Effect of Pavement Roughness on User Costs

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After the construction of a pavement system, deterioration occurs because of traffic loading and weathering action and results in the formation of various types of distresses and an increase in pavement roughness. "Roughness" can be defined as irregularities of pavement surface that affect driver safety and increase user costs, including fuel consumption, repair and maintenance, depreciation, and tire costs. In this study, pavement roughness was predicted with the use of the newly released *Mechanistic–Empirical Pavement Design Guide* for levels of initial roughness condition. Four alternative maintenance and rehabilitation (M&R) strategies were used to estimate the life-cycle cost of pavement over a 35-year analysis period. Various categories of user costs were calculated on the basis of different cost models and from data reported in the literature. From this analysis, pavement roughness was found to affect user costs dramatically. A comparison was made between agency investment and user costs related to pavement roughness. The results of this analysis showed that agency costs were small compared with roughness-related user costs over the life of the pavement (less than 4% of total costs) and that agency investment in increased rehabilitation activities could have a 50-fold return in the form of reduced user costs. A strong case is made for the critical importance of investing in enhanced M&R activities to reduce pavement roughness. This case is strengthened by hypothesized benefits in pavement system sustainability through reduced user fuel costs and reduced tire wear and increased remaining life of pavement.

Not long after the construction of a pavement or a new pavement surface, various forms of deterioration begin to accumulate because of the harsh effects of traffic loading combined with weathering action. This deteriorated pavement condition, which is the sum effect of a number of distinct deterioration modes or distresses, increases not only agency costs but also user costs. There are many indices that represent pavement condition. The international roughness index (IRI) is widely used to quantify pavement smoothness. From the viewpoint of driving comfort, smoothness is considered the most important aspect of pavement condition, and it is especially important for pavements with elevated speed limits. Highway agencies generally have their own specifications of IRI level for different classes of roadways. Roughness increases user costs including fuel, repair and maintenance (R&M), depreciation, and tire costs. User costs across a vehicle fleet resulting from increased roughness are undoubtedly significant but have not been quantified in light of newly available prediction tools.

In this study, pavement roughness is used to estimate user costs associated with the overall pavement surface condition (*1, 2*). According to ASTM E867-06, pavement roughness is defined as "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality." After a detailed investigation, the IRI was chosen as the standard reference roughness index, expressed in units of inches per mile or meters per kilometer. IRI depends on different pavement factors including age, environment, traffic loading, pavement structure and drainage, pavement layer strength, stiffness, and the amount and severity of cracking, potholes, raveling, rutting, and so on. Roughness (IRI) is determined from a mathematical model, which simulates the vehicle's suspension response to roughness at a speed of 50 mph. The model is referred to as a quarter-car simulation; a quarter-car model (one wheel of a passenger vehicle) with two degrees of freedom on a rough pavement is used to estimate IRI. Pavement roughness significantly affects user costs, since roughness has an effect on fuel consumption, R&M costs, vehicle depreciation, tire costs, and other costs.

Although Zaniewski et al. report (from a study based on a survey of truck fleet owners) that the effect of roughness on fuel consumption is not statistically significant at a 95% confidence level (*3*), more recent studies performed by the World Bank with the HDM-4 model, a vehicle operating cost (VOC) model, indicate that pavement roughness does indeed increase fuel consumption. Zaabar and Chatti calibrated the HDM-4 model for U.S. conditions (*4*). Jackson reported that on the basis of a study of five pavement sections in Florida, a 10% reduction in roughness would raise fuel economy by about 1.3% (*5*). NCHRP Project 1-33 concluded that a 1-in./mi increase in IRI would result in a $280 (in 1999 dollars) increase in R&M costs for a passenger car operated on a primary road (*1*), an increase which would amount to approximately $375 in 2011. Drivers prefer to drive on smoother pavements even though it might require taking a longer route, thereby increasing fuel costs.

The objectives of this study are to estimate the different types of user costs incurred from pavement roughness and to compare agency investments for different maintenance and rehabilitation (M&R) strategies and associated roughness-related user costs. A comparison of previous studies with the current study is summarized in Table 1.

The following sections provide background on the various user costs needed to conduct a life-cycle cost analysis (LCCA) that considers user costs and their relation to pavement roughness. FHWA defines LCCA (*6*) as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

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TABLE 1 Factors Considered in Previous Studies Versus Current Study

Category	Previous Studies	Current Study
User costs	Included only a subset of total user cost, i.e., repair and maintenance or depreciation.	Includes a comprehensive array of user costs related to roughness.
	Fuel consumption not considered	Fuel consumption considered by using calibrated HDM-4 model
	Total user costs for single vehicle or fleet considered for different acceptable and unacceptable IRI levels for different classes of highways	Total user cost for single vehicle and 10,000 AADT was considered for Interstate, primary, and secondary roads.
	Incomplete link between user costs and IRI	Functional relationship between IRI level and user costs
Agency costs	Agency costs not considered along with user cost	Agency costs considered and compared with user costs related to roughness
Miscellaneous	Historical or IRI data from transportation agency were used.	MEPDG program is used to predict IRI at different traffic and weather conditions, with different initial IRI levels.

NOTE: AADT = annual average daily traffic; MEPDG = *Mechanistic–Empirical Pavement Design guide*.

PAVEMENT COSTS

Although agency costs for a given pavement facility are significant at the time of initial construction and when major rehabilitation activities are performed, pavement user costs may also be significant when the total fleet using those facilities is considered. Pavement agency costs include initial construction, maintenance, rehabilitation, and engineering administration. Pavement user costs include fuel, oil, tire repair and replacement, vehicle maintenance and repair, depreciation, travel time delay, and driver discomfort or injury.

Agency Costs

Various departments of transportation have their own unique pavement rehabilitation and maintenance strategies. In this study, four alternative strategies were considered. Cost information for different M&R techniques was collected from departments of transportation as retrieved from the literature. Since these data were collected from different sources, the data were inflated by using the relevant consumer price index (CPI) and expressed in 2011 dollars. According to FHWA, "the Consumer Price Index (CPI) measures the changes in the cost of purchasing products and services" (*7*). FHWA also maintains a similar cost index for highway construction activities. The federal-aid highway construction index is computed on the basis of the unit costs of excavation, resurfacing, and construction and reflects cost changes for materials such as reinforcing steel, bituminous concrete, portland cement, and other ingredients for highway projects across the country (*7*). Since the construction index is not available for most recent years, the CPI was used in this study.

Pavement User Costs

Fuel Cost

Fuel is an important component of pavement user costs and has been reported to account for as much as 50% to 75% of total pavement user costs (*8*). Fuel consumption depends on factors that affect fuel consumption including vehicle type, class, and age; vehicle technology; pavement surface type and condition; speed; roadway geometry; environment; and more. According to the American Automobile Association, the composite national average driving cost per mile for 2010, based on a fuel cost of $2.88 per gallon, was 58.5 cents (*9*).

Fuel consumption is directly related to forces acting on the vehicle, including aerodynamics, rolling resistance, gradient, curvature, and inertial forces. Zaniewski reported that fuel consumption of automobiles is not dependent on pavement surface type (*10*). Lu reported that pavement rolling resistance depends on pavement roughness and that an IRI reduction of 129 in./mi will result in a 10% drop in rolling resistance (*11*). A decrease in rolling resistance by 10% increases fuel economy by 1% to 2% according to TRB Special Report 286 (*12*). This increase in fuel economy would save about 1.75 to 3.5 billion gallons of fuel per year of the 175.2 billion gallons consumed by the total highway fleet in 2008 (*13*) if this improvement in rolling resistance could be attained. Thus, maintaining pavement surface smoothness could potentially save billions of dollars annually in the United States.

Many models are available to estimate vehicle fuel consumption, which are often termed VOC models. The models include the Texas Research and Development Foundation model; the World Bank's HDM-4 model; the Saskatchewan, Canada, models; the Australian road fuel consumption model; the New Zealand VOC model; the South African VOC models; and the Swedish mechanistic model for simulations on road traffic. HDM-4, the most recent VOC model, clearly shows that pavement roughness affects fuel consumption. Since the HDM-4 model was developed on the basis of data from developing countries, Zaabar and Chatti calibrated the model to consider U.S. conditions (*4*). They estimated the increase in fuel consumption based on pavement roughness for different types of vehicles, which was converted into equation form for the purposes of this study:

$$\text{percent increase in fuel consumption} = 0.0157 \times \text{IRI} - 0.996 \tag{1}$$

where IRI is pavement roughness expressed in units of inches per mile. Equation 1 was used to estimate the increase in pavement user costs as described later.

The U.S. Environmental Protection Agency (EPA) estimates annual fuel costs for different types of vehicles. For this study, a mid-sized Honda Accord M-6 car was selected arbitrarily. According to EPA, the fuel cost for this car is 15.12 cents/mi considering 15,000 mi driven per year (55% city, 45% highway) and a fuel price of $3.78/gal (*14*).

R&M Costs

R&M includes user costs (parts and labor) required because of vehicular wear and tear. Zaniewski et al. developed the only model found in the literature that was based on U.S. conditions (*3*). The

TABLE 2 MFs for R&M Costs Generated from Report by Zaniewski et al. (3)

PSI	IRI (in./mi)	MF for Passenger Car and Pickup Trucks	Vehicle Class	Average Cost ($/1,000 mi) Zaniewski et al. (3)	2007 Value, Zaabar and Chatti (4)	2011 Cost
4.5	40	0.83	Small car	34.50	64.73	69.77
4.0	63	0.90	Medium car	41.84	64.73	69.77
3.5	84	1.00	Large car	48.33	64.73	69.77
3.0	123	1.15	Pickup	53.12	83.31	89.81
2.5	180	1.37	Light truck	99.59	148.24	159.80
2.0	320	1.71	Medium truck	140.82	190.83	205.71
1.5	610	1.98	Heavy truck	140.82	191.95	206.92

World Bank's recent HDM-4 model is based on data from developing countries (*15*); however, Zaabar and Chatti reported that R&M cost predictions by the HDM-4 model are reasonable for U.S. conditions (*4*). According to HDM-4, the effect of pavement roughness on R&M cost is negligible at low IRI (193 in./mi). However, Zaniewski et al. modified a World Bank study based on data from Brazil to investigate the effect of roughness on R&M costs and proposed adjustment factors based on the present serviceability index (PSI), which provides a numeric rating of current pavement condition (*10*). According to the authors, the multiplying factor (MF) for R&M cost would be 1.00 at a PSI value of 3.5. Later Hall and Correa converted PSI values to IRI (Table 2) by using a transfer equation (*16*).

The following equation was fitted to find a relationship between IRI and R&M cost:

$$\text{MF for R\&M} = 5\times10^{-6}\times \text{IRI}^2 + 0.0049\times \text{IRI} + 0.6239 \quad (2)$$

where $R^2 = .9986$ and IRI is in inches per mile.

Zaniewski et al. proposed R&M costs for different types of vehicles (*3*) and Zaabar and Chatti updated this cost to 2007 dollars (*4*). In this study, cost information was updated to 2011 dollars to estimate additional user costs incurred as a result of pavement roughness.

Depreciation Cost

From a study based on data from developing countries, Chesher et al. reported that the vehicular depreciation rate is dependent on pavement roughness (*17*). Studies performed in developed countries have also shown that roughness affects depreciation costs. Vehicle depreciation cost depends on mileage driven and age of the vehicle. According to Haugodegard et al. (*2*), a major part (70%) of the depreciation cost depends on vehicle age and a minor part (30%) on mileage. They also observed that mileage-related depreciation depends on pavement roughness. Zaniewski et al. studied depreciation cost based on a survey and vehicle registration data (*3*). They proposed adjustment factors based on a PSI of 3.5. Table 3 gives the MFs for depreciation cost.

The following equation was developed with data reported in Table 3 to establish a formulaic relationship between IRI and depreciation cost:

$$\text{MF for depreciation} = -1\times10^{-6}\times \text{IRI}^2 + 0.0007 \times \text{IRI} + 0.9535 \quad (3)$$

where $R^2 = .9983$. Equation 3 was used in this study to estimate the depreciation cost at different levels of IRI.

FHWA reported average vehicle depreciation cost of different types of vehicles (*18*). This study found that mileage-related depreciation costs for a medium-sized or large automobile was 9.8 cents/mi in 1995 dollars. According to Barnes and Langworthy, the baseline depreciation cost of an automobile on the highway and smooth pavement was 6.2 cents/mi in 2003 dollars (*19*). By applying the CPI, this depreciation cost would be 7.53 cents/mi in 2011 dollars, which was used in this study to estimate the additional cost incurred by pavement roughness.

Tire Costs

Zaniewski et al. developed an adjustment factor to estimate tire cost as a function of pavement condition by using a PSI of 3.5 as a reference, where tire cost increases with pavement roughness (*3*). The effect of distance traveled and tire load is greater than that of pavement roughness on tire wear (*1*). Tire wear depends on roughness, and highly abrasive aggregate has an effect on tire wear (*1*). On the basis of a Norwegian study, Haugodegard et al. (*2*) showed a definite increasing trend of tire wear with pavement roughness. Table 4 presents MFs for tire cost.

The following equation was fitted from Table 4 to find a relationship between IRI and tire cost:

$$\text{MF for tire cost} = -9\times10^{-6}\times \text{IRI}^2 + 0.0064\times \text{IRI} + 0.5133 \quad (4)$$

where $R^2 = .9989$. Equation 4 was used in this study to estimate tire cost at different levels of IRI.

TABLE 3 MFs for Depreciation-Cost-Based IRI and by Zaniewski et al. (3)

PSI	IRI (in./mi)	MF for Passenger Car and Pickup Trucks
4.5	40	0.98
4.0	63	0.99
3.5	84	1.00
3.0	123	1.02
2.5	180	1.04
2.0	320	1.06
1.5	610	1.09

TABLE 4 MFs for Tire-Cost-Based IRI and by Zaniewski et al. (3)

PSI	IRI (in./mi)	MF for Passenger Car and Pickup Trucks
4.5	40	0.76
4.0	63	0.86
3.5	84	1.00
3.0	123	1.16
2.5	180	1.37
2.0	320	1.64
1.5	610	1.97

According to Barnes and Langworthy, the baseline tire cost for an automobile operated on a highway with smooth pavement was 0.9 cent/mi in 2003 dollars (*19*). By using the CPI, this tire cost is 1.1 cents/mi in 2011 dollars, which was used later to estimate the additional cost incurred because of pavement roughness.

ROUGHNESS PREDICTION

Pavements begin deteriorating after construction because of traffic loads and environmental factors. Pavement surface roughness increases with the extent and severity of various distresses, which affects ride quality, safety, travel speed, and VOC. Many pavement roughness models were developed by using different distresses for new and overlaid pavements (*20*). In this study, the IRI model that appears in the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) was used to predict pavement roughness (*21*):

$$\mathrm{IRI} = \mathrm{IRI}_0 + 0.0150 * \mathrm{SF} + 0.400 * \mathrm{FC}_{\mathrm{Total}} + 0.0080 * \mathrm{TC} + 40 * \mathrm{RD}$$

where

IRI_0 = initial IRI (in./mi),
SF = site factor,
$\mathrm{FC}_{\mathrm{Total}}$ = area of fatigue cracking (combined alligator, longitudinal, and reflection cracking under wheelpath) (% of total lane area),
TC = length of transverse cracking (ft/mi), and
RD = average rut depth (in.).

The following inputs were used for MEPDG analysis of 12-in. full-depth asphalt pavement along with the program default values:

- Annual average daily traffic (AADT) = 10,000;
- Asphalt binder = PG 64-22;
- Asphalt creep and strength data: University of Illinois, Buttlar group database;
- Initial IRI = 63 in./mi and 70 in./mi;
- Climate: Champaign, Illinois; and
- Design life: 20 years.

Table 5 shows the predicted IRI of a 12-in., full-depth asphalt pavement.

Perera and Kohn reported that for pavement sections with IRI greater than 97 in./mi before an overlay was applied, the IRI after placement of the overlay was reduced to between 52 to 76 in./mi (*22*). They also reported that IRI values would be less than 64 in./mi after the application of an overlay when preoverlay IRI values of less than 97 in./mi were present. Thus, for roughness prediction of pavement following rehabilitation, an IRI level of 63 in./mi was assumed in this study.

TABLE 5 Prediction of IRI with MEPDG Software Program

Year	IRI (when initial IRI = 63 in./mi)	IRI (when initial IRI = 70 in./mi)
1	76.3	83.3
2	80.1	87.1
3	83	90
4	86.6	93.6
5	89.6	96.6
6	93.5	100.5
7	98.5	105.5
8	101.4	108.4
9	104.3	111.3
10	108.3	115.3
11	111.2	118.2
12	114.6	121.6
13	117.8	124.8
14	121.2	128.2
15	124.9	131.9
16	128.3	135.3
17	131.6	138.6
18	135.4	142.4
19	138.8	145.8
20	142.5	149.5

Maintenance includes pavement improvement activities performed when the pavement is in a structurally sound, good condition. Al-Mansour et al. studied the effect of crack sealing, chip seal, and sand seal on roughness in flexible pavements used on Interstates and state highways (*23*). They reported low benefits in roughness reduction due to maintenance activities in the case of new pavements and increased benefit in roughness reduction for maintenance applied to aged pavements. Hall et al. studied the effect of various maintenance activities, including slurry seal, chip seal, crack seal, and thin overlays, on pavement roughness (*24*). On the basis of a statistical analysis, they reported that the effect of chip seals, crack seals, and slurry seals was not significant compared with a control section that did not receive a maintenance treatment. However, thin overlays were found to reduce pavement roughness significantly. In this study, no improvement in IRI was considered for pavements undergoing chip seals, slurry seals, and crack seals, and a roughness reduction resulting in a restored IRI level of 63 in./mi was assumed following the application of an overlay. Although the rate of change in IRI for overlays is higher than new pavement IRI deterioration, the same rate was considered for simplicity of calculation.

ESTIMATION OF COST DUE TO PAVEMENT ROUGHNESS

Different types of pavement user costs were estimated by using the equations and user cost data provided in the preceding sections. Table 6 shows increases in user costs (i.e., fuel consumption, R&M,

TABLE 6 Increase in Total User Cost Due to Pavement Roughness

IRI (in./mi)	Increase in Fuel Cost by Equation 1 ($/mi)	Increase in R&M Cost by Equation 2 ($/mi)	Increase in Depreciation Cost by Equation 3 ($/mi)	Increase in Tire Cost by Equation 4 ($/mi)	Total Increase in User Cost ($/mi)	Total Cost per Year for 10,000 Vehicles ($)	Total Cost per Year per Vehicle ($)
63.00	0.00000	0	0	0	0.00000	—	—
76.3	0.00031	0	0.00008	0	0.00039	46,428	5
80.1	0.00040	0	0.00024	0	0.00063	75,841	8
83	0.00046	0	0.00035	0	0.00082	98,113	10
86.6	0.00055	0.000742	0.00050	0	0.00179	214,581	21
89.6	0.00062	0.001575	0.00061	0.00016	0.00297	356,126	36
93.5	0.00071	0.002648	0.00077	0.00036	0.00449	538,386	54
98.5	0.00083	0.004009	0.00096	0.00061	0.00641	769,284	77
101.4	0.00090	0.00479	0.00106	0.00076	0.00751	901,780	90
104.3	0.00097	0.005565	0.00117	0.00090	0.00861	1,033,230	103
108.3	0.00106	0.006625	0.00132	0.00110	0.01011	1,212,824	121
100[a]	0.00087	0.004413	0.00101	0.00069	0.00698	837,947	84
110[b]	0.00111	0.007072	0.00138	0.00118	0.01074	1,288,548	129
125[c]	0.00146	0.010931	0.00190	0.00188	0.01618	1,941,125	194
175[d]	0.00265	0.022673	0.00340	0.00390	0.03262	3,914,234	391
200[e]	0.00324	0.027896	0.00401	0.00472	0.03987	4,784,164	478
250[f]	0.00443	0.037047	0.00495	0.00600	0.05242	6,290,776	629

NOTE: — = not applicable.
[a]IRI level for adequate smooth pavement of Interstate highways.
[b]IRI level for adequate smooth pavement of primary roads.
[c]IRI level for adequate smooth pavement of secondary roads.
[d]IRI level for inadequate smooth pavement of Interstate highways.
[e]IRI level for inadequate smooth pavement of primary roads.
[f]IRI level for inadequate smooth pavement of secondary roads.

depreciation, and tire cost) at different levels of IRI as predicted by the AASHTO MEPDG software program. Total roughness-related user costs are also shown in Table 6 for a fleet of 10,000 vehicles, assumed to travel an average of 12,000 mi per year. From Table 6, it can be seen that a vehicle owner will incur an additional $129/year for a vehicle driven on a road with an IRI of 110 in./mi, which is considered to be an adequate smoothness level for a primary road. This additional user cost would be higher ($478/year) if the same vehicle were driven on a road with an IRI of 200 in./mi, which is the highest acceptable IRI level for a primary road.

Agency costs for four M&R strategies were estimated. The effects of M&R activities on pavement roughness were estimated from data found through the literature review (*24*). Table 7 shows agency costs for four alternative M&R strategies. To calculate the life-cycle cost of pavement, a 35-year analysis period and a 3% discount rate were considered. A comparison was then made between agency costs and costs related to pavement roughness, as shown in Figure 1.

In Figure 1, roughness cost was calculated by assuming 12,000 mi/year and a 10,000 AADT level. It can be seen that the present worth of the pavement from the LCCA was found to be about $350,000, whereas the cost related to roughness was about $9,910,000 to $15,460,000 depending on the initial roughness of the pavement. These findings suggest that highway agencies only expend about 2.3% to 3.6% of the amount that is spent by users as a result of pavement roughness over the period of the LCCA.

In this study, agency costs and costs incurred because of pavement roughness were considered, not total VOC. Figures 2 and 3 show that vehicle R&M costs increase significantly with IRI, amounting to about 56% to 60% of the total costs considered, depending upon initial IRI.

The current analysis strongly suggests that increased investment in pavement M&R activities aimed at reducing pavement roughness could result in a manyfold savings in user costs. It is acknowledged that the typical values, models, and other assumptions used in this study will vary from region to region and will change with time (with changes in fuel, material, and vehicle maintenance costs; changes in transportation policies; etc.). A spreadsheet-based program is currently being developed to facilitate the LCCA analysis performed here, which will allow this model to be readily applied in various regions across the United States and abroad.

Tables 8 and 9 provide sensitivity analyses comparing agency and user costs for differing average daily traffic (ADT) levels and analysis periods, respectively. It was assumed that agency cost would be 10% less and 10% more for 8,000 ADT and 12,000 ADT, respectively, compared with 10,000 ADT, to account for variation in full-depth asphalt design pavement thickness as a function of design traffic. Although these two variables clearly affect agency and user costs, the overall conclusion of the study (that users bear the bulk of the financial burden when pavements become rough) is unchanged.

A final analysis is now presented to further demonstrate that increased pavement maintenance activities will pay off many times over in reduced user costs. Table 10 shows the M&R strategy used to conduct this analysis. An example of additional investment and user cost reduction follows:

- Present worth of Alternative 1: $367,115;
- Present worth of M&R in Table 10: $475,325;
- Additional investment: $108,209;
- Roughness-related user costs for Alternative 1 with initial IRI of 63 in./mi: $9,910,426;

TABLE 7 Alternative Pavement M&R Strategies for 1-mi Section

Year	Action	Cost ($)	Year	Action	Cost ($)
Alternative 1			Alternative 2		
0	New pavement	206,712	0	New pavement	206,712
3	Crack seal (4 years)	1,500	3	Crack seal (4 years)	1,500
7	Crack seal (4 years)	1,500	7	Mill and patch 20% spot repair	18,050
10	2-in. overlay (10 years)	92,810	15	2-in. mill and 2-in. overlay	94,090
13	Crack seal (4 years)	1,500	18	Crack seal (4 years)	1,500
16	Slurry seal (4 years)	11,265	20	Mill and patch 20% spot repair	18,050
20	2-in. mill and 2-in. overlay	94,090	27	1.5-in. mill and 3-in. overlay	110,860
23	Crack seal (4 years)	1,500	30	Crack seal (4 years)	1,500
26	Chip seal (5 years)	12,530	35	Salvage value	−33,258
30	2-in. mill and 2-in. overlay	94,090			
35	Salvage value	−47,045			
	Present worth =	367,115		Present worth =	332,735
	EUAC =	17,085		EUAC =	15,485
Alternative 3			Alternative 4		
0	New pavement	206,712	0	New pavement	206,712
3	Crack seal (4 years)	1,500	3	Crack seal (4 years)	1,500
5	Chip seal (5 years)	12,530	5	Crack seal (4 years)	1,500
10	1.5-in. overlay (10 years)	77,585	9	Mill and patch 20% spot repair	18,050
14	Crack seal (4 years)	1,500	12	Chip seal (5 years)	12,530
17	Slurry seal (4 years)	11,265	17	2-in. mill and 2-in. overlay	94,090
20	2-in. mill and 2-in. overlay	94,090	20	Crack seal (4 years)	1,500
23	Crack seal (4 years)	1,500	23	Slurry seal (4 years)	11,265
26	Fog seal (2 years)	9,700	27	1.5-in. overlay (10 years)	77,585
30	1.5-in. overlay (10 years)	77,585	30	Crack seal (4 years)	1,500
35	Salvage value	−38,792	35	Salvage value	−15,517
	Present worth =	359,962		Present worth =	325,497
	EUAC =	16,752		EUAC =	15,148

NOTE: EUAC = equivalent uniform annualized cost.

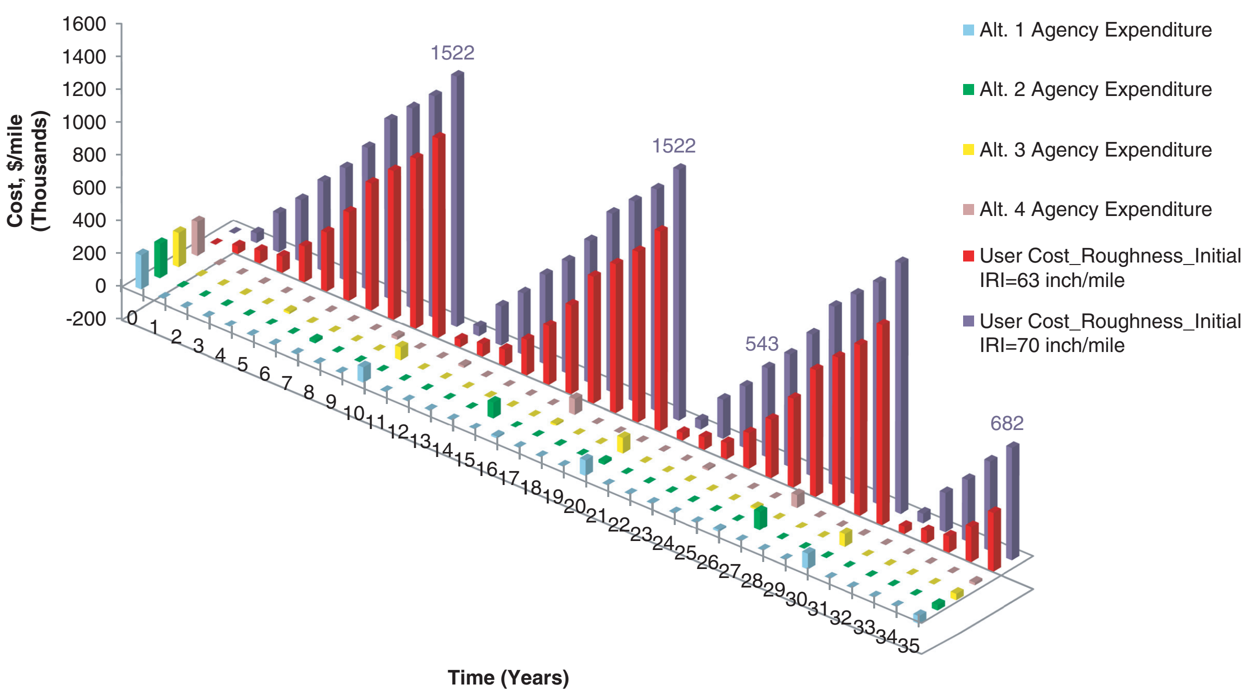

FIGURE 1 Comparison between agency costs and user costs related to pavement roughness (alt. = alternative).

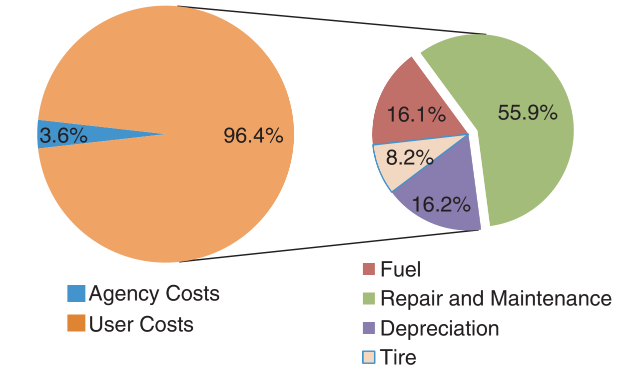

FIGURE 2 Present worth of agency costs and user costs related to roughness over 35-year analysis period of pavement (initial IRI = 63 in./mi).

- Roughness-related user costs for M&R with initial IRI of 63 in./mi (Table 10): $4,740,484;
- Reduction of user costs: $5,169,943;
- Roughness-related user costs for Alternative 1 with initial IRI of 70 in./mi: $15,460,936;
- Roughness-related user costs for Table 10 M&R with initial IRI of 70 in./mi: $9,725,724; and
- Reduction of user costs: $5,735,212.

Table 11 shows increases in user costs.

If the enhanced M&R strategy shown in Table 10 were used, it would require an additional transportation agency expenditure in terms of present worth of $108,209 over the 35-year analysis period. According to Table 10, this would save $5,169,943 to $5,735,212 (52% and 37%, respectively) of user costs over the 35-year life cycle depending on the initial roughness of the pavement. Stated otherwise, increased maintenance activities resulting in smoother pavement condition over the life of the pavement will have about a 50-fold return on investment in terms of reduced user costs. Additional justification for the increased maintenance expenditures can be made from a sustainability standpoint; increased pavement maintenance activities will significantly reduce fuel consumption and tire wear over the life of the pavement and will extend the overall life of the pavement system (the enhanced M&R strategy results in a higher salvage value and therefore a higher remaining life in the pavement section at the end of the 35-year analysis period, thereby delaying reconstruction). It is hoped that the current analysis will provide compelling information that can be used by transportation policy makers to make a strong case for increased M&R activities to help reduce the financial burden carried by users resulting from rough pavement. Although not included because of space limitations, additional diagrams along the lines of Figures 2 and 3 have been generated to demonstrate the dramatic user cost savings that could be realized by employing a more aggressive M&R strategy to maintain pavement smoothness over the life of the pavement. These diagrams will be shared with transportation policy makers through events at the NEXTRANS center (the sponsoring agency for this research) and in related publications.

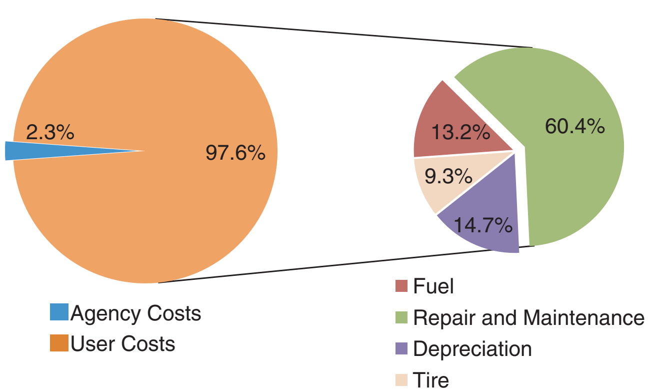

FIGURE 3 Present worth of agency costs and user costs related to roughness over 35-year analysis period of pavement (initial IRI = 70 in./mi).

TABLE 8 Sensitivity Analysis for Traffic Level

Traffic Level (ADT)	Agency Cost ($)	User Cost ($) Initial IRI = 63 in./mi	User Cost ($) Initial IRI = 70 in./mi
8,000	330,400	7,928,341	12,368,748
10,000	367,115	9,910,426	15,460,936
12,000	403,825	11,892,512	18,553,123

CONCLUSIONS

Roughness is an important aspect of pavement condition that significantly affects driver comfort and, moreover, user cost. A comprehensive investigation was conducted to study the effect of pavement roughness on agency and user costs. Some unique features of the research conducted include the following:

1. A comprehensive array of user costs related to roughness was considered;
2. Fuel consumption was computed with a calibrated HDM-4 model;
3. Total user costs for a single vehicle and 10,000 AADT were considered for Interstate, primary, and secondary roads;
4. A functional relationship between IRI level and user costs was developed;
5. Agency costs were simultaneously considered and compared with user costs in the context of pavement roughness; and
6. The newly released MEPDG program was used to predict IRI at different traffic levels and weather conditions and with a different initial IRI level.

TABLE 9 Sensitivity Analysis for Analysis Period

Analysis Period (years)	Agency Cost ($)	User Cost ($) Initial IRI = 63 in./mi	User Cost ($) Initial IRI = 70 in./mi
35	367,115	9,910,426	15,460,936
40	388,723	11,345,212	17,409,807
45	405,547	11,561,089	17,929,249

TABLE 10 Costs of Enhanced M&R Strategy Used to Conduct Analysis of 1-mi Section

Year	Action	Cost ($)
0	New pavement	206,712
3	Crack seal (4 years)	1,500
7	2-in. mill and 2-in. overlay	94,090
10	Crack seal (4 years)	1,500
13	2-in. mill and 2-in. overlay	94,090
16	Slurry seal (4 years)	11,265
20	2-in. mill and 2-in. overlay	94,090
23	Crack seal (4 years)	1,500
26	2-in. mill and 2-in. overlay	94,090
30	2-in. mill and 2-in. overlay	94,090
35	Salvage value	–47,045
	Present worth =	475,325
	EUAC =	22,121

The analysis conducted demonstrated that user costs including fuel consumption, R&M, depreciation, and tire costs dramatically increase with increased pavement roughness, which far outweigh agency costs associated with the construction and maintenance of the facility itself. For the two main examples presented, agency costs based on typical maintenance practices by state departments of transportation were in the range of 2.3% to 3.6% of the combined costs (agency plus user) associated with a unit section of roadway.

Investing in additional maintenance (resurfacing every 7 years instead of every 10 years, on average) would save $5.1 million to $5.7 million (52% and 37%, respectively) in user costs over the 35-year life cycle depending on the initial roughness of the pavement as compared with the additional $108,000 agency investment required for this additional rehabilitation step. This savings equates to a 50-fold return on investment in terms of reduced user costs. Additional justification for the increased maintenance expenditures can be made from a sustainability standpoint; increased pavement maintenance activities will significantly reduce fuel consumption and tire wear over the life of the pavement and will extend the overall life of the pavement system.

Additional analyses are recommended to verify the results obtained here and to expand the findings to include more pavement types, rehabilitation strategies, and so forth. Furthermore, it is recommended that the analysis conducted here be incorporated into a more holistic life-cycle analysis, so that the hypothesized benefits resulting from enhanced M&R activities can be quantified in conjunction with pavement system sustainability. It is surmised that by adding sustainability concepts into the equation, the case for investing in practices that promote smoother pavements will be further justified.

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TABLE 11 User Costs for Enhanced M&R Strategy

	Initial IRI of Pavement = 63 in./mi				Initial IRI of Pavement = 70 in./mi		
Year[a]	IRI (in./mi)	Total Increase in User Cost ($/mi)	Total Cost per Year for 10,000 Vehicles ($)	Total Cost per Year per Vehicle ($)	IRI (in./mi)	Total Increase in User Cost ($/mi)	Total Cost per Year for 10,000 Vehicles ($)
0	63	0	—	—	70	0	—
1	76.3	0.000386899	46,428	5	83.3	0.000481	57,709
2	80.1	0.000632008	75,841	8	87.1	0.001986	238,297
3	83	0.000817608	98,113	10	90	0.003124	374,906
4	86.6	0.001788174	214,581	21	93.6	0.004525	543,034
5	89.6	0.002967715	356,126	36	96.6	0.005683	681,909
6	93.5	0.004486547	538,386	54	100.5	0.007173	860,773
7	76.3	0.000386899	46,428	5	83.3	0.000481	57,709
8	80.1	0.000632008	75,841	8	87.1	0.001986	238,297
9	83	0.000817608	98,113	10	90	0.003124	374,906
10	86.6	0.001788174	214,581	21	93.6	0.004525	543,034
11	89.6	0.002967715	356,126	36	96.6	0.005683	681,909
12	93.5	0.004486547	538,386	54	100.5	0.007173	860,773
34	86.6	0.001788174	214,581	10	90	0.003124	374,906
35	89.6	0.002967715	356,126	21	93.6	0.004525	543,034
		Present worth =	4,740,484			Present worth =	9,725,724

[a] Data for Years 13–33 not included for space reasons.

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