Roughness and Roadway Safety

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Roughness can play a significant role in roadway accidents and should be considered when evaluating pavement safety as well as when planning and designing safety improvements. Roadway roughness can cause problems with steering, braking, maneuvering, and response that can lead to loss of vehicle control and can result in an accident. In addition, rough pavements can sometimes shake or bounce a vehicle so severely that it will lose part or all of the load it is carrying, which then leads to lost-load accidents. This paper discusses the magnitude of the various problems associated with vehicle performance on rough roads and the types of accidents and safety problems that result. The various individual parameters that cause roughness are examined and their overall effect on safety are prioritized. Examples of corrective actions and their benefits are discussed. In the future additional consideration should be given to this problem and to using safety funds to make rehabilitations that decrease roughness and improve the ride quality and safety of a highway.

For many years the driving public has been keenly aware of the effects of pavement roughness. The driver usually can gage the relative comfort and safety of the road. Comfort factors, however, are more easily identified by engineers and the driving public than are safety factors. Most people recognize the potential for hazardous vehicle-driver-pavement reactions on unusually rough roads, but quantification of the problem and all its variables has not been accomplished and it is difficult to pinpoint why this hazardous condition exists.

For example, Why is the smooth road safer than the rough road and to what degree? In some cases, the level of comfort does not have to be at a very low level to cause safety problems. It may never be possible to quantify all variables that affect this relation, but it is important that the highway official be aware of the underlying key factors and relations that exist in order to deal effectively with these problems. In order to do this, the individual variables that affect the safety of a vehicle driving on the surface of a roadway need to be identified. Numerous variables can be considered; however, this paper will deal with those related primarily to the smoothness or roughness of the roadway surface.

KEY FACTORS

The condition of a roadway can range from excellent to very poor, depending on the various distress manifestations of the surface. The roughness of a roadway will vary with time and usually follows a trend of decreasing performance with age. Roughness can be caused by many variables, all of which lead to surface irregularities. These irregularities can be created during the original construction or can occur afterward because of cracking, wear, subsidence, or surface degradation. The increase in roughness with time will vary for each roadway depending on its structural qualities, exposure to traffic, and environment. When a roadway becomes extremely distressed and vehicles can no longer travel at reasonable speeds because of extreme roughness, it becomes obvious that a safety problem will occur. Unfortunately, there is a gray zone where roughness levels may be in a fair-to-poor range but may still present a safety problem to the user.

Ivey and Griffin (1) wrote a report several years ago that analyzed and ordered various roadway attributes by level of significance in relation to accidents. This work was based in part on North Carolina's analysis of 15 968 accidents that occurred in the state in 1974 and also by use of the Delphi technique of using a panel of highway and highway safety engineers to evaluate various characteristics. The list below shows the results of this investigation and lists the importance of various road conditions in relation to safety.

1. Pavement edge-shoulder drop-off,
2. Curbs and raised medians,
3. Hydrodynamic drag (standing water),
4. Poor shoulder maintenance (includes soft shoulders),
5. Washboard surfaces,
6. Corrugations due to weak subgrade,
7. Blow-ups of continuously reinforced concrete pavements,
8. Corrugations due to braking at intersections,
9. Expansive clay and shale waves,
10. Frost heave boils,
11. Grade crossings at railroads,
12. Superelevation--too much or too little,
13. Drainage dips on low volume roads,
14. Intersections that cross drainage channels along intersection roads,
15. Patches or absence of patches,
16. Rutting,
17. Joint faulting,
18. Potholes,
19. Depressions or elevations at drainage structures, and
20. Bridge approach slabs.

Note that the washboard and corrugated surfaces were the first two items in the list that actually dealt with the pavement riding surface. In addition, these two items were numbers 5 and 6 on the list as compared with potholes, which were number 18. Thus, washboard or wavey surfaces may have a potentially greater impact on safety than do potholed or patched surfaces. This may be due in part to the possible localized problems of potholes and their usual rapid repair by maintenance crews, as compared to the washboard surface that may be of a lower maintenance priority. In any case, all of the items listed are of concern and should be considered in any pavement safety evaluation.

The following general groups and their effects are presented in order to help analyze the relations that exist.

Major Distress

Major distress, such as large and numerous potholes or depressions in the pavement, can present a safety problem by physically causing a tire to blow, be totally deformed, or cause large differential forces to be applied to the vehicle that the driver may not be able to correct.

Loss of Tire-Pavement Friction

This problem can be a major contributor to accidents and is not as easily identified as the problems associated with vehicle damage. The problem with loss of friction or pavement traction is twofold. The first part deals with side force, or cornering frictional components that affect steering. The second part deals with braking or stopping power.

Figure 1. Tire slip angle.

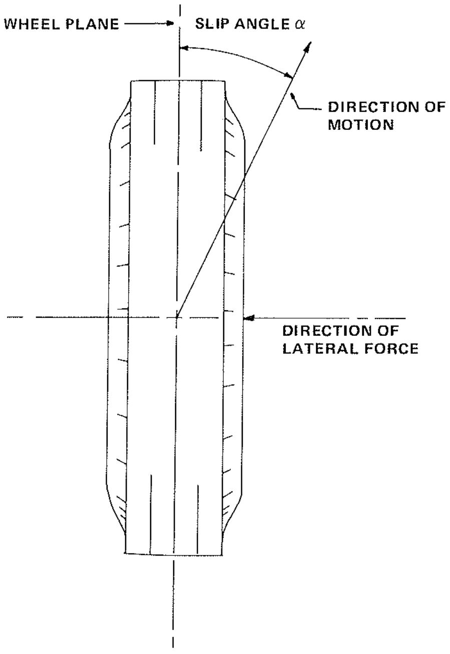
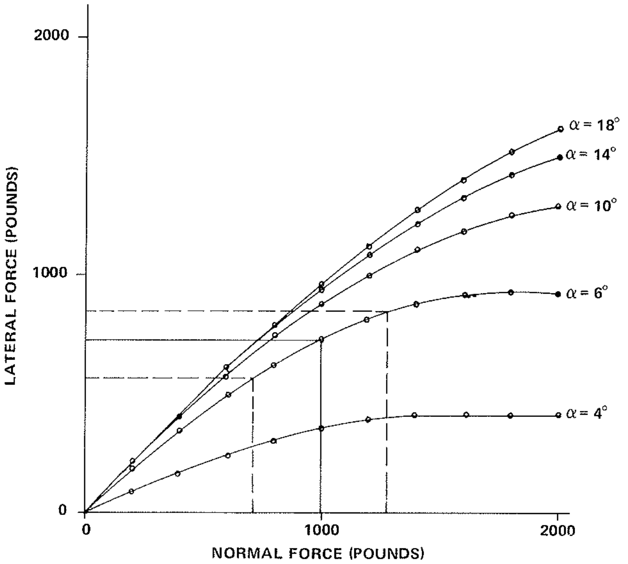


Figure 2. Tire force characteristics.



Effects on Steering

The roughness of a pavement influences the steering capabilities of a vehicle by changing the normal forces that act at the tire-pavement interface and by affecting the lateral forces needed to control a vehicle. Some of the many factors that will affect steering are vehicle characteristics, cornering, stiffness of tires, vehicle loading, and surface friction. The roughness attributes we will discuss are those that deal with the roadway surface alone.

A driver guides the vehicle down the road by a series of understeer and oversteer inputs. This allows the driver to maintain the vehicle in the desired position on the roadway and to make the necessary turns, lane changes, and other maneuvers necessary to traverse the roadway safely. In order to make these steering corrections, lateral forces must be generated between the tire and pavement. These are forces that act parallel to the road and at right angles to the axis of the wheel plane. As a result of this side force, the direction of motion is at an angle to the plane, which is called the slip angle. The magnitude of the force that acts at the tire-road interface is dependent on the normal force exerted by the tire and the slip angle. This is usually not a linear relation, and thus changes in loading can have different effects on the steering input necessary for a particular maneuver. Figure 1 shows a typical tire and the side forces acting on it. Figure 2 shows the typical relation among slip angle, normal force, and lateral forces. This example is for a reasonable level of friction, and the effect of a very slippery pavement would be to greatly reduce the values of the lateral force generated. However, in this paper the effect of actual pavement slipperiness is not shown. Figure 2 shows that the relation is nonlinear. For a normal force of 1000 lb and a slip angle of 6°, the lateral force generated is 760 lb.

If the normal force is increased by 300 lb, however, the lateral force will only be increased by 160 lb. This is extremely important to note in evaluating the safety aspects of roughness because if pavement roughness causes the normal force to fluctuate as the tire rises and falls, the resulting average of the lateral force for an average of say 1000 lb normal force will not be 760 lb, but will be less. On relatively smooth pavements, the variation in normal force is very small; however, on rough pavements, these variations can be very large and reduce significantly the lateral force available to control the vehicle. In situations where high lateral forces are necessary or where a vehicle requires a particular lateral friction level to make a maneuver, this loss of force could lead to loss of control of the vehicle.

A lot of research has been done in this area. Quinn and Hildebrand (2) reported on the various factors that affect lateral force, and Figure 3 is an example of their findings. It shows the side slip and steer angle necessary to make a 90° turn on smooth and rough pavements. It can be seen that this maneuver is possible on the smooth surface without excessive values or loss of control. On the rough surface, however, this is not true, and there is considerable variation and more steering required. For the rough road, the steer angle and side slip angle curves are terminated at a point where there exists no steer angle that will produce the required forces to hold the vehicle on the desired path. For this study, at that point the vehicle was out of control.

This problem is magnified during turning operations because, as the driver compensates for this loss of lateral force, he or she inputs a greater steer angle. Unfortunately, in many circumstances the road is not uniformly rough. As the driver progresses down the highway and hits a smoother section of pavement, he or she will be oversteering and so must correct back again. If this happens too frequently, the driver cannot respond rapidly enough and will lose control of the vehicle.

Effects on Vehicle Braking

In addition to the reduction of lateral force on a cornering tire, roughness can also cause significant loss of braking force or slip resistance on a vehicle. Wambold and others (3) conducted research in this area several years ago to determine the effects of roughness on braking force. They studied a range of five roughness amplitudes from 0.041 to 0.707 in,

Figure 3. 90° turn on rough road at 30 mph.

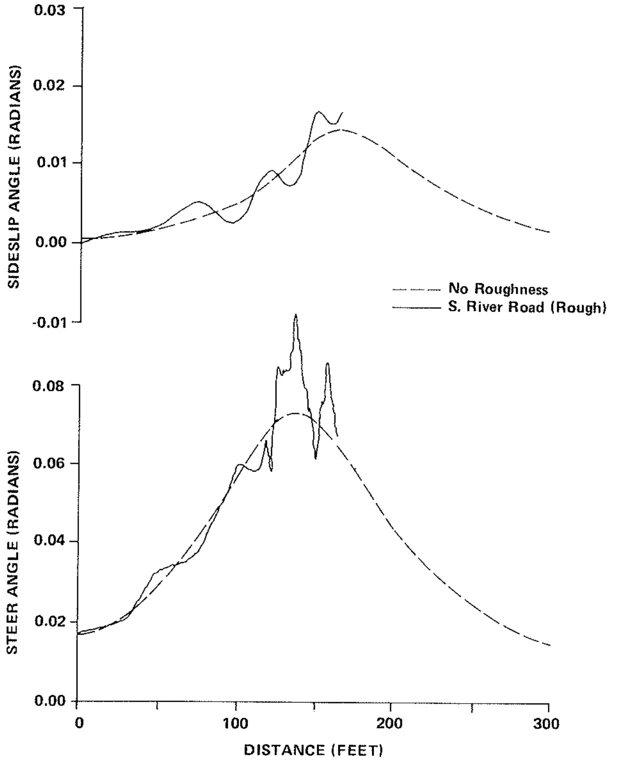
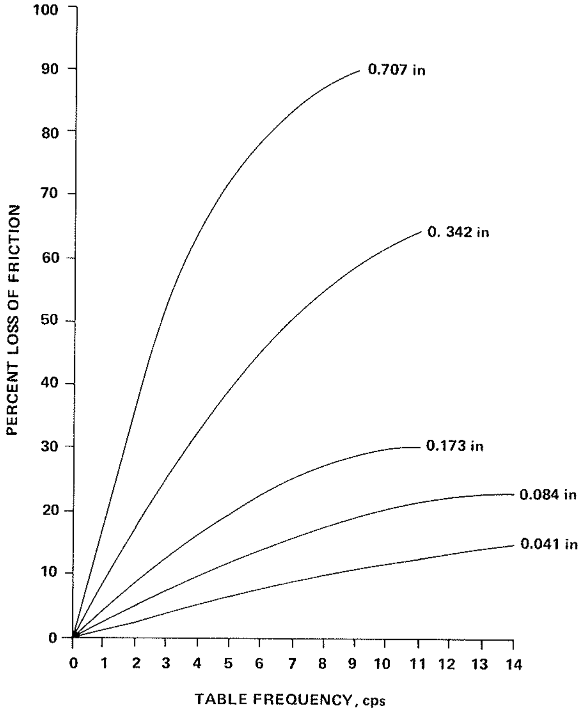


Figure 4. Average loss of friction versus table frequency at nominal load of 400 lb.



a range of roughness frequencies from 0 to 14 Hz, and three speeds that ranged from 0.18 to 0.46 mph. They found that, as roughness and amplitude increased, the coefficient of friction generated between the tire and pavement in a braking mode decreased. At a small amplitude that produced barely observable gross movements of the tire tread, roughness increased to 14 Hz and caused a 30 percent loss of friction value. When they used low frequency values around 3 Hz and increased roughness amplitude to 0.707 in, they found it caused a friction loss of 60-80 percent, depending on the amplitude.

This reduction in friction is caused by a reduction of actual sliding speed of the tread elements caused by tread windup and also by an overall lowering of the adhesion and hysteresis components of friction. Figure 4 shows an example of the results they developed. Although the sliding speeds tested in the laboratory were low, they depict the relation of how tire-pavement friction is related to roughness without the effects of vehicle suspension interfering.

Under highway braking conditions, the normal force on a tire will change on a rough or undulating roadway. If the roughness is great enough, the tire may lose partial or complete contact. In such cases, the sliding friction component can be reduced almost to zero. When the tire makes full contact with the pavement surface, the additional normal forces will be increased to compensate for the loss of contact; however, the frictional forces generated on renewed contact may not make up for the loss of contact time. This inability to obtain as high a level of friction as might be expected with renewed contact can occur because of the frictional limitations of the pavement surface or because of destructive actions that occur at the tire-pavement interface at high-load, high-friction contacts. In such cases, the tire or pavement is physically damaged and causes the dissipation of energies that would have otherwise been used to stop the vehicle.

In addition to these problems with stopping, other problems can arise because roadway roughness can (and usually does) vary in each of the wheeltracks of a lane. When a vehicle brakes, these differences in roughness in each wheel path can cause differences in the braking and sliding forces that act on the vehicle. The final result is that the vehicle is exposed to different levels of friction on each side, which can cause a significant safety problem. The effect of differential friction has been studied (4), and the results show that the situation can have a significant effect on a braking vehicle and can cause a potential hazard to the driving public.

Driver Response

A rough pavement can reduce friction, cause uneven lateral and vertical forces, and do physical damage to a vehicle. In any and all of these, the driver may or may not be able to maintain control of the vehicle and proceed safely. In considering the severity of the problem, one must break the problem into two parts to evaluate a driver's response. These two parameters are magnitude and frequency. Magnitude would represent the size of the bump or pothole, and frequency would represent the number of bumps or potholes per second or distance. When a driver experiences a rough pavement, he or she must correct for any effect it has on the vehicle. The time it takes will be a function of the magnitude and frequency. Variation of roughness in a transverse and longitudinal direction adds to this problem. When a roadway requires steering inputs that reach or exceed driver response time, then either the driver must slow down, the roadway must be improved, or safety will be reduced.

Vehicle Suspension

Vehicle suspension also plays a role in the effects of roughness on safety. Considerable research has been done in this area, and several computer programs have been written to analyze their relation and determine how a vehicle with given suspension will react to various roadway geometrics and vertical and horizontal deviations. Besides conventional considerations, frequency can have a major effect on automobiles and trucks that can cause severe safety problems. When roughness occurs at a repeated amplitude and frequency, it can have two effects. First, if the frequency is in phase with the vehicle, a rough road can seem to be smooth. Second, if the roughness is out of phase with the natural frequency, the roughness can be magnified. This phenomenon causes a problem when repeated upward forces continually reinforce already existing, upward forces of the vehicle. When this occurs, the vehicle starts to move up and down with the roadway in ever-increasing movements until the car or truck tires actually leave the roadway and become airborne. This crow-hopping can cause numerous problems associated with cornering, braking, and loss of material from the bed of the vehicle. Long-bed trucks that are lightly loaded are usually more affected by this problem; however, passenger cars can also find similar problems with roughness.

Roughness Related to Accidents

In general, loss of control, running off the road, and hitting fixed or moving objects are the typical types of accidents associated with rough roads and do not need much further discussion. Another type of accident, however, is less recognized but is significant and can be attributed to rough roadways. This is the lost-load accident that occurs when vehicles are bounced so much in driving over a rough road that they actually lose part of their load, which falls on the roadway. After this occurs, the material lying in the road becomes a serious hazard that can cause massive chain reaction accidents on congested roadways. Besides loads being lost, parts of vehicles can be lost, such as chains, repair equipment, boxes, tires, and other such material. There have also been repeated occurrences of accidents where a tire has been jarred loose and bounced down a roadway until it ran or bounced over a median wall into the path of an oncoming vehicle, resulting in severe damage or loss of life. Roughness can cause problems not only with the vehicle in question but also with other vehicles on the roadway. Therefore, other accident statistics may have to be examined for an accurate safety analysis.

The problem of the lost-load accident has been around for many years; it was probably first recognized by public safety personnel rather than engineers. One department of public safety's district commander wrote in 1971 to the superintendent of the state and suggested ways of improving the urban freeway system in the capital city. He wrote

> ...Our suggestion would, we admit, be quite costly, but in the interest of safety we feel it is necessary. This suggestion is for the planning of the concrete surface of the present urban freeway.....At the present time, as is well known by anyone that uses this system, the surface is so rough it literally shakes vehicles apart. Heavy equipment, such as gravel trucks, when unloaded bounce down the freeway rather than roll....I am told that the City Police Supervisors have instructed their "motors" to stay off the freeway, unless absolutely necessary, because of the hazard of riding at high speed on the rough surface.

Although not an engineer, the commander seemed to identify the appropriate points and made a fair assessment of the problem and its solution. How many other roadways in the United States have similar problems that are familiar to the public safety community but not to the engineering community?

CASE HISTORY

The Arizona Department of Transportation has always been safety conscious. This is especially true for a section of Interstate located within the City of Phoenix that is a six-lane concrete freeway with the greatest traffic levels in the state.

In the 1970s, an increase began to occur in wet-pavement and lost-load accidents due to a polishing of the portland cement concrete pavement (PCCP) and an increase of pavement roughness due to warping of the roadway from expansion of the concrete. An example of the increase in lost-load accidents is shown in Figure 5. This figure shows a disproportionate increase of lost-load accidents with increase in traffic. It was later shown that this increase in lost-load accidents was primarily attributed to increased roughness. Figure 6 further shows that the heaviest periods of lost loads were not at the peak traffic hours but at moderate average daily traffic (ADT) periods when traffic was able to move at greater speeds. In fact, the peak periods for lost loads were at 11 a.m. and 9 p.m. Due to this increase in lost loads, a section of highway in this area was experimentally ground to

Figure 5. Traffic volume and lost-load accidents on I-17, milepost 195.0-210.0.

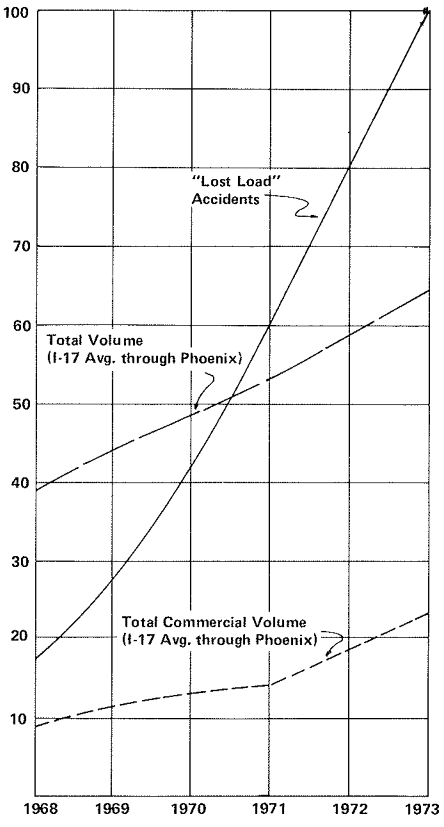


Figure 6. Hourly distribution of accidents.

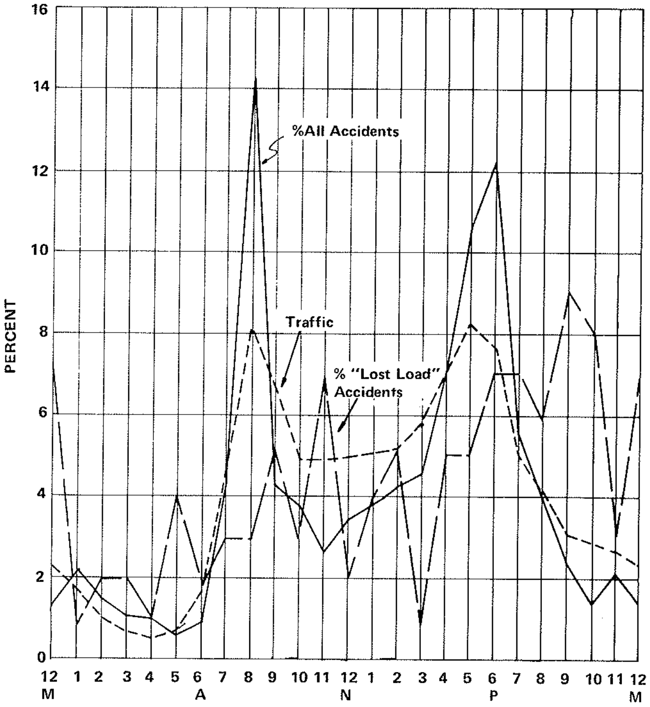


Table 1. Before and after analysis of I-17 pavement grinding.

Item	Control Section[a] No.	Control Section[a] Rate	Grinding Section[b] No.	Grinding Section[b] Rate	Black Canyon Freeway[c] No.	Black Canyon Freeway[c] Rate
Total accidents						
Before	84	1.80[d]	170	3.16[d]	876	1.74[d]
After	278	4.83[d]	296	4.61[d]	1846	3.15[d]
Change (%)	+231.0	+168.3	+74.1	+45.9	+110.7	+81.0
Total injuries						
Before	32	0.69[d]	84	1.56[d]	430	0.85[d]
After	104	1.81[d]	152	2.37[d]	704	1.20[d]
Change (%)	+225.0	+162.3	+81.0	+51.9	+63.7	+41.2
Total fatalities						
Before	1	2.15[e]	0	0[e]	2	3.97[e]
After	0	0[e]	0	0[e]	5	8.54[e]
Change (%)	-100	-100.0	-	-	+150	+115.1
Dry pavement accidents						
Before	76	1.65[d]	151	2.86[d]	811	1.64[d]
After	252	4.50[d]	268	4.29[d]	1698	2.98[d]
Change (%)	+231.6	+172.7	+77.5	+50.0	+109.4	+81.7
Wet pavement accidents						
Before	8	9.41[d]	19	19.39[d]	65	7.08[d]
After	26	17.11[d]	28	16.47[d]	148	9.54[d]
Change (%)	+225.0	+81.8	+47.4	-15.1	+127.7	+34.7
Total travel						
Before	46.85[d]		53.79[d]		504.36[d]	
After	57.50[d]		64.17[d]		585.31[d]	
Change (%)	+22.7		+19.3		+16.0	
Wet pavement travel						
Before		0.85		0.98		9.18
After		1.52		1.70		15.51
Change (%)		+78.8		+73.5		+69.0

[a] I-17, mileposts 195.0-196.0.
[b] I-17, mileposts 200.9-201.9.
[c] Mileposts 198.8-208.23.
[d] Rate or number per million vehicle miles.
[e] Rate per 100 million vehicle miles.

determine the effects of grinding on future reduction in accidents. This was done in hopes of reducing the lost-load-accident rate by smoothing the roadway and by decreasing wet-pavement accidents by improving the skid resistance of the pavement.

The section selected for grinding was on Interstate 17 north-and-south-bound in all three lanes from milepost 200.9 to 201.9. To compare the effects of grinding, an unground control section of comparable roughness, accident history, and ADT was selected on I-17 from milepost 195.0 to 196.0. In addition, the overall accident history for I-17 from milepost 198.8 to 208.23 was also compared.

Table 1 shows total dry and wet pavement accidents for a two-year period before and after the pavement grinding was completed. In all cases there was a significant increase in all types of accidents. All of these increases were of a higher percentage increase than the actual increase in vehicular travel. Especially significant was the increase in wet pavement accidents. By using the methodology developed elsewhere (5), it was found that, during the before period, the pavement was wet only 1.82 percent of the time. During the after period, the pavement was wet 2.65 percent of the time for a 45.6 percent increase in the hours of wet pavement. Wet pavement accidents in both the control section and the entire freeway section were significantly higher, but the ground section only experienced approximately the same increase as the hours of wet pavement. A better analysis can be seen in Table 1, which shows the accident rates based on miles of vehicular traffic.

When wet-pavement accident rates were used as a measure of the ground sections' effectiveness, the ground section showed a 15.1 percent decrease in wet-pavement accident rate, however, the control and the Black Canyon Freeway sections experienced from 34.7 to 81.8 percent increases in wet-pavement accident rates. If the ground section had not been improved, a conservative estimate of 34.7 percent increase in wet-pavement accident rate or 26.12 wet-pavement accidents/100 million vehicle miles of wet-pavement travel would have been expected. This rate translates into a total number of expected wet-pavement accidents of 45, or 60.7 percent more than was reported.

The table below reflects the change in anticipated accidents based on adjacent section accidents:

Accident Type	Actual After	Anticipated After	Significant Difference	Change (%)
Wet	28	47	19	-40
Dry	268	317	49	-15
Total	296	364	68	-19

The number of anticipated after accidents assumes that the same percentage change in accidents would have occurred on the treated section as occurred on the adjacent control section [27 (after) - 11 (before)/11 = 145.5 percent increase on adjacent section]. The reduction in wet and total accidents by calculating anticipated after accidents was 40 percent and 19 percent, respectively. Thus, 68 percent more wet-pavement accidents and 23 percent more total accidents would have potentially occurred if the pavement had not been ground.

The ride quality of this section of highway was poor and the results on ride quality before and after grinding are shown in Table 2. Arizona uses the Mays ride meter and converts inches of roughness into a ride index, which in Arizona is similar to present serviceability index (PSI) but is based solely on roughness and then correlated back to a panel rating. A ride index of 2.5 or less is considered a terminal level for design, and the panel rating indicated that a rating of 2.0 or less could produce an unsafe driving condition. The test results showed that there was a major decrease in roughness and major improvements in ride quality after grinding with diamond saws. The ride index changed from poor to good after grinding on all

Table 2. Grinding section.

			Before 1/19/76		After 9/30/76		After 12/22/76		After 4/12/77		After 12/1/78	
Direction	Lane	Milepost-Milepost	Inches of Roughness/Mile	Ride Index	Inches of Roughness/Mile	Ride Index	Inches of Roughness/Mile	Ride Index	Inches of Roughness/Mile	Ride Index	Inches of Roughness/Mile	Ride Index
Northbound	Center lane	200.00-200.87, unground	310.68	2.14	346.21	1.91			350.40	1.89	304.53	2.18
		200.87-201.91, ground	267.47	2.43	166.21	3.10	116.16	3.53	164.94	3.11	139.48	3.31
	Right lane	200.00-200.87, unground	321.51	2.07	337.04	1.97			336.53	1.98	302.93	2.19
		200.87-201.91, ground	314.49	2.12	144.36	3.27	99.61	3.70	145.43	3.26	144.85	3.27
Southbound	Center lane	200.00-200.87, unground	283.20	2.32	317.29	2.10	228.51	2.68	332.67	2.07	279.50	2.35
		200.87-201.91, ground	276.34	2.37	135.08	3.35	76.86	3.95	126.71	3.43	108.72	3.60
	Right lane	200.00-200.87, unground	293.72	2.25	298.31	2.22			309.58	2.15	282.18	2.33
		200.87-201.91, ground	299.41	2.22	143.27	3.24	101.43	3.68	136.62	3.34	139.93	3.31

Table 3. Before and after analysis of lost-load accidents.

	Traffic			Lost-Load Accidents			Lost-Load Accident Rate		
Location	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Control section A–I-17, milepost 195.0-196.0	46.85	57.50	+22.7	4	72	+1700	0.09	1.25	+1289
Grinding section–I-17, milepost 200.9-201.9	53.79	64.17	+19.3	4	35	+775	0.07	0.55	+686
Black Canyon Freeway	504.36	585.31	+16.0	32	381	+1091	0.06	0.65	+983

sections and the friction level increased from a Mu meter reading of 30 to 78.

Tests two years after grinding showed that the ground section had an average ride index of 3.4 as compared with 2.19 for the unground control section. This is a significant increase and, with proper maintenance, there should be only a gradual decrease in ride quality in the future. Note that the roughness on all sections changed in a cyclic fashion with time. This was because the major cause of roughness on this freeway was due to buckling or warping of the concrete slabs with heating. During the summer periods the pavement was much rougher than during the winter period on any given section. This is an important factor to note in planning any type of grinding or overlaying operation. The reason for this is that the time of year can determine how effective grinding or smoothing may be. If the grinding is conducted during cold periods when the pavement is smooth, it may not eliminate much of the roughness that will occur later when hot temperatures are reached. In addition, it is advisable to beware of excessively harsh grinding to remove high spots that, at a later date, may subside and become low spots. In addition to the planning operation, consideration should be given to such items as improving joints to avoid future buckling or structural problems. Thus, the cause as well as the result, must be addressed.

Table 3 compares lost-load accidents that have been reported on the previously described three sections of Interstate freeway. All sections reported significantly higher numbers and rates of lost-load accidents from the before to the after periods. This significantly higher amount of lost-load accidents is explained partly by the increase in traffic, the increase in reportability of lost-load accidents due to the increased cost to the motorist of these accidents, and the need to substantiate those losses to insurance companies.

Although the data are limited, the control section reported lower numbers of lost-load accidents and lower rates of lost-load accidents per million vehicle miles of travel--51 percent lower than the adjacent comparative section of I-17.

Based on a comparison of the 1-mile grinding section of I-17 on Phoenix Black Canyon Freeway with other sections of the Black Canyon Freeway, Arizona conservatively estimated that grinding of the concrete pavement had the following net effects:

1. Reduction in wet-pavement accident rate by 60.7 percent,
2. Reduction in the rate of lost-load accidents per million miles of vehicular travel by 51 percent, and
3. Reduction in total wet-pavement accidents expected by 40 percent (i.e., 68 percent more accidents would have occurred if the pavement had not been ground).

The information developed in this study was used in developing a project to grind for safety a 6.3-mile section of the northbound, PCCP lanes on the same highway in 1979. Better beneficial results were found with this project than were anticipated from the test section studies. In the test section, the ride index improved from 2.12 to 3.15 after grinding; however, on the large 6.3-mile project section, it was found that the ride index was improved on a reported average from 2.14 to 3.55. It is interesting to note that on the 6.3-mile section, additional federal safety funds were made available for the grinding operation. This was reportedly the first time such an operation had ever been eligible for safety funding. This is because of the Federal Highway Administration's open attitude to implementing better techniques and systems and improving safety practices via experience gained from observing the performance on new methods, and also due to Arizona's efforts to document the effects and benefits of this technique. Due to Arizona's study, it was shown that grinding of the 6-mile section of silicious, polish-resistant PCCP would produce greater friction and a smoother ride, and thus a safer surface. It is hoped that similar programs that smooth pavements or increase their frictional properties will also be eligible for safety funding.

PLANNING SAFETY IMPROVEMENTS

As we have seen, roughness plays a role in the safety of a highway and should be considered when planning safety improvements and rehabilitation strategies. In order to make the most use of this information, the level and cause of roughness and deterioration must be identified correctly. In addition, the benefit to be derived from rehabilitating the roadway must be evaluated. Evaluation of the benefit means determination of how smooth the new roadway will be after the corrective action, the number of years the roadway will maintain its new acceptable ride, the cost of the improvement, and the additional safety areas that will be improved in addition to smoothing the roadway. For the last item, certain operations can also increase friction, improve geometrics, and improve drainage. With regard to life expectancy, engineers can better predict this variable if a thorough pavement evaluation is made beforehand to identify the true cause of roughness. The first factor of knowing the present condition can be done by use of various pavement evaluation techniques or ride analysis. There exists today several devices that can accurately monitor and profile the pavement by using accelerometers and peripheral computer equipment. These devices can give an almost-true profile of the pavement surface. Recently, additional computer programs have been developed not only to analyze the profile of pavements but also to determine the amount of material needed to be added or removed to give the desired new profile. The programs are so sophisticated they can also determine quantities and costs if given the type of equipment and screed or sensor lengths. This information is now available on a project-by-project basis; however, these types of devices and analyses are usually costly and are not often used on a system approach or for preliminary engineering where oftentimes the actual priority decisions are made. In an effort to allow such information to be used in priority programming, the Arizona Department of Transportation recently developed (6) an equation that is used in their pavement management system to predict what the new ride quality will be after a pavement is overlaid with a given thickness of asphaltic concrete. The equation in use is as follows:

$$R_N = 65.29 - 0.78(R_B) - 7.76(TH) \qquad R^2 = 0.938 \tag{1}$$

where

R_N = change in roughness one year following an overlay by using Mays ride meter (in/mile),
TH = thickness of overlay (in), and
R_B = roughness before overlay (in/mile).

Note, if calculated R_N is less than 50, roughness is equal to 50. In Arizona's work, it also related the Mays ride meter number in inches per mile to slope variance (SV) by the equation

$$SV = 3.819 \times 10^3(\text{MAYS})^{1.56} \qquad R^2 = 0.97 \tag{2}$$

Thus, if a pavement had a Mays ride meter reading of 384 in/mile (ride index of 1.68, poor ride) and a 1-in overlay was applied, then the calculation would be as follows:

$$R_N = 65.29 - 0.78(384) - 7.76(1) \text{ or } R_N = -242.$$

The Mays ride meter reading would then decrease 242 in from the original 384 in; thus, one year after, the Mays ride meter reading would be 142 in/mile (ride index of 3.3, good ride).

This work was based on overlay data that ranged from 0.75 in and up on a great number of overlays throughout Arizona. This equation is currently used in the Arizona Department of Transportation's pavement management system, which also predicts change in roughness with time for any section of its entire highway system. By using such a program, effective priorities can be established. Other states, such as California, are now adding such decision-making information to their pavement evaluation and management systems.

CONCLUSION

The information in this paper has shown that roughness affects safety in many ways and needs to be considered in any evaluation of pavement safety. Roughness can reduce the steering and braking forces and significantly affect the controllability of a vehicle. Washboard surfaces and repeated cyclic undulations of the surface can cause significant control problems and can shake a vehicle and cause it to lose part of the load it is carrying. Thus, in addition to creating problems for the driver, it may affect the safety of others in surrounding lanes.

In establishing the priority of corrective actions, the effects of road roughness on safety must be considered. Besides evaluating present conditions, the future condition and performance of the pavement need to be analyzed. In evaluating benefits of certain measures, the value of other improvements derived from certain leveling operations needs to be addressed.

Further consideration should be given to allow federal safety funds to be made available for improving road roughness, as this problem has a significant impact on highway safety.

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