Du Plessis et al. reported that for the range of road roughness tested in their study, an increase in fuel consumption of up to 20% can be expected for medium trucks and buses travelling at 80 km/h when driven on very rough, unpaved roads compared to smooth, paved roads (*30*). Sandberg found that fuel consumption was "influenced very much by road unevenness and megatexture, but somewhat by macrotexture," such that the "fuel consumption varies over a range of approximately 11% from the smoothest to the roughest road tested if texture wavelengths in the range of 0.6 to 3.5 m are considered" (*31*). McLean and Foley (*32*) summarized these studies (*28-31*) among others (*19*, *24, 25, 33*) relating roughness to fuel consumption and/or rolling resistance between 1982 and 1990. For those studies that reported only a change in rolling resistance, McLean and Foley applied a factor of five for cars and four for trucks to convert the results to an equivalent change in fuel consumption. The roughness measurements were not consistent among these studies; therefore, McLean and Foley converted the roughness measurements to IRI (*32*). This resulted in IRI values that ranged between 0.5 and 15 m/km, with the maximum IRI (converted from the report by du Plessis et al. (*30*)) equivalent to 951 in/mile, likely due to the earthen and gravel surfaces included in that study and well above what the FHWA considers unacceptable (IRI greater than 170 in/mile) (*22*). However, on the low end, IRI reported by McLean and Foley was on the order of 32 in/mile, falling into FHWA's category of very good. McLean and Foley reported that the percent change in fuel consumption per unit of IRI ranged from 0.5 to 3.6% for a car and 0.5 and 4.1% for a truck (*32*).

2.1.1 Recent U.S. Studies

Barnes and Langworthy chose not to include the effect of pavement roughness on fuel consumption in the development of vehicle operating costs in Minnesota, basing their decision on the notion that the results from previous studies did not reflect conditions in the U.S. (*34, 35*). However, several studies in the U.S. have reported a positive correlation between pavement roughness and fuel consumption. Results from WesTrack revealed a positive correlation between pavement roughness and fuel consumption (*36*). Fuel mileage was recorded for eight weeks prior to and seven weeks after rehabilitation of a section, with a 10% reduction in IRI. A 4.5% improvement was reported in fuel mileage on the smoother, rehabilitated surface over the deteriorated surface. It was reported that prior to the rehabilitation the pavement roughness was such that the "driver would not be able to tolerate the ride for more than a few hours," with IRI values reaching or exceeding 150 in/mile (Epps et al., 1999) (*37*). The rehabilitation reportedly improved the ride with IRI values of approximately 75 in/mile noted in the weeks after rehabilitation (*37*).

A 2004 preliminary report for a Florida study also revealed that a positive correlation existed between pavement smoothness and fuel consumption (*38*). Fuel consumption was measured on five pavement sections, with four of the five sections being asphalt concrete pavement and having IRI values between 45.7 and 54.9 in/mile and the fifth section being a concrete pavement averaging an IRI of 148.4 in/mile.

In a 2006 study, the Missouri Department of Transportation (MoDOT) reported a 2.461% increase in fuel efficiency on new, smoother pavements relative to the rough pavement prior to resurfacing (*39*). As part of Missouri's Smooth Roads Initiative (SRI), a section of I-70 was resurfaced in the summer of 2006. Pavement smoothness was determined by measuring the roughness and vehicle fuel consumption on an existing section of I-70 prior to and after resurfacing using MoDOT's Automated Road Analyzer (ARAN). The average IRI (including eastbound and westbound directions) before resurfacing was 130.25 in/mile and was reduced 53.2% to an average IRI of 60.99 in/mile after-resurfacing. Prior to resurfacing, the four dump trucks averaged 5.97 miles per gallon, whereas after resurfacing, the average was improved to 6.11 miles per gallon. It was also found that the use of the vehicles' brakes decreased 58 times per night on average when driven on the smoother, resurfaced pavement relative to the pavement prior to resurfacing. It has also been shown at the National Center for Asphalt Technology's Pavement Test Track that fuel consumption increases with increased IRI (*40*).

As part of the NCHRP 1-45 project (and documented in the NCHRP Report 720), existing vehicle operating cost models were reviewed in order to select one for calibration to U.S. conditions (*20*). Based on Chatti and Zaabar's review, the HDM-4 model, the widely adopted model for computing total transport costs, was selected. The model was then calibrated to reflect roughness levels of U.S. roadways and improvements in vehicle technology. Prior to calibration, the HDM-4 models were evaluated for U.S. conditions having a range of IRI between 0.8 and 8.5 m/km (51 to 539 in/mile). In evaluating the effect of roughness and texture on fuel consumption, an analysis of covariance was conducted to assess the quality of fit for the HDM-4 fuel consumption model. It was found that roughness was statistically significant. The HDM-4 model was found to under-predict the effect of roughness on fuel consumption; however, the calibrated HDM-4 model resulted in improved predictions. A sensitivity analysis was completed for the HDM-4 and the calibrated HDM-4 model for fuel consumption relative to IRI. The analysis was completed for a speed of 55 mph (88 km/h). Increasing IRI from 1 to 3 m/km (63.4 to 190.2 in/mile) at 30°C (86°F), while holding mean profile depth (MPD) at 1 mm and grade at 0%, resulted in a 0.5% and 1.8% increase in fuel consumption for the original and calibrated HDM-4 models, respectively, for light trucks. Likewise, increasing IRI from 1 to 3 m/km (63.4 to 190.2 in/mile) under the same conditions was found to result in a 0.9% and 2.9% increase in fuel consumption based on the original and calibrated HDM-4 models, respectively, for articulated trucks. Chatti and Zaabar concluded that the most important pavement condition factor relative to fuel consumption was surface roughness in terms of IRI. Chatti and Zaabar reported that an increase of 1 m/km (63.4 in/mile) would result in an approximate 2% increase in fuel consumption (regardless of speed) for passenger vehicles. For heavy trucks, it was found that at normal speeds (60 mph), a 1% increase would result from the same increase in IRI and about a 2% increase for a 1 m/km (63.4 in/mile) increase at a low speed of 35 mph. By decreasing IRI by 1 m/km (63.4 in/mile), Chatti and Zaabar estimated that as much as 24 billion dollars could be saved in fuel costs per year in the U.S. based on a 3% decrease in fuel consumption for the 255 million passenger cars in the U.S. using fuel prices at the time of the report (2012) (*20*).

2.2 Impact of Pavement Roughness on Tire Wear Costs

In the 1987 HDM report, it is suggested that "road improvements can have a disproportionate impact on tire costs relative to the other components" (*19*). Thus, the influence of pavement condition on tire wear cost has been an important part of vehicle operating cost studies. De Weille reported that tire wear on gravel and earth roadways was higher than on paved roads (level and tangent) (*21*). He also reported that tire wear is more significant than engine oil consumption when determining the operating costs of a vehicle, particularly for heavier vehicles.

Zaniewski et al. (*27* (and later summarized by Zaniewski and Butler in 1985 (*41*)) estimated tire wear by updating cost tables previously developed by Winfrey (*16*) and by applying the slip-energy theory developed by the Forest Service to estimate tire wear for the 1982 FHWA-sponsored study on vehicle operating costs (*27*). The slip-energy method was selected for their total VOC tables. However, it was reported that there was a lack of data to support the selection of coefficients for use in this model to analyze the effect of surface type and condition on tire wear. To evaluate roadway effects on tire costs, Zaniewski et al. instead utilized relationships developed in a previous study in Brazil to determine cost adjustment factors for the "proportionate change in tire consumption as roadway surfaces vary from the assumed baseline condition of 3.5 SI" (*27*). Cost adjustment factors increased with decreasing serviceability index (SI) for both passenger vehicles and single unit trucks, indicating that rougher pavements result in a higher tire expense related to tire wear (*27, 41*).

Watanatada et al. (*19*) developed a tire wear prediction model as a function of vehicle and road characteristics. Data used to develop the model was from the Brazil study (*23*), which included a road-user cost survey and was applicable to buses and trucks with cross-ply tires only. Limited data were available for the cars and utility vehicles. As a result, "the tire wear prediction model for cars and utilities was calibrated as a simple linear function of road roughness" (*19*). Watanatada et al. compared results for tire wear prediction models developed in the four primary cost studies conducted between 1970 and 1982 with their mechanistic tire wear prediction model. The tire wear models showed a general increase in tire wear in terms of the number of equivalent new tires per vehicle for every 1,000 km with road roughness. It was reported that the models developed from studies in Kenya and the Caribbean for medium/heavy trucks and buses "predicted more than twice the influence of roughness" (in reference to the rate of increase or slope of the linear relationship). However, these models did not include the impact of road-geometry on tire wear. The remaining models (Brazil and India) for medium/heavy trucks and buses had similar influence of pavement roughness on the prediction of tire wear over the entire range of roughness. Chesher and Harrison reported that the effects of road roughness were larger in the Kenyan and Caribbean models than in the Brazilian and Indian models for truck tire consumption. An increase in roughness from 5.1 to 8.5 m/km (323.34 to 538.9 in/mile) would predict an increase in tire consumption of 11, 10, 31 and 27%, respectively for the Indian, Brazilian (medium truck), Caribbean, and Kenyan models (*18*). For the tire wear prediction model developed in 1987, it was also reported that roughness has a small effect on tire wear for a level road and a much greater effect when the road is steep (*19*).

Barnes and Langworthy (*34*) based their adjustment factors for vehicle operating costs of personal vehicles due to pavement roughness on the study conducted by Zaniewski et al. in 1982 (*27*). Barnes and Langworthy concerned that in the Zaniewski et al. report, "the impacts of roughness on operating costs seem unrealistically large, especially for smoother pavement levels" limited the range of pavement roughness used to develop adjustment factors for vehicle operating costs in their study for the Minnesota Department of Transportation (MnDOT) (*34*). As a result, they developed adjustment factors for passenger vehicles for various levels of pavement roughness defined by PSI and IRI (note, the conversion between IRI and PSI is not stated), as shown in Table 2. The authors "assume that pavement roughness will affect truck costs in the same way as car costs" (*34*). For truck costs, they used an increase of 5% for a PSI of 3.0 (IRI of 105 in/mile), 15% for a PSI of 2.5 (IRI of 140 in/mile), and 25% for a PSI of 2.0 (170 in/mile) and below to account for the effect of pavement roughness on all vehicle operating costs with the exception of fuel consumption costs.

Table 2 Adjustment Factors for Pavement Roughness levels for Passenger vehicles (*after 34*)

PSI	IRI (in/mile)	IRI (m/km or mm/m)	Adjustment multiplier
≤ 2.0	170	2.7	1.25
2.5	140	2.2	1.15
3.0	105	1.7	1.05
≥ 3.5	80	1.2	1.00

Based on a consensus in previous literature that pavement roughness affected maintenance, tire, and repair costs, Barnes and Langworthy considered an effect of pavement roughness on all three cost components, as well as depreciation (*34*). Using a set of assumptions (maintenance cycles, tire-life, fuel costs and fuel economy corresponding vehicle type, repair cycles and and five-year repair costs, and depreciation rates), they estimated baseline per-mile costs (in 2003 cents) for a highway with smooth pavement. They also calculated the cents per mile costs using the same assumptions for the baseline conditions for an "extremely rough" highway pavement (corresponding to a PSI of 2.0 or 170 in/mile, which is consistent with the threshold identified by FHWA, in Table 1). Costs associated to tire wear due to extremely rough pavements resulted in an increase over the baseline costs by 0.2 cents per mile for automobiles, 0.2 cents per mile for pickup/van/SUVs, and 0.9 cents per mile for commercial trucks (*34*).

In applying the calibrated HDM-4 model for U.S. conditions, Chatti and Zaabar concluded that by increasing IRI by 1 m/km (63.4 in/mile), tire wear for passenger cars and heavy trucks would increase by 1% at 88 km/h (55 mph) (*20*). Furthermore, it was found that based on the calibrated VOC models resulting from the NCHRP 1-45 project, for the same IRI value, at a grade of 0%, the tire wear increases with increasing speed and thus, the effect of roughness is greater at higher speeds. Chatti and Zaabar estimated that decreasing IRI by 1 m/km (63.4 in/mile) could result in savings for tire wear costs of 340 million dollars per year based on 255 million passenger cars with an average annual mileage of 15,000 miles, an average tire life of 45,000 miles and an average cost of $100 per tire.

2.3 Impact of Pavement Roughness on Maintenance and Repair Costs

Based on vehicle fatigue response testing, pavement roughness influences the response of vehicle suspension and can result in accelerated fatigue (*42*). In addition, correlations between maintenance and repair costs and pavement roughness have been observed in several studies in the U.S. and abroad. However, the modeling of maintenance parts and labor costs received the least research attention of all the VOC components (*14*).

As was done for tire wear expenses, Zaniewski et al. (*27, 41*) updated maintenance and repair costs based on Winfrey's cost tables (*16*). They then used the updated costs in conjunction with the information from the earlier study in Brazil to develop adjustment factors to account for changes in roadway surface conditions. The factors identified the proportionate changes in expenses as the roadway surface deviated from a baseline serviceability index of 3.5. Adjustment factors for maintenance and repair expenses were determined for passenger cars, single unit trucks, and semi-trucks. As serviceability index decreases, adjustment factors increase, thus resulting in additional expenses for lower serviceability indices (i.e., increased pavement roughness).

The four primary studies on user costs indicated an effect of pavement roughness on maintenance costs (*18)*. As a result of the Kenyan and Caribbean studies, road roughness was modeled as a linear relationship relative to parts consumption, whereas the Brazilian and Indian models revealed an exponential relationship between parts consumption and roughness. While this exponential relationship results in very large increases in parts consumptions for rough roads, there are notable differences between the studies. The differences in the relationships between parts consumption and roughness are in part, attributed to the surface type and the effects of roughness on vehicle deterioration due to various models of vehicles. It should be noted that the data collected in the Caribbean and India were mostly on paved roads, while the data collected in Kenya were from paved and unpaved surfaces and the study conducted in Brazil included paved, gravel and earthen roads.

According to Watanatada et al., an attempt was made to develop a wholly mechanistic model for the vehicle maintenance parts using data from the Brazilian study; however it could not be developed due in part to lack of sufficient data (*19*). Rather, simpler models correlating spare parts and mechanics' labor with road characteristics were developed. 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, consistent with an exponential relationship reported by Chesher and Harrison (*18)*. As a result, the parts consumption cost model used an exponential relationship up to a transitional value of roughness (in QI). Beyond the transitional value, a linear relationship was used to alleviate overprediction of parts consumption costs for high values of roughness. Relative to the maintenance labor hours model, it was reported that only buses had a significant effect in the Brazilian study. However, a coefficient for roughness was included in the exponential relationship with labor hours used in the model, with the caveat that a coefficient with value zero would imply an insignificant effect of roughness. Referring to the maintenance cost component of the total vehicle running costs, the authors note that it “increases sharply with increase in roughness.” The authors observed that for a utility vehicle on a paved road, the increase in predicted maintenance costs is slightly less than three-fold when increasing the roughness from QI 25 (1.92 m/km or 121.92 in/mile, assuming IRI = QI/13) to QI 125 (9.62 m/km or 609.62 in/mile). On very rough surfaces, it was found that the proportion of maintenance costs to total costs increases considerably.

In 1992, Poelman and Weir published a report on vehicle fatigue, specifically the fatigue of vehicle suspension components due to pavement roughness (*42*). In this study, two different instrumented vehicles were driven over 25 sites with PSI ranging from 0 to 2.5. A roughness meter was used to measure surface roughness of the roadway, which resulted in measurements of its longitudinal profile in centimeters per kilometer or inches per mile. Once calibrated to the test location, these values were converted to values of PSI based on the state of Pennsylvania’s conversion equations for asphalt and concrete pavements. The authors compare the resulting PSI values to the same scale as PSR, where a PSI value of 0 is equivalent to a PSR of 0 and refers to a pavement that is impassable. Likewise a PSI value of 2.5 is equivalent to 2.5 on the PSR scale and is categorized as a rating of “fair”. The fatigue response was measured in suspension components of the vehicles as they were driven at traffic speeds ranging between 25 and 50 miles per hour. For pavements with PSI less than 2.5 (categorized as “fair” pavements) and equal to or greater than 1.0, vehicle suspension fatigue was found to occur and greatly accelerate on roadways with a PSI less than 1.0 (categorized as “poor” pavements).

Barnes and Langworthy accounted for the effect of pavement roughness by applying a percent increase in each vehicle operating cost related to trucks, including costs for maintenance and repair based on the level of PSI (IRI) (*34*). The adjustment factors developed in the MnDOT study imply an additional maintenance and repair cost of one cent per mile between the smoothest and roughest pavements (*35*). Barnes and Langworthy estimated baseline costs for each vehicle type based on assumptions as described earlier for tire wear costs. They went on to estimate maintenance and repair costs in cents per mile for an extremely rough highway pavement assuming a PSI of 2.0 (with IRI equivalent reported as 170 in/mile) while holding all other assumptions consistent with baseline estimates. In comparing the maintenance and repair costs to the baseline maintenance and repair costs (smooth highway pavement), an additional 0.8 cents per mile was reported for automobiles, 1.0 cents per mile for pickup/van/SUVs, and 1.8 cents per mile was reported for commercial trucks (*34*).

Chatti and Zaabar reported that for their calibrated HDM-4 model, no effect of roughness was found on repair and maintenance costs up to an IRI of 3 m/km (190.2 in/mile) (*20*). However, they reported an increase in roughness beyond 3 m/km (190.2 in/mile) would result in increased repair and maintenance costs and as shown in Figure 2, the rate of increase varies by IRI level. For example, an increase in IRI from 3 to 4 m/km (190.2 to 253.6 in/mile) would result in a 10% increase in repair and maintenance costs for passenger cars and heavy trucks, while an increase from 4 to 5 m/km would result in a 30 to 40% increase in repair and maintenance costs for passenger cars and heavy trucks, respectively. It was reported that decreasing IRI by 1 m/km (63.4 in/mile) could result in a savings of between 24.5 and 73.5 billion dollars per year in repair and maintenance costs. These estimates were made by applying the 10% and 30% incremental changes in repair and maintenance costs for passenger cars listed above for IRI greater than 3 m/km (190.2 in/mile), using annual repair and maintenance costs totaling $244.8 billion for passenger cars (*20*).

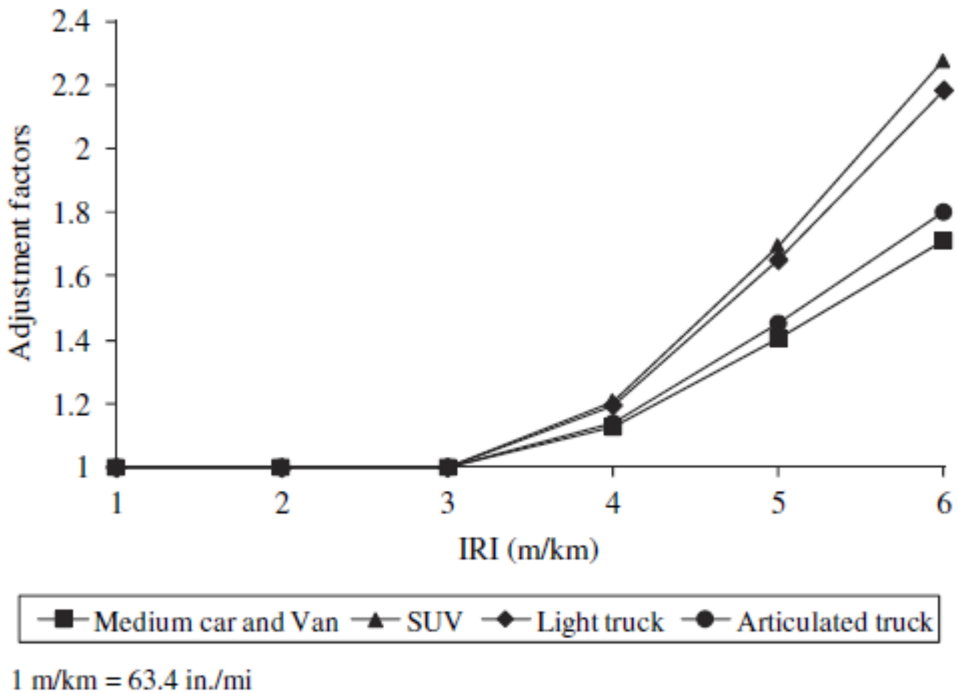

Figure 2 Effect of Roughness on Repair and Maintenance Costs (*20*)

2.4 Impact of Roughness on Oil Consumption Costs

De Weille compared oil consumption by road type, which showed earthen roads resulted in higher oil consumption than paved roads (*21*). However, De Weille reported that this "is by far the least important in the total makeup of vehicle operating costs". Furthermore, Chesher and Harrison stated that lubricant costs are generally small, making up less than 3% of total VOC, and they are difficult to analyze (*18*). Accordingly, this component of vehicle operating costs has not been researched extensively and may explain the limited research in the area of the influence of pavement roughness on oil consumption costs.

Although limited, research has shown that the influence can be high for cars in India. Chesher and Harrison summarized the predicted engine oil consumption based on the four primary user cost studies (India, Brazil, Kenya, and Caribbean) (*18*). Based on their Table 5.6, it is deduced that in Kenya, the predicted oil consumption for a truck increased two-fold from an IRI of 2.8 to 7.4 m/km (177.5 to 469.2 in/mile). The effect was less pronounced in Brazil—the same change in IRI for a truck resulted in a 20% increase in predicted oil consumption.

Previous truck oil consumption estimates developed by Winfrey in 1969 (*16*) were updated to reflect longer intervals between oil changes and differences in oil consumption information from trucking firms (*27, 41*). The relationship determined in the 1982 Brazilian study for oil consumption due to pavement roughness was extrapolated for the updated oil consumption estimates in the U.S. As a result, cost adjustment factors were developed for the normal range of SI in the U.S. (2-4) assuming a baseline SI of 3.5. Decreasing the SI from 4.0 to 2.0 for trucks resulted in a change in adjustment factor from about 0.82 for an SI of 4.0 and about 1.1 for an SI of 2.0, indicating that rougher pavements increase oil consumption costs. The same change in serviceability for passenger cars resulted in a much more severe change in adjustment factors.

2.5 Impact of Pavement Roughness on Depreciation Costs

Limited research has been conducted on the effect of pavement roughness on vehicle depreciation. According to Chesher and Harrison, "little information on depreciation and interest costs" was provided in the four primary cost studies (Brazil, the Caribbean, India, and Kenya) (*18*). The difficulty in relating roughness to depreciation costs was explained, "in order to estimate the effects of varying road characteristics on vehicle depreciation and interest costs, one needs to establish the effects of road characteristics on (i) vehicle life and (ii) vehicle utilization. Unfortunately, neither of these relationships has ever been properly quantified empirically; traditionally they have simply been assumed in benefit-cost studies of road investments" (*19*).

In the HDM-III model, a model for vehicle depreciation and interest costs was developed based on the relationships previously investigated as part of the four primary cost studies (Brazil, the Caribbean, India, and Kenya) (*19*). While annual vehicle depreciation costs were quantified with respect to the age of the vehicle in Kenya, India, and Brazil, the effects of road characteristics on annual vehicle depreciation were not included (*19*). However, the effects of road characteristics on depreciation and interest costs per kilometer were incorporated into the Brazil models through vehicle utilization (*19*).

Zaniewski et al. contributes the difficulty in estimating depreciation costs accurately to the determination of "what, if any, portion of the expense should be assigned to operation on the road" (*27*). In their 1982 FHWA study, the use-related expense was considered by approximating the reciprocal of the maximum vehicle life mileage and data from the earlier study in Brazil to adjust expenses for pavement conditions through cost adjustment factors as a function of serviceability index (*27, 41*). To determine vehicle operating costs in Minnesota, Barnes and Langworthy included depreciation, basing their decision on experience, which suggested "a car that is driven almost exclusively on smooth highways will last more miles than one that is driven mostly on rough pavement" (*34*). They estimated depreciation costs for each vehicle type on an extremely rough pavement (approximately 170 in/mile) assuming the same set of circumstances as was assumed for the baseline estimates (smooth highway pavement). Depreciation costs on the extremely rough roadway were approximately 25% greater for automobiles, pickup/van/SUVs, and commercial trucks compared to baseline estimates for each vehicle type.

3. SUMMARY

It has been shown through various studies dating back several decades that pavement roughness influences vehicle operating costs. This report discussed the effect of pavement roughness on the various components of vehicle operating costs (fuel, tire wear, maintenance and repair, oil consumption, and depreciation).

Extensive work has been completed on the subject of the effects of pavement roughness on fuel consumption. For the majority of the literature reviewed, pavement roughness was reported to have a positive relationship with fuel consumption and its costs, such that an increase in pavement roughness resulted in increased fuel consumption costs. It should be noted, however, that much of the early studies, particularly those conducted in developing countries, were conducted on roadway surfaces with roughness levels that extend well beyond those considered unacceptable in the U.S. Although a 1982 FHWA study reported that such an effect was not statistically significant (*27, 41*) and researchers in Minnesota dismissed any effect of pavement roughness on fuel consumption, citing that testing conditions in previous studies were inconsistent with U.S. conditions (*34, 35*), there have been several studies conducted in the U.S. that have found pavement roughness to influence fuel consumption. Studies conducted at WesTrack (*36*), Florida (*38*), Missouri (*39*), and NCAT (*40*) found 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 transportation costs was calibrated to U.S. conditions, reflecting roughness levels and improvements in vehicle technology (*20*). 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%.

Costs associated with tire wear, maintenance and repair, oil consumption, and depreciation were also found to be influenced by pavement roughness. Although research in the areas of oil consumption and depreciation costs was limited, early studies in developing countries found that an increase in pavement roughness resulted in an increase in oil consumption (*18*). Maintenance and repair costs, as well as tire wear costs, were also found to increase with increases in roughness, albeit the rate varied from study to study. Chatti and Zaabar reported an effect of roughness on repair and maintenance costs for IRI levels greater than 3 m/km (190.2 in/mile) (*20*). While this effect varies by vehicle type and IRI level, they reported an increase in roughness from 3 to 4 m/km (190.2 to 253.6 in/mile) could increase repair and maintenance costs by 10% for passenger cars and heavy trucks. Chatti and Zaabar also reported that a 1 m/km (63.4 in/mile) reduction in IRI could translate to a savings of 340 million dollars per year in tire wear costs for passenger vehicles.

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