Current Smoothness Assessment Methods and Vehicle Response

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ABSTRACT

"Current Smoothness Assessment Methods and Vehicle Response"

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The primary purpose for constructing and maintaining smooth pavements is to minimize vehicle dynamic response. Pavement roughness is more than just a ride quality issue. Excessive loads induced into a vehicle will reduce its useful life. Rough pavements increase vehicle operational costs due to added maintenance. Rough pavements can reduce a vehicles braking ability and severe roughness can be a safety issue, particularly during emergency stopping.

Pavement roughness also affects pavement life. Dynamic loads resulting from moderately rough pavement can be 150% of static load or more. The dynamic loads can overstress pavement-causing damage that reduces service life. A primary concern with the current and projected growth in the industry is that unscheduled maintenance will have a severe impact on infrastructure capacity.

For the purpose of this paper, pavement roughness is not texture. Surface roughness is unevenness or undulations in the surface that results in increased dynamic loading induced into the vehicles using it. This paper discusses two basic types of vehicle response caused by pavement roughness.

"Shock" loading can result from short wavelength roughness (spalls, step bumps, shoving, potholes, etc. It causes a "shock" to be transmitted through the suspension system. This type of roughness can be measured by using the IRI (a single degree of freedom model) smoothness assessment method.

"Whole vehicle" loading is response resulting from longer wavelength roughness as well as profile differences between the left and right wheel tracks. This type of loading influences the vehicles rigid body modes of vibration (pitch, plunge and roll). Rigid body response is "coupled". The rigid body modes can also couple with the vehicle's first few flexible modes of vibration (particularly on large truck/trailer combinations). For example, a truck pulling a boat trailer will have a completely different response than the same truck without the trailer. IRI, or any single degree of freedom model cannot predict vehicle response to this type of roughness.

This paper discusses the various methods used to assess existing pavements for roughness and states the need for additional pavement roughness assessment techniques.

MEASURING PAVEMENT PROFILE

Elevation Profile Measurements

A fundamental component of most smoothness assessment methods is a profile of the roadway being assessed. For the purpose of this paper, there are two types of profile data, “relative profile data” and “topographical profile data”. Automated devices are available for collecting topographical and relative elevation profile data.

Relative Profile Measuring Devices

Many types of high-speed devices are capable of measuring relative profile are available and have been used for years on highways. The primary advantage of these devices is speed. They can measure relative profile data on very frequent intervals at typical highway speeds. NCHRP Report 434 recommends a maximum sample interval of 6 inches for IRI calculations and 1-inch for Ride Number (RN). The primary disadvantage is that these devices cannot measure all grade changes and wavelengths. Another disadvantage is that lead and lag pavement is required for vehicle acceleration and deceleration which makes it difficult to measure from one specified point to another if there is no room for acceleration or deceleration. However, laser/inertial profilometer devices have shown great success in identifying and quantifying road roughness.

Another method of relative profiling is the California Profilograph (CP) type device. These and other straight edge methods are frequently used to assess newly constructed pavements for smoothness. In fact, pavement smoothness specification requirements are often defined as allowable “inches per mile” using a CP type device. Figure 1 at the end of this document is a picture of a typical California Profilograph.

Topographical Profile Measuring Devices

The advantage of the topographical devices is that they can capture all grades and wavelengths that affect vehicle dynamic response and can be used for any of the assessment methods described in section below. The primary disadvantage of these devices is speed. This device can require 30 minutes or more to conduct a mile of survey depending on the device or method used. Figure 2 is a picture of APR Consultants’ Auto Rod and Level, an automated topographical profile measuring device.

One additional advantage of topographical profile data is that it can also be used to track the changes in the true profile year after year. Areas of excessive settlement for example, can be easily detected by simple overlaying the periodic profiles. This process can become a structural integrity tool used in pavement management.

ASTM (E-17) has established standards to classify many types of profile measuring devices. A recent example of a standard that is being balloted by the E-17 committee members is for Inclinometer type devices. These are considered to be topographical types of devices in that they can be used to produce profile containing all grade changes and wavelengths. The draft standard calls for an elevation accuracy of .001 inch. There is no mention of accuracy requirements with regard to longitudinal distance traversed or lateral tracking accuracy requirements. The primary purpose of measuring the profile is to describe the surface that the vehicles that use these surfaces will encounter. To do this would require a certain accuracy in the x, y and z directions. Is there any benefit in measuring to an elevation accuracy of .001" if the transverse or longitudinal location is not as precise? With this in mind, do we really need an elevation accuracy of .001": particularly if the exact lateral and transverse locations are not known? It is the opinion of the authors that the ASTM Class I elevation accuracy requirements are unnecessarily restrictive and are not required to define the surface that is encountered by the vehicles that use that surface. In addition, the transverse and longitudinal accuracy requirements should be defined. This raises the question; should not the focus of the ASTM standard be on how well the profile measurement instrument lends itself to identifying roughness that affects the dynamic response of the vehicles that use that surface? Should we not redefine what is really required for accuracy in the x, y and z directions? Should we not measure what the vehicles are exposed to? The true measure of merit for a profile-measuring device should be assessed by how well it's data can predict the response of the vehicle(s) that travels that surface.

SMOOTHNESS ASSESSMENT METHODS

The purpose of assessing a pavement for smoothness (or roughness) is ultimately to determine how the vehicles that use these surfaces responds to it. To achieve this, the industry has over the years developed and uses tools that help construct, assess and maintain pavements that minimize vehicle dynamic response.

Straightedges of varying lengths have been used as long as pavements have been in existence. Using a straightedge is a simple way to evaluate the smoothness of any pavement. It is limited in its capability and is slow to use. Although it could be a useful tool in evaluating a pavement, there was still plenty of room for improvement.

California Profilograph (CP) advanced the capabilities of the standard straightedge and became the industry standard for pavement acceptance. The CP was more accurate than a standard straightedge and brought in many additional capabilities such as pavement marking and real time calculations. The CP is limited in that it does not actually see a pavement the same way a vehicle sees the pavement. The CP does not always directly correlate with the ride quality of a pavement.

IRI was the next step in pavement evaluation. It focused on looking at pavement from a vehicle's point of view by simulating a quarter car. It is much more accurate than previous assessment methods, simple to calculate, and can be computed real time. "The Little Book of Profiling" by Michael Sayers and Steven Karamihus states that "IRI and ride number have been statistically proven to correlate pavement roughness and to the ride quality of pavement. Figure 3 is an illustration of the quarter car model.

Historically, it has been an effective tool and it replaced many outdated methods. IRI cannot, however, by its nature, relate how the motion in one axle of a vehicle will affect the motion in another axle. This is true for vehicle roll as well as pitch. IRI is limited in that it cannot see a pavement the same way a vehicle would.

The next logical step would be to simulate the entire car, rather than simulating a quarter car. Or, even further, simulate a large tractor-trailer truck pulling a 54-foot trailer. Whole vehicle simulation is a mature science. The technology gap between current pavement smoothness assessment standards and the ultimate goal of predicting the response of the vehicles that use them can be bridged with existing technology. If the goal of the industry is to continually improve the ride quality and useful life of pavements, more focus should be placed on examining the pavement from a vehicle response point of view. Whole vehicle simulations could be used as acceptance tools along with IRI and straightedge criteria, in much the same fashion.

It is not suggested here that current methods like IRI, CP and others be replaced, but that an additional tool be added to the arsenal of assessing methods. Each has their strengths and weaknesses. A truck towing a boat and trailer will have a completely different response to pavement roughness than the truck alone. The truck/trailer combination has a tendency to amplify the motion of multiple bumps often setting up a resonant motion. The technology already exists to predict this type of response. None of the forms of analysis that are currently in use account for how different types of vehicles respond to varying types of roughness.

If this technology is viable and applicable to the entire paving industry, it must be determined how to use it to identify unwanted roughness. In other words, how rough is too rough? Since vehicle accelerations are measured in G forces, it must be determined how many g's are tolerable. A good starting point for this determination is a study published in the first and second edition of the Shock and Vibration Handbook, Chapter 44, "*Effects of Shock and Vibration on Man*" by D. E. Goldman and H. E. Von Gierke. This reference is an extensive study that has defined the "threshold of discomfort" based on experimental tests conducted on humans in a controlled testing environment. The study determined the .4 g is the basic threshold for human discomfort.

When aircraft are simulated traversing runway pavements, this .4 g threshold has proven to be reliable. Hundreds of runways have been analyzed with known rough areas. Generally, when the accelerations at the pilot's station are over .4 or .5 g for any length of time, it has been in an area that causes pilot and crew complaints. When the accelerations at the aircraft's center of gravity are over .4 of .5 g for any length of time, it has been in an area that causes aircraft fatigue damage.

The addition of whole vehicle simulation (a multiple degree of freedom model) would account for coupled type of pavement roughness and fill the current technology gap. The technology has been evolving for over 30 years and is mature enough to be used in the "real world" of pavement roughness assessment. With aircraft, the simulation models have been validated with extensive field-testing. The aircraft simulation models in use today have proven to be accurate and reliable. Validation of the car and truck model would be accomplished by comparing measured vehicle response data to predicted values. The limits of acceptability should eventually be specified in an ASTM standard. One method could be to build and maintain a qualifying test track and instrumented test vehicle(s) combination to qualify a simulation model(s)

Once validated and accepted by the highway paving industry, vehicle simulation could be used to assess the ride quality of road surfaces in "g" forces. This is a true measure of what the traveling public feels regardless if the motion is the result of a symmetrical profile or not. The "g" values predicted can be compared to the published "threshold of discomfort" values published in the Shock and Vibration Handbook, mentioned above.

Other indices such as IRI, PI, and Straight Edge Analysis will be computed as well. Each method can be correlated with the user perception data identified in the existing LTPP studies. The best method(s) to locate, measure and quantify the objectionable characteristics for each type of roughness should be utilized accordingly.

Acceptance of a new pavement or assessment of an existing pavement could be based on a number of different indices designed to insure that all forms of roughness that the traveling public finds objectionable would be identified.

Multiple Degree of Freedom simulation models, what is required?

The simulation model(s) should be capable of accurately predicting the response of the vehicles traversing that surface. Consequently, the models should include all parameters needed to accomplish this. Most likely the model(s) should include pitch and roll degrees of freedom as well as vertical translation and variable speed with accelerating and decelerating capabilities. It may be necessary to include certain non-linear suspension characteristics. It will most likely include a degree(s) of freedom to represent a vehicle (like a boat trailer) being towed. It is also important to be able to predict vehicle response in special operations like emergency braking because roughness can have a dramatic effect on the distance required to get the vehicle stopped. This is an important roughness issue because it can be a safety concern, not just ride quality. Even though the multiple degree of freedom is more complex, it is important to keep the results in an "easy to understand" and "apply" format. The results or indices adopted by the paving industry must be in a format acceptable by all disciplines of the paving industry.

Profile data, what is required?

The profile data, when used in the simulation model, should be capable of predicting the response of the vehicle(s) using it. Consequently, the profile data requirements should include sufficient accuracy in the x, y and z directions to accomplish this. This will most likely require multiple profiles to account for roll motion. It may require topographical data that includes grade and long wavelengths or relative profile data may be sufficient depending on the motion that the profile induces into the vehicle. There is no advantage in making unnecessarily stringent accuracy requirements if they are not required to predict the response of the vehicle. The overall objective is to predict the response of the vehicle.

CONCLUSIONS

Over the years, many pavement smoothness assessment methods have been developed. Some of them have been effective and useful tools in extending pavement's useful life and improving ride quality. It is time to move forward, though, into the next advancement. Simulating an entire vehicle or a vehicle pulling a trailer will allow for a more complete analysis of a pavement.

By calculating vertical accelerations in a vehicles center of gravity or at the driver's seat, the evaluator will be able to get an overall picture of where pavement roughness most impacts dynamic vehicle response. Not only that, the evaluator will also be able to pinpoint where repairs to the pavement will be most effective in reducing dynamic vehicle response.

References

1. Harris, C. M. and Allan Piersol. The Shock and Vibration Handbook 2nd Edition. McGraw-Hill Companies, Inc., New York, 1977

2. Sayers, M., and Steven Karamihus. “The Little Book of Profiling.” The University Transportation Research Institute, Ann Arbor, 1998

List of Figures

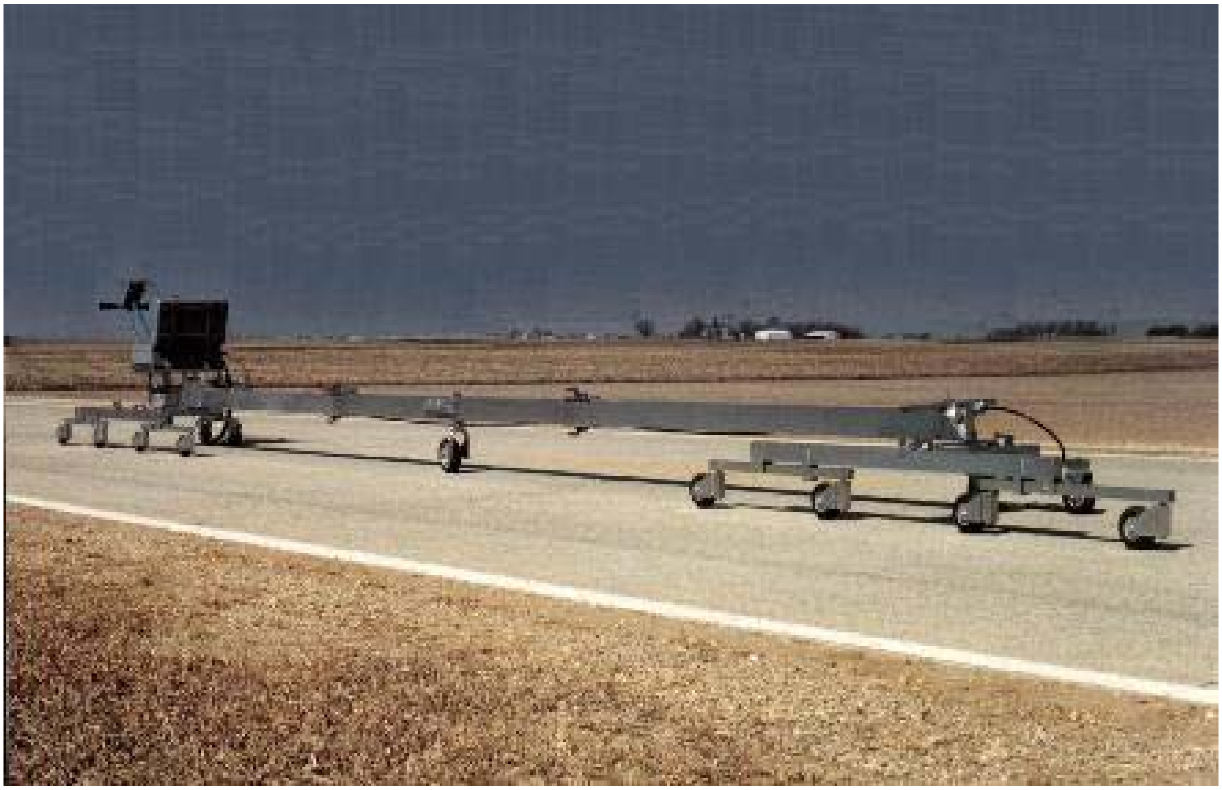

Figure 1. Picture of a Profilograph-Type device.

Figure 2. Picture of APR Consultants' Auto Rod and level.

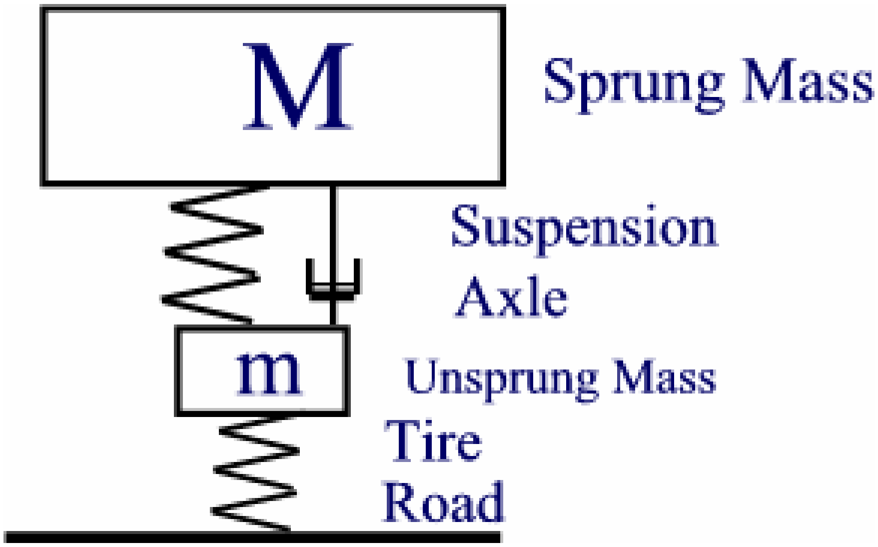

Figure 3. Illustration of Quarter Car Model, IRI.