Research Record
Issue Number 79 Materials and Technology June 1996

Evaluating Pavement Surfaces: LISA and RQI

MDOT's Lightweight Inertial Surface Analyzer (LISA) & the Michigan Ride Quality Index (RQI)

Ancient history tells us that Roman engineers developed methods and tools to produce smooth roadways throughout their empire. Clearly, the Romans understood the economic relationship between a road surface and vehicle damage, cargo damage, and passenger discomfort.

Motorist comfort and vehicle life isn't the only reason why roads should be smooth. The fact is, smooth roads last longer. The dynamic weight of a truck bouncing along a rough road can be as much as twice its static weight. That increased impact results in a breakdown of the road surface, which makes the road rougher, which makes the impact worse, and so on. Vehicle impact combined with Michigan's freeze thaw effect create a spiral of deterioration at the expense of the taxpayer.

As the quest for smooth pavement continues, MDOT staff at the Research Laboratory Section in the Materials and Technology Division have focused on laser guided tools and modern scientific theory. Using a true road profile gathered by the Lightweight Inertial Surface Analyzer (LISA) and derivation of the Michigan Ride Quality Index (RQI), MDOT can evaluate new pavement construction and also do life-cycle evaluations to determine the best mix designs and paving techniques.

Road Profiles of the Past

Contemporary techniques for measuring the roughness of pavement date back to the early 1940's. The original measure in Michigan was the rod and level. Although very accurate and considered the "golden" method, readings taken every 75 mm is a very time consuming process. Next came the 3 meter rolling straight edge, but inaccuracies caused it to fall out of favor in a short time. Then MDOT's Bureau of Public Roads (BPR) developed the Roughometer, a crude inertial type machine, to gather data on new pavement surfaces.

The Roughometer concept involved a heavy beam hitched to a towing vehicle. In the center of the beam a single, auto-sized wheel was suspended on a spring. A one-way integrating clutch accumulated vertical motion between the axle and the frame. An accelerometer measured the vertical acceleration of the frame (see figure 1).

Although the concept was sound, practical considerations required a beam that was not heavy enough to provide an adequate inertial reference. In addition, the science of mechanical systems was not advanced enough in those days to provide the correct damping shocks (to prevent bounce of the beam) or to calibrate the unit correctly.

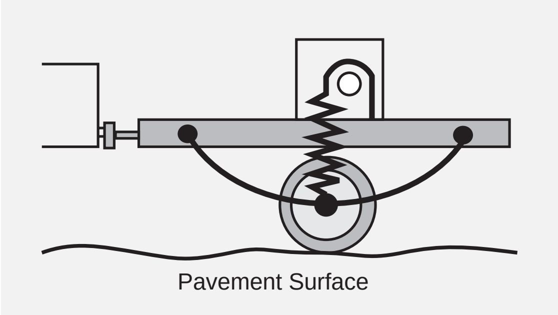

Figure 1: BPR Roughometer

Because there were no quality control programs in place at the time, the accumulated Roughometer data was for informational purposes only. The result of the effort was both beneficial and puzzling; demonstrating that there was no direct correlation between surface data and motorist's opinion of ride quality.

M&T Research Record is published by Michigan Department of Transportation's Materials and Technology Division

In the mid-1960's, engineers Elson Spangler and Bill Kelly at the General Motors Tech Center were searching for a way to create a demonstration profile of a road for use on a shake table in testing suspension systems. They revolutionized the roughness business by developing an electronic model of the Roughometer.

Through electronic trickery they were able to simulate a beam of physically impossible weight and damping. They used hydraulics to track the moment of the rolling wheel frame. Then came the revelation! Why use hydraulics if the signal is already there? Their answer opened the door to the application of signal processing theory to road profiles and the birth of a new generation of road profile instruments.

Signal Processing in a Nutshell

The theory and method of signal processing is based in electrical engineering, but has become widely used in image analysis, biomedical engineering, acoustics, and other fields of study. The use of signal theory in road profile analysis has broken new ground and made it possible to analyze a road profile with significant insight.

Signals are everywhere. Sounds are mechanical signals coming to your ears, voltages and currents are electrical signals, this page is a light signal to your eyes. Most signals are a collection of pure periodic waves with different frequencies. Combining individual waves, known as *synthesis*, is easy; we do it every time we speak.

The irregular surface of pavement is also a signal, at least to the proper receiver. It can be visualized as a "spatial signal" (cycles/meter) as opposed to a time based signal (cycles/second). The profile of a road is the summation of a large number of waves. In theory, pure waves can be combined together to replicate any actual road profile (see figure 2).

Frequency: A Different Frame of Reference

While combining waves is easy, separating a signal into its periodic components, known as *analysis*, is not as easy, but it can be done through mathematical manipulation. Systems, such as sounds and images, become much easier to analyze when they are expressed as a function of frequency rather than a function of time. In the case of pavement, function of frequency takes the place of function of distance.

Using the Fourier transform, one of the most commonly used techniques in signal processing, it is possible to change a profile of signals (the pavement surface) from a distance function into a frequency domain representation. Once in the frequency domain, it is easier to analyze the "frequency content" of a signal. When the Fourier transform is plotted on a graph, the relative proportion of the different frequencies present in the input can be visualized. The x-axis is now frequency, not distance. For example, the transform of a sine wave would look like a single spike, indicating that only one frequency was present. The profile of signals can be broken down into its component parts to give the strength of the individual waves, and hence in the analysis of the pavement, a plot of bump strength rather than spatial frequency (see figure 3).

Revealing Pavement Secrets

As was stated previously, the data acquired with the old Roughometer didn't correlate directly with motorist's opinions on ride quality. Not surprisingly, the data acquired through signal analysis didn't correlate directly either. But Materials and Technology Division project staff knew that some correlation must exist.

Using Psychometric techniques (Psychometry is the psychological theory of mental measurement) they developed a test to apply motorist's subjective opinion to

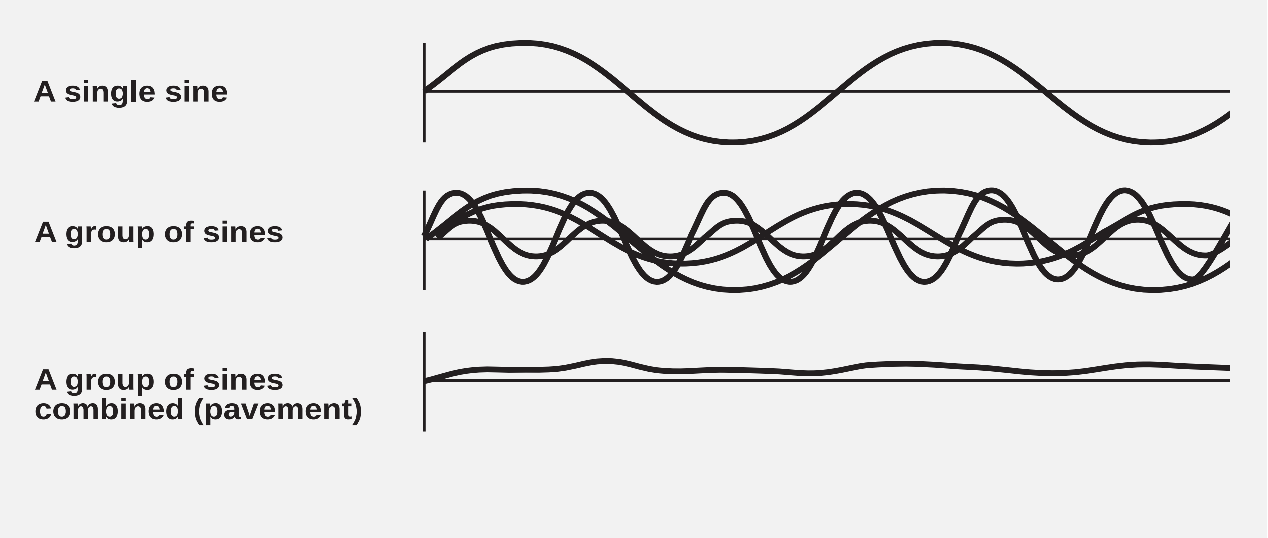

Figure 2: Profile of a road as the summation of a large number of waves

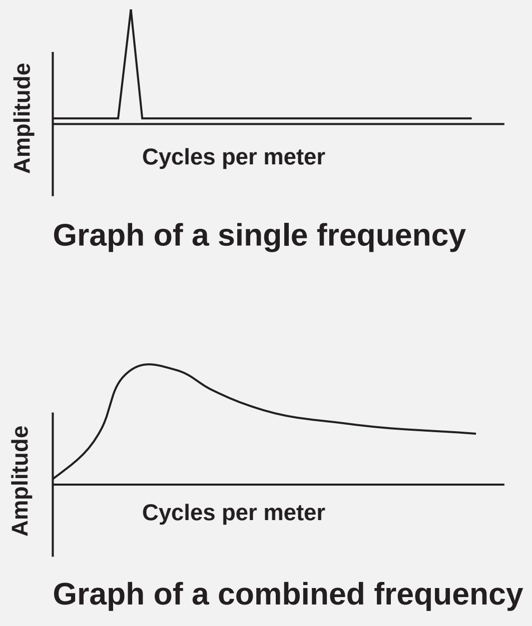

Figure 3: Visualization of the Fourier Transform

gathered road profile data. Sixty-eight subjects, representing a cross section of users, provided opinion on 28 test sections. These sections covered the full range of roughness ever expected in typical road systems. Rather than ask, “What do you think of the ride?” the subjects were asked, “What do you think of the road?” This may seem like a trivial difference, but the type of vehicle driven significantly influences the opinion of the motorist with concern to ride. When asked to describe the road, it was found that people can be very accurate. To simplify the collection of opinion, a subjective response word scale was developed and adapted into a notebook form. The opinion scores were summarized to fit a scale from 0 to 100; impossibly smooth to extremely rough.

Giving Short Bumps Full Recognition

The psychometric tests found that some components of a road have a strong effect on opinion, while others have significantly less effect. Through a series of mathematical and statistical steps, the Power Spectral Density measure (PSD) was found to correlate at 90 percent with subjective opinion. Based on this measure, the profile was split into three wavelength bands: .61 m - 1.52 m, 1.52 m - 7.62 m, 7.62 m - 15.24 m. Subjective opinion showed that wavelengths shorter than .61 m mostly create tire noise and those longer than 15.24 m fail to disturb the vehicle suspension.

The RQI is calculated from a three band PSD by sending the original profile through three bandpass filters. The signal variance from each band is transformed by taking the natural logarithm. It is then multiplied by a constant that indicates how much that band affects ride quality. The multipliers are 9, 6 and 3 respectively for the short, intermediate and long wave bands (see figure 4). Therefore, the short waves from .61m - 1.52m have twice the effect of intermediate waves and three times the effect of long waves.

The RQI is an index because it is a single number summary of multiple inputs. The lower the index number the better. At present, an RQI of 22 will get the paving contractor 100 percent of the incentive payment, an RQI of 45 results in no incentive payment, and an RQI over 45 is a problem.

MDOT’s LISA Takes to the Road

In the mid-1980’s, M & T staff considered designing and building a Lightweight Inertial Surface Analyzer (LISA) to take advantage of the advancements in signal theory. Since then, a decade of testing and refinement has gone into its development.

The heart of the system is a laser sensor and accelerometer that feeds road profile data to a computer. Soft-

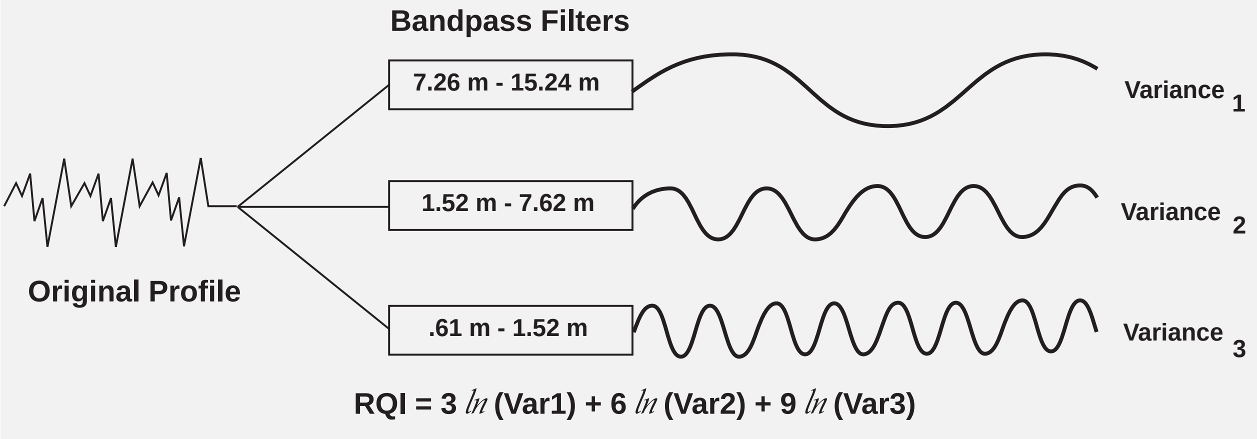

Figure 4: Three band PSD variance calculation

ware processes the data, calculates the Michigan RQI, and prints the profile. The system (laser, computer, printer, and monitor) is carried on a John Deer Gator; an 800 pound utility vehicle. It is equipped with high-flotation tires that allow it to be driven on fresh pavement. At a speed of 13 to 20 km/h the laser takes a profile reading every 75 mm. The laser can measure fluctuations in the pavement as small as .0254 mm. The operator can exclude sections of pavement, such as railroad tracks or bridges, from the profile. When the profile of the test section is complete, the RQI can be calculated at a rate of 12 seconds per mile.

Michigan RQI Ranks Near the Top

Methods developed nationwide for determining road profiles have been examined as part of an independent study that focused on initial pavement smoothness. The study, conducted by ERES Consultants, Inc., ranked the Michigan RQI in the top 5, along with the Janoff Ride Number and the Sayers Ride Number. These three all correlate best with user response.

The draft report noted that all three "provide promise as the smoothness statistics of the future, given their excellent correlation with driver comfort." "Increased exposure of the RQI to paving contractors and departments of transportation in other states will allow it to be compared on a national level," says Lynn Evans, Senior Engineer. "Support for nationwide comparison is in the interest of the entire paving community."

Using RQI to Assure Quality

Since the late 1980s MDOT has paid incentive bonuses to contractors for constructing pavements that meet smoothness criteria, and incurred penalties or required complete reconstruction on pavements that were excessively rough. Contractors can profile their pavements with a LISA type machine using RQI or with a California Profilograph (CALPRO) using inch/mile as an output. Although the CALPRO does not give a true profile, due to its wide availability and current use MDOT still accepts inch/mile data.

To achieve a low RQI it is necessary to minimize the amplitude of the bumps in the .61 m to 1.52 m wavelength band, because these waves have the strongest effect on ride quality, pavement performance, and hence on RQI. These bumps include ripples and deviations that can be readily controlled during the paving process. The long bumps in the 7.26 m to 15.24 m wavelength band are usually a function of base control and need to be corrected during the grading operation. The cause of intermediate bumps in the 1.52 m to 7.62 m wavelength band may be similar to either the short or long waves. That assessment and prescribed remedy needs to be made by an engineer on site.

Contractor Experience: Putting RQI to the Test

Paving contractors benefit significantly by using the LISA and the Michigan RQI. "Using the LISA allows us to analyze the pavement surface while the job is in progress, rather than at the end of the day," says Paul Strpko, QA Manager, Reith Riley. "It helps us pinpoint the problem and make corrections immediately."

The Michigan RQI benefits good pavers by assisting them in placing a pavement that will give maximum performance. "The weighted average used to calculate the RQI is a great idea," notes Strpko. "Not just because it provides a quality ride for the motorist, but because it lets us eliminate the flaws that disrupt service life." This is especially critical in situations such as bridge deck approaches. There, excessive deviation leads to undue stress on the surface, which then fails and leads to stress on the subgrade, which then also fails.

The true profile aspect of the RQI also enhances long term performance analysis. Contractors and researchers can use the RQI to determine historical performance. This data will help them evaluate paving materials, mix designs, and paving techniques. "This idea should propel its way through the paving industry just as QA and QAC has," adds Strpko. "Its a good example of an instance where the builder wins, the owner wins, and the user wins."

Reference Material on Signal Processing

Digital Signal Processing
William D. Stanley, Reston 1975.

Digital Signal Processing: principles, algorithms & applications
Proakis & Manolakis, Prentice Hall 1996.

Analog and Digital Signal Processing
Ashok Ambardar, PWS 1995.

Signals and Systems Made Ridiculously Simple
Zoher Karu, ZiZi Press 1995.

To obtain permission to reprint text or graphics from the Research Record, or if you have suggestions or questions, contact Jon Reincke, MDOT Engineer of Research; 517-322-1632, FAX 517-322-5664.

M&T Research Record is produced by Michigan's Local Technical Assistance Program

Editor .... Terry McNinch

M&T Research Record is a news bulletin authorized by the transportation director to disseminate technical information to MDOT personnel and is published by the Materials and Technology Division. The cost of publishing 850 issues is $175.00, and it is printed in accordance with Executive Directive 1991-6.