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Terrain Regime Identification and Classification for Condition Based Maintenance

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Abstract

In order to ascertain the current "condition" or "health" of a vehicle-based system and to predict the need for future maintenance, one of the primary pieces of information that must be understood is the terrain environment in which the vehicle system is operating. By combining an understanding of the actual terrains in which a given vehicle is operating, with an understanding of how damage accumulates in that vehicle's subsystems under usage regimes within specific terrain types, certain aspects of vehicle health can be ascertained. Ideally, this understanding would include a full spectrum of characteristics such as surface roughness, intensity of slopes, and soil mechanics. The United States Army Materiel Systems Analysis Activity (AMSAA) has successfully demonstrated that low-cost and embedded sensors can be used to characterize this broad spectrum of terrain regime classifications in on-board and real-time operational environments.

Keywords: Terrain, Mobility, Condition Based Maintenance, Vehicle Health, Operational, Surface Roughness, Slopes, Wheeled Vehicles

Introduction

Within the AMSAA Condition Based Maintenance (CBM) team, two HUMS boxes are used. The System Health And Reliability Computer (SHARC) was developed in-house and is the larger, more expensive of the two boxes and is used in development situations and special studies because it is highly programmable. The Vehicle Monitoring Unit (VMU) is installed on wide-spread, fully developed applications. Both boxes have the ability to record vehicle bus data and sensor data. These sensors often include accelerometers, global positioning systems (GPS), and gyroscopes. The boxes can also perform algorithm computation and histogram generation onboard. It is the SHARC and VMU that are utilized in the development and implementation of Terrain Regime Identification and Classification (TRIC).

AMSAA has developed and implemented a vehicle-specific surface roughness identification algorithm, a vehicle-specific mid-wavelength algorithm, and a universal long-wavelength identification algorithm using a combination of embedded and added sensors. The currently implemented surface roughness algorithm is based upon the comparison of the low-frequency responses of specific vehicle types traversing known measured terrains at the Army's proving grounds at various speeds to the responses of these vehicle types while in operation

throughout the world. This method relies upon the acceleration responses of unsprung mass suspension components and is sensitive only to short and some medium wavelength terrain inputs. The mid-wavelength algorithm is based upon the pitch and roll response of specific vehicle types traversing known measured terrains at the Army's proving grounds to the responses of these vehicle types while in operation throughout the world. This method relies upon the angular movement responses of a gyroscope sensor and is sensitive only to medium and some long wavelength terrain inputs. Very long wavelengths of hilly terrains are identified by the use of a GPS, using an all-encompassing percent grade identification process. Through this, AMSAA has successfully demonstrated that low-cost and embedded sensors can be used to characterize a broad spectrum of terrain regime classifications.

TRIC is used to identify the specific combination of terrain components at any given moment, and then histogram them to gain a perspective of the overall characteristics of the terrain that that vehicle traverses. Ultimately, a damage accumulation factor will be assigned to each terrain combination in order to ascertain the vehicle's component health.

Background

There is no single standardized classification of terrains community-wide, but the United States Army has often used three general categorizations for terrain that are measured using a profilometer. These include primary, which is represents hard surfaces of a displacement amplitude range of 0.1-0.3 inches Root Mean Square (RMS), secondary which is hard or loose surface of 0.1-0.6 inches RMS, and off-road which is loose surface or virgin terrain of 0.1-4.5 inches RMS. However, this measurement type can become confusing because the off-road amplitude range is inclusive of the secondary amplitudes, and the off-road and secondary are both inclusive of the primary amplitudes. This overlap leads to unclear divisions, and undistinguished categories. Other than large amounts of overlap in the RMS values, there are also no defined upper and lower wavelength bounds, and this method does not account for wavelength distributions, which does not work well for CBM applications. This methodology also does not adhere to CBM principles in that it does not account for mid- to very long-wavelengths which results in missing component health degradation information and means it is concerned more with mobility than condition degradation. But the most important thing to note is that this method cannot be implemented on in-operation vehicles due to cost, robustness, and calibration issues, thus making it impossible to integrate into a CBM HUMS box. [1]

Figure 1 illustrates several of the shortcomings mentioned above. The figure shows two overlaid Wave Number Spectra (WNS)– power spectral densities (PSD) of the terrain profile displacements - with the same nominal amplitude in inches RMS. However, the two PSD curves have completely different shapes, including different wavelength distributions, different lower limits (longer wavelengths) despite equal upper limits (short wavelengths), and filtered out or missing long wavelengths. These two PSD plots actually represent two totally different terrains, despite having the same nominal amplitude in inches RMS. [2]

CBM requires a methodology where measurements can be easily made on in-operation vehicles. Those measurements must, therefore, represent vehicle responses to terrain rather than a direct terrain measurement. Algorithms that can be implemented on low-cost HUMS, a

taxonomy that can be related more directly to system degradation, and a taxonomy that is broad spectrum to include short to long wavelengths and transients are imperative to the CBM mission.

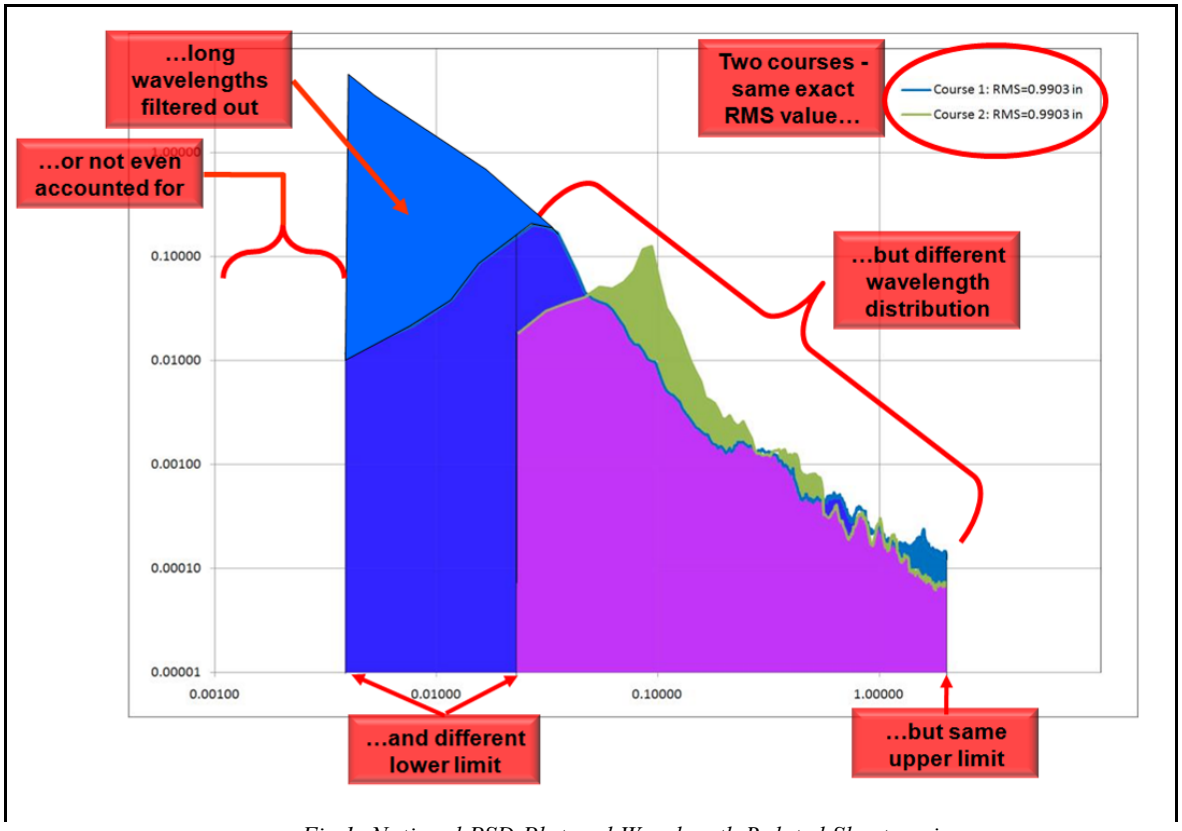


Fig 1: Notional PSD Plot and Wavelength Related Shortcomings

Procedure

Because the power spectral density curves are so specific and complicated, they cannot be implemented on a HUMS box that only has limited computing power capabilities. The TRIC concept can be thought of as a simplification of the WNS where the curve is divided into just three general wavelengths - short, medium, and long – and three amplitude levels - low, mid, and high. This results in each wavelength category having three possible levels of severity. Using this method, at any moment in time the terrain can be described by its level of severity in each of the three wavelength categories. The outcome is 27 different regime possibilities.

Short Wavelength

Short wavelengths consist of small repetitive bumps, which translate into vibration of the vehicle. A short wavelength input will affect a vehicle's fastened joints, electronics, human comfort, and human safety. The three levels of severity for the short wavelength are established by determining and drawing discrimination lines on a scatter plot, based on known

proving ground data. The scatter plot is used to determine level of roughness by cross-plotting the unsprung mass acceleration amplitude in g's Root Mean Square (gRMS) and mean vehicle speed over 20-second periods. This scatter plot, and coordinating discrimination lines, must be measured and determined on each vehicle type since it is based on vehicle responses which can vary greatly vehicle-to-vehicle. The short wavelength category is referred to as the "roughness" of the terrain or the spectrum ranging from "smooth" to "rough" in layman's terms.

Medium Wavelength

Medium wavelengths consist of large repetitive bumps, which translate into dynamic pitching, rolling, and heaving of the vehicle. A medium wavelength input will affect the vehicle's suspension, steering, human comfort, and vehicle stability. The three levels of severity for the mid wavelength are determined by the average severity of the pitch-roll vector magnitude over 20-second periods. The pith-roll vector magnitude is a factor that relates how quickly the vehicle is pitching and rolling, or an angular change rate. The general correlation is that the faster the change, the "bumpier" the terrain. These rates, and coordinating discrimination lines, must be measured and determined on each vehicle type since it is based on vehicle responses which, again, can vary greatly vehicle-to-vehicle. The medium wavelength category is referred to as the "bumpiness" or the spectrum ranging from "flat" to "bumpy" in layman's terms.

Long Wavelength

Long wavelengths consist of very large, long, or steep hills, which translate into static pitching of the vehicle. A long wavelength input will affect the vehicle's engine, transmission, fuel economy, and brakes. The three levels of severity for the long wavelength are determined by a grading factor. This factor is determined, using the GPS, by a ratio of the altitude change to the distance traveled over a 20-second period. These factors, and coordinating discrimination lines, do not need to be measured and determined on each vehicle type since it is not based on vehicle responses. The long wavelength category is referred to as the "hilliness" or the spectrum ranging from "level" to "hilly" in layman's terms.

HUMS and Sensors

For the purposes of TRIC testing, a SHARC HUMS box was used. The SHARC consists of an eDaq Lite, 1939 and 1708 bus modules, and sensor hook ups. Sensors, in both test and operational scenarios, include a Garmin GPS receiver, a MircoStrain 3DM-GX1 gyroscope-type orientation sensor, and one variable capacitive accelerometer. The orientation sensor is mounted on the inside lid of the SHARC. The GPS receiver is mounted on the roof of the vehicle. The accelerometer is mounted on the passenger-side front axle. For each vehicle type, the box and sensor locations are kept consistent.

Test Methods

After carefully instrumenting the test vehicle with the hardware described above, the test vehicle was driven over a variety of proving ground courses, incorporating the various

wavelength types and severities. The vehicle was driven over the courses at speeds ranging from 5 MPH up to the maximum safe speed mandated by state or proving ground authorities. In order to get a sufficiently dense data population, it was critical to spend a minimum of two minutes in each 5 MPH band (i.e. 5 to 10 MPH, 10 to 15 MPH, etc). During this entire period of time bus, accelerometer, gyro, and GPS data are being taken. The data runs are started at the very beginning of each course and stopped at the very end of the course, with no access road included in the measurements, so as to not pollute them. [3]

Tire Pressure Sensitivity

Tire pressure sensitivity tests and analyses were performed in order to determine tire pressure affects on the terrain classification results. The tests involved running a prescribed set of test courses at various tire pressures and analyzing the differences in sensor data. For vehicles with no Central Tire Inflation System (CTIS) information broadcast on the vehicle bus, there is no way of being sure of the vehicle's tire pressure so it is necessary to select classification discrimination lines (see Figures 2 and 4) that result in the lowest erroneous reporting of the terrain classification. On those vehicles with broadcast CTIS setting information, the TRIC algorithm comprehends these differences. This was critical to the project because it is nearly impossible for the vehicles instrumented in field to have their tire pressures reported back to AMSAA on a regular basis.

Weight Sensitivity

Vehicle weight sensitivity tests and analyses were performed in order to ascertain vehicle weight affects on the terrain classification results. The tests involved running a prescribed set of test courses at various vehicle weights and loading schemes and analyzing the differences in sensor data. Since there is no way of being sure what the vehicle's payload is at any given time it is necessary to select discrimination lines that result in the lowest erroneous reporting of the terrain classification. This was particularly critical to the project because it is nearly impossible for the vehicles instrumented in field to have their weights reported back to AMSAA on a regular basis.

Results

Short Wavelength

The short wavelength discrimination lines were determined by inputting the various course data, sampled at 100 Hz, into a 20-second average g's RMS vs. Vehicle Speed scatter plot, and determining population densities. These line equations will vary depending on the vehicle since the acceleration responses change by vehicle type. However, the line equation will always be linear. In Figure 2, a sample is shown of what three courses might look like in a scatter plot for the short wavelength, with respective discrimination lines. Three notional courses are depicted that purposefully have densities in each severity for graphical ease. Each marker represents a 20-second sample.

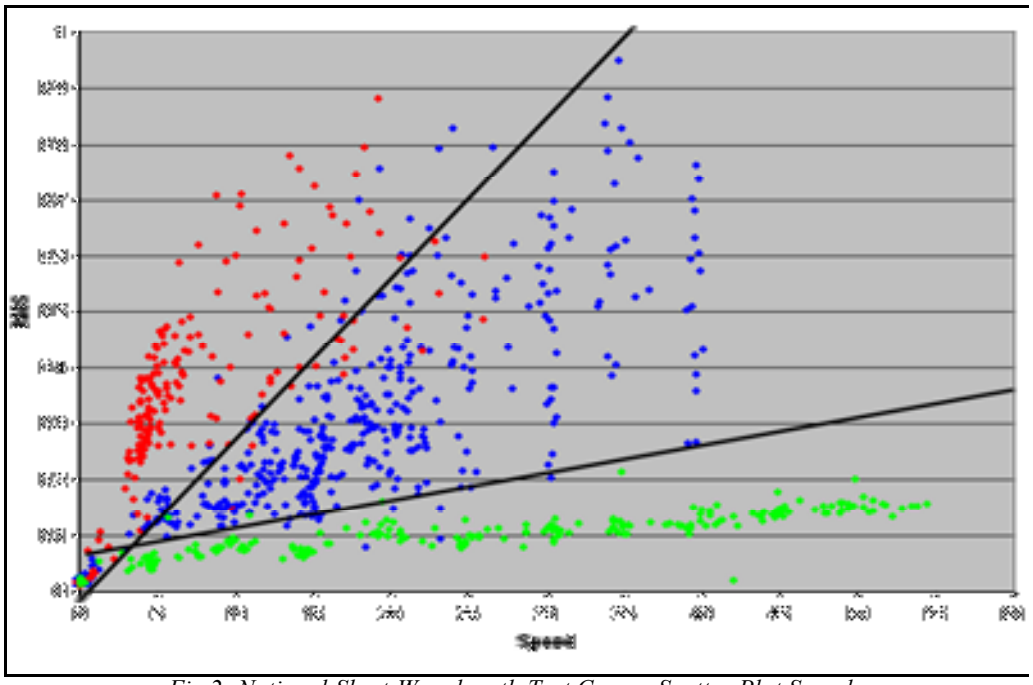


Fig 2: Notional Short Wavelength Test Course Scatter Plot Sample

When data is taken in-field the files are put into a solver, compared to the equations for the discriminating lines determined from proving ground data, and output as a low, mid or high intensity value for each 20-second sample. Figure 3 represents what an actual result of this process might look like.

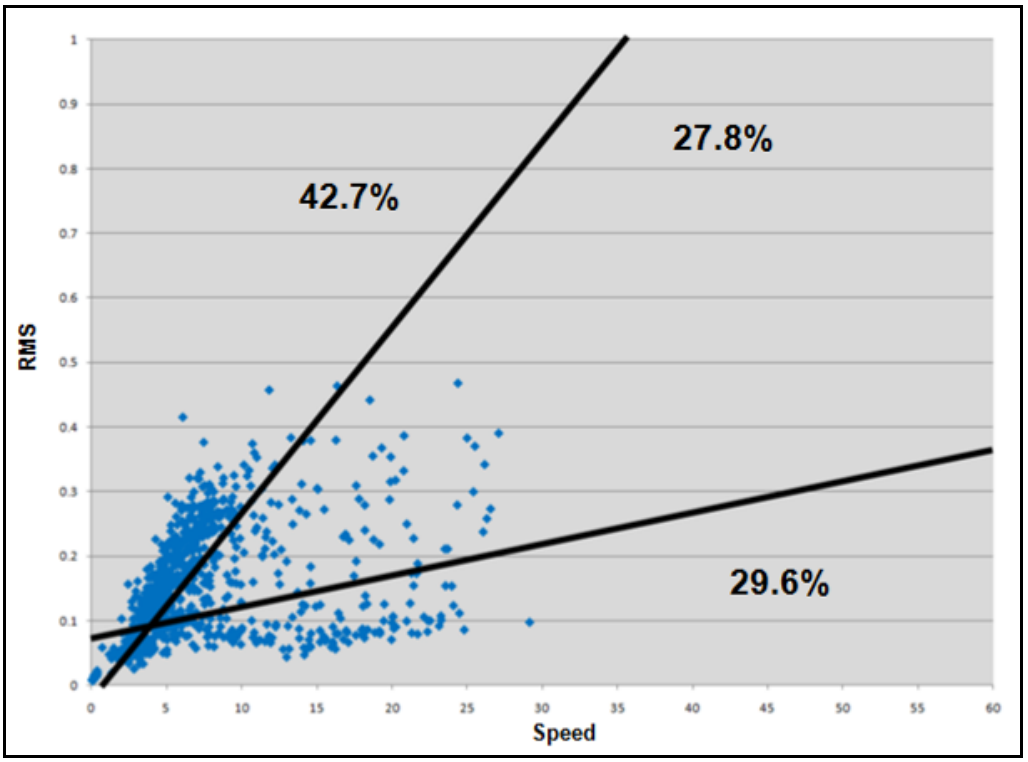


Fig 3: Short Wavelength Notional Field Data Scatter Plot Sample

Medium Wavelength

The medium wavelength discrimination lines were determined by dividing the various course data, sampled at 50 Hz, into 20-second intervals, for which the average pitch-roll vector magnitude was determined, and population densities were analysed. The average pitch-roll vector magnitude is calculated by determining the average of the pitch-roll vector magnitude over a 20-second period, as determined by Equation 1. This factor tells the rate of change of the vertical angle of the vehicle. The faster the vehicle is pitching and rolling, the bumpier the terrain, and the higher the severity factor.

$$P\text{-}R\ Vector\ Magnitude = \sqrt{\Delta pitch^2 + \Delta roll^2} \quad (1)$$

These line equations will also vary depending on the vehicle since the angular responses change by vehicle type. However, the line equation will always be linear, with a zero slope. In Figure 4, a sample is shown of what three courses might look like in a scatter plot for the medium wavelength, with respective discrimination lines. Three notional courses are depicted that purposefully have densities in each severity for graphical ease. Each marker represents a 20-second sample.

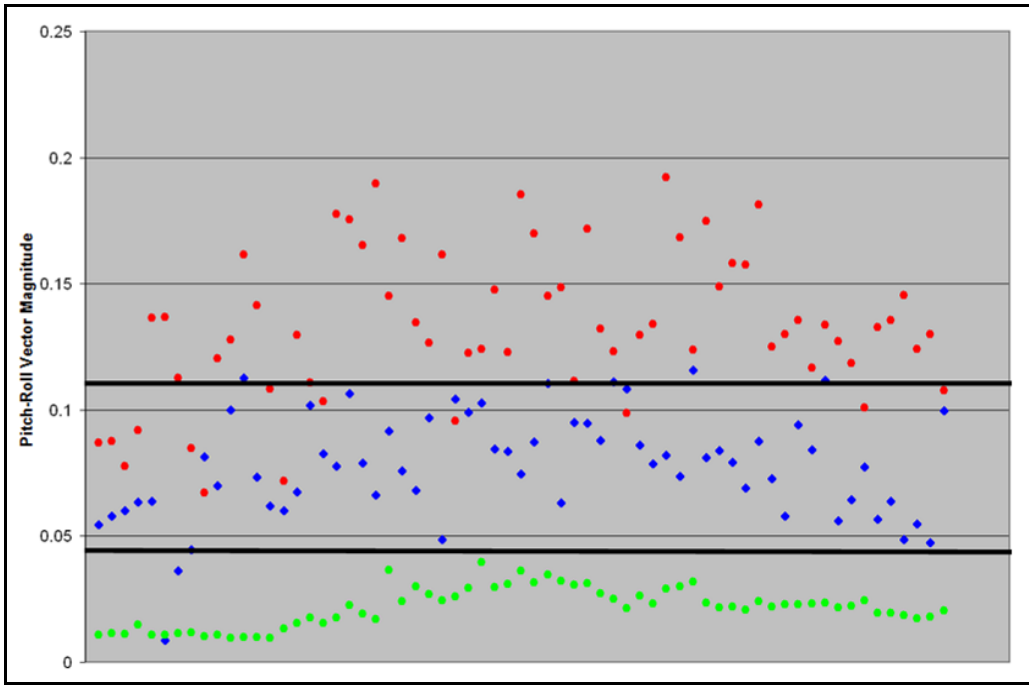


Fig4: Notional Medium Wavelength Test Course Scatter Plot Sample

When data is taken in-field the files are put into a solver, compared to the equations for the discriminating lines determined from proving ground data, and output as a low, mid or high intensity value in the medium wavelength for each 20-second sample. Figure 5 represents what an actual result of this process might look like.

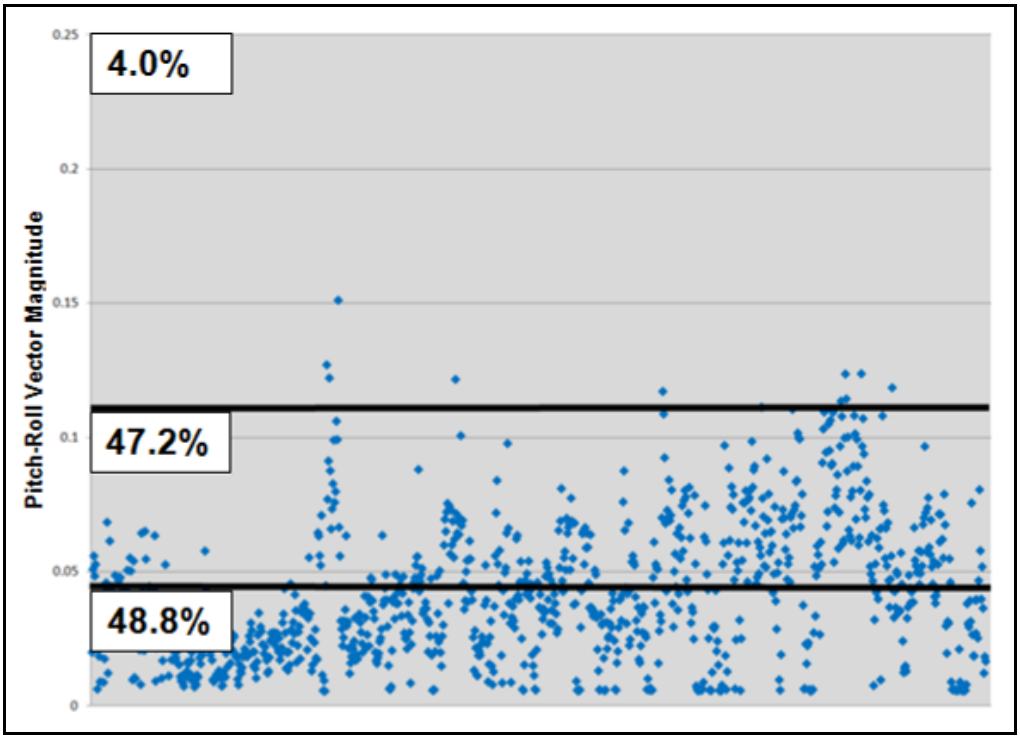


Fig 5: Medium Wavelength Notional Field Data Scatter Plot Sample

Long Wavelength

The long wavelength discrimination lines were determined by calculating a percent grade factor over 20-second periods and determining population densities. The percent grade factor is calculated by Equation 2.

$$\textit{Percent Grade Factor} = \Delta \textit{altitude} / \textit{distance travelled} \quad (2)$$

These line equations will not vary depending on the vehicle, like the short and medium wavelengths, since the altitude and distance measurements is not response based. These line equations are linear, and have a zero slope. After analysing test data, discrimination lines were placed at the 2 percent and 8 percent factor values to determine severity levels for all vehicle types. In Figure 6, a sample is shown of what three courses might look like in a scatter plot for the long wavelength, with respective discrimination lines at the 2 and 8 percent factor marks. Three notional courses are depicted that purposefully have densities in each severity for graphical ease, however a completely high severity hilliness course does not exist so a mix is shown for the high severity course. Each marker represents a 20-second sample.

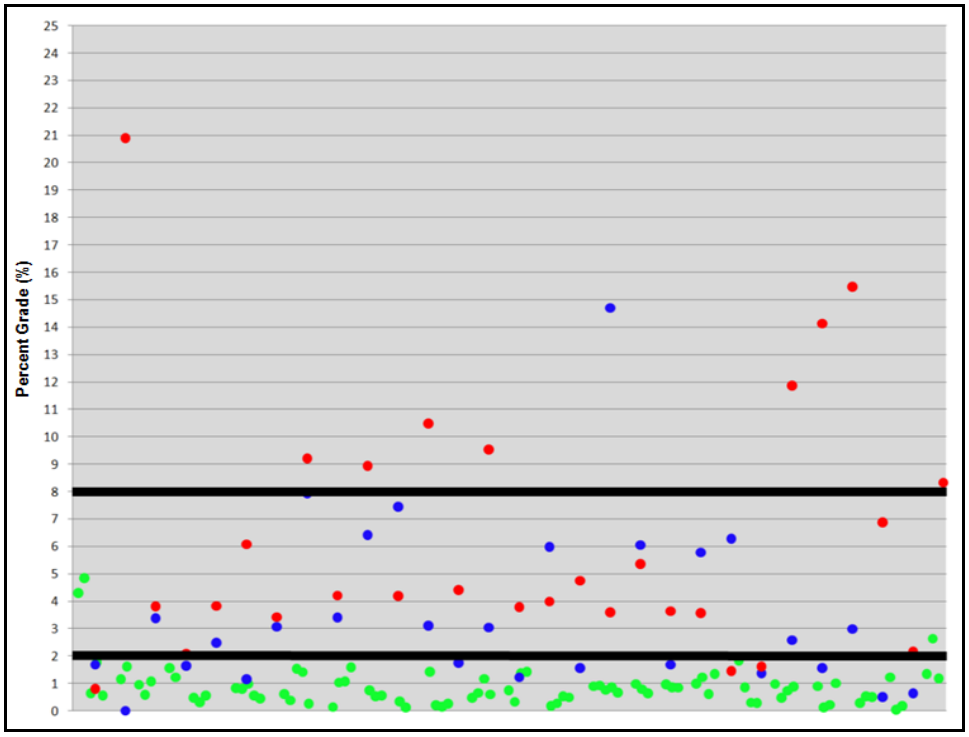


Fig 6: Notional Long Wavelength Test Course Scatter Plot Sample

When data are taken in-field the files are put into a solver, compared to the equations for the discriminating lines determined from proving ground data, and output as a low, mid or high intensity value in the long wavelength for each 20-second sample. Figure 7 represents what an actual result of this process might look like.

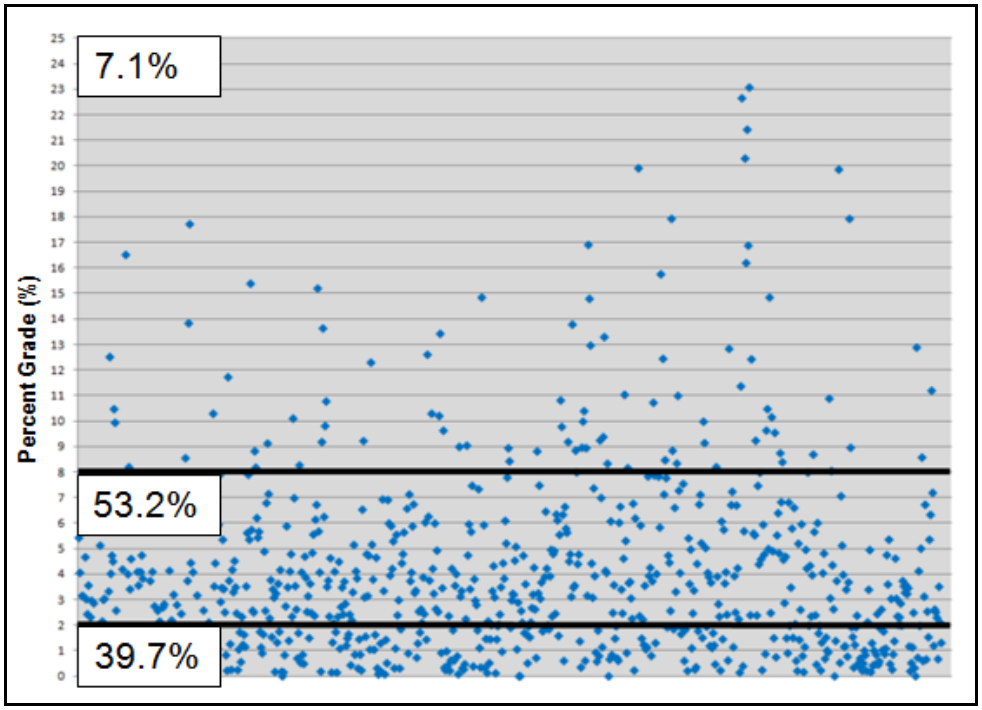


Fig 7: Medium Wavelength Notional Field Data Scatter Plot Sample

All Wavelengths Combined

TRIC is the broad-spectrum, all wavelength inclusive, identification and classification of terrain so all three wavelength results must be combined. So, for any 20-second period of time the short, medium, and long wavelength severities must all be identified so that the specific combination of terrain components at any given moment is known. This is then put into a histogram to gain a perspective of the overall characteristics of the terrain that that vehicle traverses.

The graphic used to depict TRIC is a five dimensional graph. On the x-axis is the short wavelength or "roughness", divided into three levels of severity. On the y-axis is the medium wavelength or "bumpiness", divided into three levels of severity. Each bin is further divided into three levels of severity along the z-axis for the long wavelength or "hilliness" severity. Percent time is also along the z-axis, and each bin is color-graded to indicate the overall system severity index, from green to red, with red indicating the most severe terrain. This graph allows the full spectrum of terrain to be characterized in a single, tell-all, snap shot. It can be generated for a given run, time period, or vehicle history, or instrumented vehicle type, so long as a AMSAA CBM HUMS boxes have been installed.

Figure 8 shows the TRIC histogram that compiles all of the Notional Field data shown for the short wavelength (Fig 3), medium wavelength (Fig 5), and long wavelength (Fig 7). This single graph gives all of the same information as those three previous graphs combined and more, while reflecting the complex and varied terrain that can be displayed in one run.

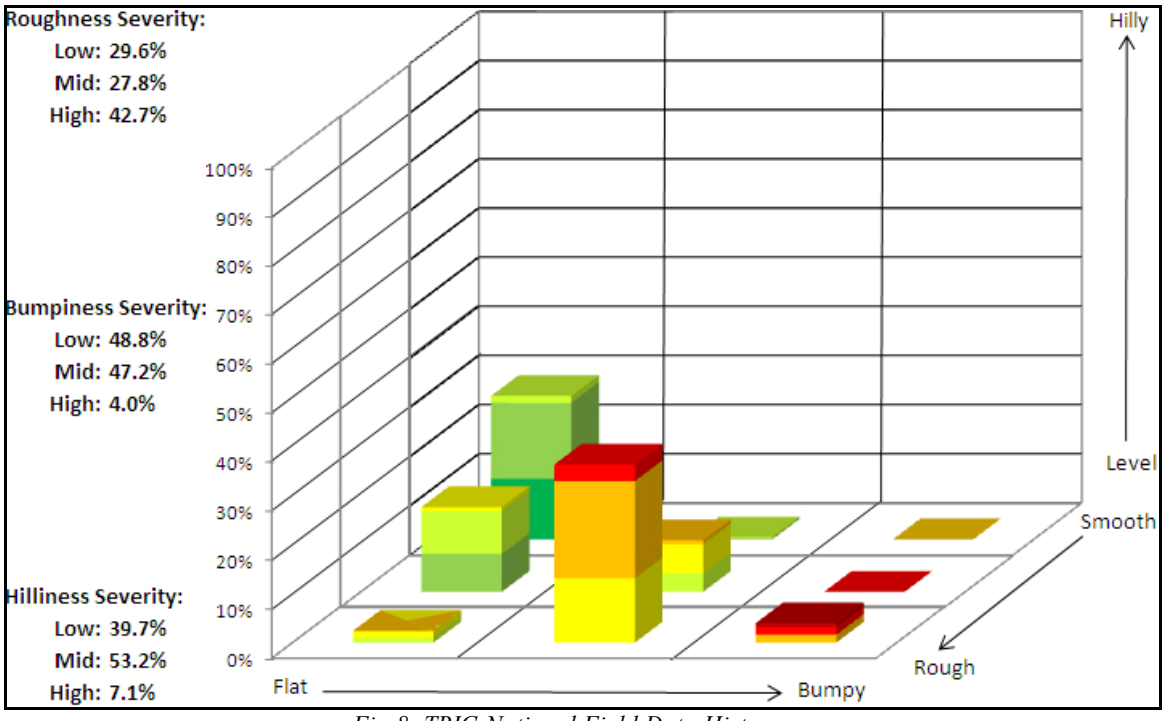


Fig 8: TRIC Notional Field Data Histogram

Applications

Currently, Terrain Regime Identification and Classification has a multitude of applications, the most useful of which utilize optimization. Using a terrain distribution profile from in-theatre as an input, and the terrain distribution profiles from known Army proving ground courses as the constants, the composition of miles per course to replicate theatre missions can be determined. This can be applied to Test Scenario Development, as well as Modelling and Simulation by establishing the appropriate and accurate course distribution based on usage via optimization. These optimization results allow for tests and simulations to truthfully reflect real data samples and therefore make results more accurate. TRIC analyses and graphs are also included in AMSAA soldier reports, which are the usage summary reports distributed to the units themselves, motor pool sergeants, and any other authorized interested parties. Ultimately, TRIC will facilitate the implementation of regime-based prognostic algorithms through the assignment of damage accumulation factors to each terrain regime in order to ascertain the vehicle's component health. This will lead to failure prediction, condition based maintenance, and condition based resets.

Conclusions

AMSAA has successfully demonstrated that low-cost HUMS and embedded sensors can be used to characterize a broad spectrum of terrain regime classifications in on-board and real-time operational environments. This spectrum includes short, medium and long wavelengths. Results have been generated and reports have been produced for in-operation missions in North America, Europe, and Asia, as well as testing missions in North America and Africa. In an effort to be able to identify terrain for any vehicle type, currently five vehicle types have been fully tested, discrimination lines determined, and algorithms implemented, while an additional two vehicle types are partially tested. AMSAA intends to test four other vehicle types, identified as mission critical, in 2011.

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