**A METHOD FOR THE CHARACTERIZATION OF OFF-ROAD
TERRAIN SEVERITY**

A Thesis

Presented in Partial Fulfillment of the Requirements for
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By

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* * * * *

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ABSTRACT

Surface measurement of paved roads is a practice that has been ongoing for decades. This sort of measurement is intended to ensure a safe level of road perturbations. The measurement may be conducted by moving an apparatus that directly measures the elevation of the road, at varying distance intervals, to obtain a road profile, with varying degrees of resolution. An alternate method is to measure the surface roughness at highway speeds using accelerometers coupled with high speed distance measurements, such as laser sensors. Vehicles out rigged with such a system are termed inertial profilers. This type of inertial measurement provides a sort of filtered roadway profile. Much research has been conducted on the analysis of highway profiles, and the associated roughness metrics involved.

In many instances, it is desirable to maintain an off-road course such that the course will provide sufficient challenges to a vehicle during durability testing. Such situations would require an off-road terrain measurement system. The Ohio State University (OSU) has developed a system that aims to take inertial measurements in non-paved situations. Off-road analysis provides new challenges to surface measurement. The surfaces are generally even more time-varying than paved-roads, they provide greater vehicle excitations, it is difficult to maintain a constant speed when traveling over extreme terrain, and the dynamics of the suspension will be excited well beyond the

points of small angle approximations and linearity assumptions. This research effort assessed and compared metrics used previously in highway applications, and adopted them to off-road conditions suitable for use in an off-road terrain severity measurement system. Further, new metrics were assessed to describe off-road terrain for the purpose of maintaining off-road courses that are used for durability testing of All-Terrain Vehicles (ATV). The overall ambition was two-fold: provide one or two profile calculations that are repeatable, meaning the same values may be found on repeated test runs; second, give future researchers a metric that alludes to the terrain severity so experienced drivers will know whether or not their vehicle may successfully traverse the environment.

In order to achieve these goals, a methodology has been formulated which will provide a complete characterization of the terrain severity. The Ohio State University's Terrain Severity Measurement System (OSU-TSMS) is capable of profiling extreme terrain at improved speeds, and together with the off-road Terrain Severity Characterization (TSC) methodology provides an improved off-road profiling and roughness measuring tool.

Dedicated to my mother and father

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TABLE OF CONTENTS

	<u>Page</u>
Abstract	ii
Acknowledgments.....	v
Vita	vi
List of Figures	ix
List of Tables	xiii
List of Equations	xiv
Acronyms List.....	xvi

Chapters:

1	Road Profile and Roughness Measurement Systems.....	1
1.1	Background	1
1.2	Off-Road Systems	5
1.2.1	The Aberdeen Test Course Profilometer	6
1.2.2	The Ohio State Terrain Severity Measurement System.....	9
1.3	Conclusion	10
2	Roughness Calculations	11
2.1	Introduction.....	11
2.2	Paved-Road Considerations.....	11
2.2.1	Pavement Condition Index.....	13
2.2.2	International Roughness Index	14
2.2.3	Ride Number.....	18
2.2.4	Power Spectral Density.....	20
2.2.4.1	Waterfall Plots	25
2.2.4.2	Wavelet Analysis	26
2.2.5	Frequency Weighted Root-Mean-Square Vertical Acceleration	27
2.3	Off-Road Considerations	32
2.3.1	Arc Length	32
2.3.2	Crest Factor.....	33
2.3.3	Spatial Derivatives.....	34
2.3.4	Suspension Forces.....	34

2.4	ATC Profilometer	37
2.5	OSU-TSMS Severity	38
2.6	Conclusion	39
3	Terrain Severity Measurement System	40
3.1	Introduction.....	40
3.2	Hardware and Vehicle Platform.....	40
3.3	Profile Measurement.....	46
3.4	Conclusion	50
4	Reporting Terrain Severity	51
4.1	Introduction.....	51
4.2	Off-Road Terrain Severity Characterization.....	51
4.3	Off-Road Data Samples	56
4.4	Sample Calculations Using YPG Data	57
4.5	Comparative Analysis of Highway Data	79
4.6	Correlation to IRI and RN.....	88
4.7	Conclusion	94
5	Closing Remarks	95
5.1	Conclusions.....	95
5.2	Future Work.....	97
	Bibliography	99
	Appendix A.....	104
	Appendix B.....	107

LIST OF FIGURES

Figure	Page
Figure 1.1: CHLOE Profiling Device	2
Figure 1.2: BPR Roughometer.....	2
Figure 1.3: Response-Type Road Roughness Measuring Systems (RTRRMS).....	4
Figure 1.4: Geometry illustration of ATC Profilometer tow arm geometry.....	7
Figure 2.1: Quarter-Car Model and System Parameters.....	15
Figure 2.2: Wave number response of the quarter-car filter used in RN.....	20
Figure 2.3: Demonstration of Change in PSD after Grading a Course.....	23
Figure 2.4: Waterfall Plot for Laguna Level Trails East	26
Figure 2.5: Frequency Weighting Curve from ISO 2631-1	29
Figure 2.6: Health Caution Zones for Vibration Exposure.....	31
Figure 2.7: Relative Suspension Displacement and Velocity from 7-DOF Model	36
Figure 2.8: Example of Relative Suspension Force from 7-DOF Model	36
Figure 3.1: Baseline Polaris 6x6 ATV	41
Figure 3.2: LMI Selcom [®] Laser Dimensions and Illustration of Triangulation	43
Figure 3.3: Sensors Mounting Locations (Side View).....	43
Figure 3.4: Sensors Mounting Locations (Top View)	44

Figure 3.5: ADAT DRS-6 Speed Sensor and Mounting Location on Side of Vehicle	45
Figure 3.6: 7-DOF Model	47
Figure 3.7: Nonlinear Damping, C_s , from 2000 Jeep Grand Cherokee	49
Figure 4.1: PSD, Course: Old 95	58
Figure 4.2: FWA, Course: Old 95.....	59
Figure 4.3: Sliding Window RMSVA, Course: Old 95	60
Figure 4.4: Simulated Work, Course: Old 95	61
Figure 4.5: Simulated Power, Course: Old 95	62
Figure 4.6: Work Comparison of Front and Rear Corners, Course: Old 95	63
Figure 4.7: Sliding Window RMS of Simulated Work, Course: Old 95	64
Figure 4.8 Moving Average of Simulated Power, Course: Old 95.....	64
Figure 4.9: PSD, Course: Laguna Level Trails East.....	66
Figure 4.10: PSD, Course: Laguna Level Trails West.....	67
Figure 4.11: PSD, Course: Gravel Loop.....	67
Figure 4.12: PSD, Course: Dynamometer Course	68
Figure 4.13: FWA, Course: Laguna Level Trails East	70
Figure 4.14: Sliding Window RMSVA, Course: Laguna Level Trails East.....	70
Figure 4.15: FWA, Course: Laguna Level Trails West.....	71
Figure 4.16: Sliding Window RMSVA, Course: Laguna Level Trails West	71
Figure 4.17: FWA, Course: Gravel Loop	72
Figure 4.18: Sliding Window RMSVA, Course: Gravel Loop.....	72
Figure 4.19: FWA, Course: Dynamometer Course	73

Figure 4.20: Sliding Window RMSVA, Course: Dynamometer Course.....	73
Figure 4.21: Simulated Work, Course: Laguna Level Trails East.....	75
Figure 4.22: Simulated Power, Course: Laguna Level Trails East.....	75
Figure 4.23: Simulated Work, Course: Laguna Level Trails West.....	76
Figure 4.24: Simulated Power, Course: Laguna Level Trails West	76
Figure 4.25: Simulated Work, Course: Gravel Loop.....	77
Figure 4.26: Simulated Power, Course: Gravel Loop.....	77
Figure 4.27: Simulated Work, Course: Dynamometer Course	78
Figure 4.28: Simulated Power, Course: Dynamometer Course.....	78
Figure 4.29: Sliding Window IRI for Smooth Highway (Section 2).....	81
Figure 4.30: Sliding Window IRI for Rough Highway (Section 6).....	81
Figure 4.31: Profile PSD for Smooth Highway (Section 2)	82
Figure 4.32: Profile PSD for Rough Highway (Section 6).....	82
Figure 4.33: FWA for Smooth Highway (Section 2).....	83
Figure 4.34: FWA for Rough Highway (Section 6)	84
Figure 4.35: Sliding Window RMSVA for Smooth Highway (Section 2).....	84
Figure 4.36: Sliding Window RMSVA for Rough Highway (Section 6).....	85
Figure 4.37: Simulated Work for Smooth Highway (Section 2)	86
Figure 4.38: Simulated Work for Rough Highway (Section 6).....	86
Figure 4.39: Simulated Power for Smooth Highway (Section 2).....	87
Figure 4.40: Simulated Power for Rough Highway (Section 6).....	87
Figure 4.41: ProRuts Correlation between RN and RMSVA	89

Figure 4.42: ProRuts Correlation between IRI and RMSVA	90
Figure 4.43: ProRuts Correlation between RN and Mean Power	90
Figure 4.44: ProRuts Correlation between IRI and Mean Power	91
Figure 4.45: Correlation between RN and Mean Power to Show Variation in Profilers..	91
Figure 4.46: Profiler Variation in RN Calculation.....	92
Figure 4.47: Profiler Variation in IRI Calculation.....	92
Figure 4.48: Profiler Variation in RMSVA Calculation.....	93
Figure 4.49: Profiler Variation in Mean Power Calculation.....	93
Figure 4.50: Profiler Variation in Work Calculation	94
Figure A. 1: 7-DOF Simulink Model.....	105

LIST OF TABLES

Table	Page
Table 2.1: IRI Scale for Gravel or Other Unpaved Roads	17
Table 2.2: RN Scale Description	18
Table 2.3: RN ¼ Car Parameters	19
Table 2.4: Parameters for the Frequency Weighting Transfer Functions	28
Table 2.5: Acceleration Limits for a Human Subject	30
Table 3.1: Labeling Nomenclature for Systems Measuring Longitudinal Profile	46
Table 3.2: 7-DOF System Matrices and Model Parameters Defined	48
Table 4.1: YPG Key PSD Values	66
Table 4.2: YPG FWA Values of Interest	68
Table 4.3: YPG Energy Values	74
Table 4.4: Highway Profile Properties from RoadRuf	79
Table 4.5: Highway Examples Key PSD Values	80
Table 4.6: Highway Examples Weighted Acceleration Values of Interest	83
Table 4.7: Highway Examples Energy Values, Front Left Corner	85
Table B. 1: Correlation Study Values	108

LIST OF EQUATIONS

Equation	Page
Equation 2.1: Moving Average Filter	14
Equation 2.2: State Space Equations and Parameters for the Quarter-Car Model.....	15
Equation 2.3: Solution to ODE of Quarter-Car Model	16
Equation 2.4: State Transition Matrix.....	16
Equation 2.5: International Roughness Index (IRI)	16
Equation 2.6: Ride Number (RN)	18
Equation 2.7: Profile Index	18
Equation 2.8: Autocovariance Function	21
Equation 2.9: PSD Estimation	21
Equation 2.10: RMS from Elevation PSD	21
Equation 2.11: Frequency Weighting Function	28
Equation 2.12: Running RMS Acceleration	29
Equation 2.13: RMSVA.....	29
Equation 2.14: Equating Two Different Vibration Exposures.....	30
Equation 2.15: Equivalent Acceleration	30
Equation 2.16: Arc Length.....	32
Equation 2.17: Arc Length for Discrete System.....	33

Equation 2.18: Crest Factor	33
Equation 2.19: Profile 1 st and 2 nd Derivatives	34
Equation 2.20: Suspension Work.....	35
Equation 2.21: Suspension Power	35
Equation 3.1: Equations of Motion for the 7-DOF Vehicle Body.....	49
Equation 3.2: Rewriting Equation 3.1.....	49
Equation 3.3: 7-DOF Wheel Equations of Motion	49

ACRONYMS LIST

AASHO - American Association of State Highway Officials

AEIPR - Accelerometer-Established Inertial Profiling Reference

APG - Aberdeen Proving Ground

ARPMV - Advanced Road Profile Measuring Vehicle

ASTM - American Society for Testing and Materials

ATC - Aberdeen Test Course

ATV - All-Terrain Vehicle

BPR -Bureau of Public Roads

CAR - Center for Automotive Research

CRTC - Cold Regions Test Center

DAQ - Data Acquisition

DOF - Degrees of Freedom

FWA - Frequency Weighted Acceleration

GPS - Global Positioning System

HMMWV - High Mobility Multi-Wheeled Vehicle

ICC - International Cybernetics Corporation

IP - Ingress Protection

IRI - International Roughness Index

IRRE - International Road Roughness Experiment

ISO - International Organization for Standardization

LISA - Lightweight Inertial Surface Analyzer

MPR - Mean Panel Rating

NCHRP - National Cooperative Highway Research Program

OSU - The Ohio State University

OSU-TSMS – The Ohio State University Terrain Severity Measurement System

PCA - Portland Cement Association

PCI - Pavement Condition Index

PI – Profile Index

PSD - Power Spectral Density

PSR - Present Serviceability Rating

RMS - Root Mean Square

RMSVA - Root Mean Square Vertical Acceleration

RN - Ride Number

RPUG - Road Profilers Users Group

RTRRMS - Response-Type Road Roughness Measurement Systems

SAE - Society of Automotive Engineers

TOP - Test Operations Procedure

TRR - Transportation Research Record

TRTC - Tropical Regions Test Center

TSC - Terrain Severity Characterization

UMTRI - University of Michigan Transportation Research Institute

YPG - Yuma Proving Ground

CHAPTER 1

ROAD PROFILE AND ROUGHNESS MEASUREMENT SYSTEMS

1.1 Background

Roadway surface degradation is a problem that has been faced ever since the advent of wheeled travel. With the automobile came mass transit, and the roads have improved, but eventual wear is still ubiquitous. As automobiles have become more sophisticated, the desire for a more comfortable ride is perpetually sought. This is a task taken on by not only the automotive industry, but also local governments. Industry takes the approach of delivering vehicles more adept at attenuating road disturbances; governments are involved in providing well maintained roadways that provide passengers with comfort and improved safety.

The concept of assessing road roughness first began in the United States in the 1950's. A study by Carey and Irick was the first to provide a statistical means of evaluating pavement condition based on subjective responses to a measured profile [1]. This was at the American Association of State Highway Officials (AASHO) Road Test Program, which is accredited as the first to use a zero to five rating system to describe the pavement ride quality. The system was termed the Present Serviceability Rating (PSR), with zero being impassable and 5 being ideal or perfect. CHLOE was the name of the

profiling device used in this study. CHLOE consisted of a one-axle trailer with two smaller wheels that could conform to the slope of the terrain, as shown in Figure 1.1. The angle between the two small wheels was recorded to give the slope as a function of longitudinal position.

Figure 1.1: CHLOE Profiling Device

Figure 1.2: BPR Roughometer

Another measuring device of this early era is the Bureau of Public Roads (BPR) Roughometer. This mechanism, shown in Figure 1.2, accumulated the relative

displacement between the trailer's axle and body. Hence, it was also known as the bump integrator [2, 3]. Many trailers like this have been used since this early model. The use of trailers that measure a response to road roughness is discussed in American Society for Testing and Materials (ASTM) E1215-93 [4]. This also gives specifications for the types of spring rates and damping ratios, tires, and general dimensions that should be utilized in a trailer profiling system.

The 1960's saw continuing attention to the concept of characterizing road roughness with the invention of the road meter [5]. A road meter had the sensors on the actual vehicle. The Mays road meter and the Portland Cement Association (PCA) road meter measure the relative displacement between the rear axle and the sprung mass of the vehicle. CHOLE, the BPR Roughometer, Mays road meter, and PCA road meter are often referred to as Response-Type Road Roughness Measurement Systems (RTRRMS) because they don't measure the profile, they measure a response of some sort and infer roughness from the measurement. For instance, the relative motion of the suspension of the Mays road meter is then accumulated and normalized by distance traveled, giving an output of in/mile or m/km [5, 6, 7, 8]. This value gives a sense for the total slope over an interval, and could imply road roughness. It is also desirable to calibrate these types of systems to give an output that resembles other roughness metrics. Standards for calibrating response type systems are given in ASTM E1448-92 and the National Cooperative Highway Research Program (NCHRP) Report 228 [2, 8, 9].

General Motors developed a new type of profiling system called an inertial profilometer in the 1960's and then sold it to K.J. Law Engineers, Inc. It was the first

profiling device to utilize an accelerometer along with a measurement of the displacement of the unsprung mass. The accelerometer signal was twice integrated, and then had the unsprung mass' displacement subtracted to obtain a filtered profile. This type of system is referred to as an Accelerometer-Established Inertial Profiling Reference (AEIPR) System. A major benefit to AEIPR systems is that they allow for high speed measurements of the real profile [2, 10]. There are currently a number of inertial profilometers available. Four examples are given, along with their computational concepts in Transportation Research Record (TRR) 1348 [12]. ASTM E950-98 also has a set of guidelines for setting up an AEIPR system [11].

Figure 1.3: Response-Type Road Roughness Measuring Systems (RTRRMS)

As technology improves there are also more systems that directly measure the profile. The rod and level method uses a surveyor's static rod and level for measuring the elevation [13]. This is a labor intensive method, with good repeatability, though the level of resolution is low since this method does not allow for a sample interval less than several feet. Several of the latest profilers that measure the terrain via relative displacement of a wheel free to move vertically includes the California type Profilograph,

[14, 15] and the walking profiler [16]. Advances in inertial profilometers include AMES engineering Lightweight Inertial Surface Analyzer (LISA) which computes the most common metrics used for roughness analysis today (these metrics are discussed in detail in Chapter 2). Laser sensors have also dramatically improved the displacement measurements in highway speed applications. Lasers are used by systems such as the International Cybernetics Corporation (ICC) profiler, ProRut, and the Advanced Road Profile Measuring Vehicle (ARPMV) [3, 17]

In 1989 the Road Profilers Users Group (RPUG) was formed. This group set out to develop standards of practice for high speed inertial profile measurements. They have published numerous papers, and focused on the advancement of highway profiling technology through their work.

There are numerous paved-road systems available for profile measurement and roughness calculation. Measuring off-road terrain requires an alternative system. This type of profile is different in several key areas. First, off-road terrain will generally be far more severe. Second, the terrain is generally intentionally severe. These courses are either for durability testing or for off-road recreational vehicles. Also, this type of terrain may consist of many different ground surfaces and soil types. The limited availability of off-road profiling technology is discussed in section 1.2.

1.2 Off-Road Systems

Off-road durability testing is a common practice in industry. The purpose of such testing is to push the limits of a new vehicle or vehicle component. It is desirable to run

these durability tests in a controlled fashion; thus, the test courses are monitored and maintained to give a desired roughness. However, there is currently nowhere near the level of sophistication in off-road testing as with paved-road profiling and roughness measuring systems. Most current systems are specifically for paved-roads, and may not cross over to all-terrain capability either because of limitations of the sensors, or simply because the measurement vehicle is incapable of negotiating the terrain.

Paved-road profiling systems generally adhere to several assumptions that may not hold in off-road scenarios. Such assumptions include linear vehicle models, vehicle models that ignore pitch and roll, and constant speed during measurement and simulation. Also, course profile changes significantly over time, and possibly even after each vehicle makes a pass. Further, the most frequent approach to addressing potholes in paved road profiles is to remove them [18]. Many off-road courses are nothing but potholes, so-to-speak, thus too much information may be eliminated. Another consideration is many highway profiling systems are designed to replicate average highway vehicles [2, 3, 5]. Clearly, a standard four-door sedan will not compare to a large multi-ton military vehicle.

1.2.1 The Aberdeen Test Course Profilometer

The off-road profiler in use by the military is the Aberdeen Test Course (ATC) Profilometer. This profiler has had several iterations, and originally was similar to CHLOE. A truck would pull the trailer which was set up as in Figure 1.4 [19]. The trailer had an inertial gyroscope and two wheels that conform to the terrain. The two wheels each had a potentiometer to measure their relative angle. In the current system, the trailer

has added 2 ultrasonic sensors to measure the height of the terrain at each track. The angle data and height measurements provide a profile. If data is collected correctly, a true profile is obtained. A true profile is one that has been measured within a reasonable range of accuracy, and may be used to accurately calculate the profile's statistics.

Figure 1.4: Geometry illustration of ATC Profilometer tow arm geometry

Since this system was created roughly 20 years ago, data storage was limited. Thus, in real time the data was converted to the spatial domain and then to a Power

Spectral Density (PSD). The PSD was found in blocks of 2048 samples, and then averaged. Once the PSD was obtained, it could be used to calculate the Root Mean Square (RMS) elevation of the profile. This methodology is discussed more in section 2.2.4.

This PSD method provided a reasonable means of tracking the spatial content of a course. Most notably, it is effective at highlighting trends such as wash boarding. All gravel or sandy courses at YPG occasionally experience wash boarding, a regular phenomenon in deserts and other dry regions that is caused by vehicles traveling at similar speeds with similar dynamic properties creating sinusoidal undulations in the earth. The undulations resemble the wavelength of the sprung mass resonance at the speed driven on the course. This is a common problem on desert courses such as at YPG because there is very little rain to help eliminate trends caused by the vehicles.

The ATC Profilometer is one of the few profilers and roughness analysis tools specifically for off-road. Though it was effective, it does leave some areas for improvement. First and foremost, it has to be driven very slowly to avoid dynamics in the trailer. Any unwanted dynamics would cause unwanted oscillations, and thus erroneous measurements since the system sought to directly measure the profile without consideration of trailer dynamics. Another main area for improvement is in data storage. If the courses can have their profile stored, then the same course can be regularly compared to locate potholes that may have been created. This would require having a very precise starting point, but that could be standardized for each course. Further, storing

the data simply allows for more post processing potential, such as loading the profile directly into vehicle dynamics simulators.

A final area for improvement is in the actual transducers. With the advancement of laser displacement sensors and improved inertial reference technology and methods, there may be potential for much faster sampling rates and improved precision. OSU has improved upon this old measurement system, and is reviewed in sections 1.2.2, 2.4 and Chapter 3.

1.2.2 The Ohio State Terrain Severity Measurement System

The system used for the off-road research in this project is the OSU-TSMS. The OSU-TSMS has been developed to meet the needs described in the end of section 1.2.1. The OSU-TSMS will be discussed in detail in Chapter 3. This system is an inertial profiler that utilizes three laser sensors, four accelerometers, a gyroscopic inclinometer, Global Positioning System (GPS), and a Doppler radar speed sensor. The aim of this profiler is to incorporate the dynamics of the baseline vehicle and calibrate the entire system such that the measurements may be made at alternating speeds over the most severe terrain. An objective is to be capable of profiling all of the courses at the Aberdeen Proving Ground (APG) and YPG. Both these facilities have some fairly severe courses that are used for endurance and durability testing of all the military's vehicles.

1.3 Conclusion

Though there are suitable systems and methods for assessing the roughness of paved-roads, they are not sufficient for off-road terrain. The type of terrain of interest is extremely severe, such that most highway legal vehicles can not cross it. Many automotive companies and the U.S. Army are heavily involved in testing vehicles on such extreme terrain. Thus there is a need for a new system specifically designed to profile and characterize the severity of these intensely rough courses.

The OSU-TSMS was designed with these courses in mind. Once the course is profiled, the methodology developed herein completely characterizes the severity of the terrain. Chapter 2 reviews roughness metrics of the paved-road community and explores some new metrics that may be insightful given off-road profile data. Chapter 3 gives an overview of the instrumentation and basic methodology for the OSU-TSMS. This is a brief review, as other papers will be published to thoroughly detail the OSU-TSMS system. Chapter 4 gives five examples of courses at YPG, and two highway courses as case studies of off-road and pave-road TSC. This methodology is suitable for any profiled course, and is demonstrated on these seven profiles to illustrate the reporting procedure. In the end, a recommended procedure for defining TSC is outlined with some suggestions for areas that need further investigation.

CHAPTER 2

ROUGHNESS CALCULATIONS

2.1 Introduction

Roughness is a measure of the deviations in a road surface from a true planar surface that affects vehicle dynamics and ride comfort. There are currently numerous methods to characterize roughness of paved-roads, and the most prevalent are reviewed in section 2.2. This is followed by a few new concepts in section 2.3 that can be used to give insight to the ride quality of terrain and the damage seen by the vehicle. Sections 2.4 and 2.4 discuss the current off-road systems: the ATC profilometer and the OSU-TSMS, respectively.

2.2 Paved-Road Considerations

There are a variety of metrics, both subjective and quantitative, for assessing paved-road wear and condition. Generally, subjective metrics involve experienced technicians grading pavement quality based on number and size of various deformities, such as cracking, bumps and potholes [23]. Other subjective measures are dynamic and involve test subjects rating the quality of ride [5]. Usually a scale of 0 to 5 is used, with zero being impassable and 5 being perfectly smooth.

Quantitative roughness measurements are produced through two broad methods: measuring the profile and then calculating a statistic to describe the level of roughness, or by directly taking a measurement that may be calibrated or inferred to a roughness level. If it is the true surface profile being measured, then the quantitative measurements often incorporate some sort of vehicle dynamics model [20, 21]. Such is the case for systems that calculate metrics like the International Roughness Index (IRI) and Ride Number (RN). Both of these metrics utilize a quarter-car model to filter the profile and simulate a vehicle response. RTRRMS measure either the axle acceleration, or the relative displacement between the sprung and unsprung masses. Then, the roughness is inferred from these measurements. For instance, the relative displacement between the sprung and unsprung masses may be accumulated, and then divided by the total distance traveled. This measurement gives a metric that is characteristic of the total displacement of the suspension, and thus the total work done by the suspension over a certain distance traveled by the vehicle. It is inherently similar to metrics like IRI, and thus may be calibrated to output a value that is in the same scale as IRI [12]. IRI and RN are discussed in detail in the sections 2.2.2 and 2.2.3.

In the frequency domain, any number of measured values can be analyzed by their PSD. Acceleration, surface profiles, or relative displacement of the suspension all make good candidates for a PSD evaluation. PSD provides a means of tracking the frequency content of a profile. For more stationary terrain like paved-roads, averaging techniques will provide a PSD that is a good record of the frequency content. For non-stationary

data, PSD may be used to view waterfall plots. These details are discussed in section 2.2.4.

There are other roughness metrics that look at the acceleration of the sprung mass for a sense of the ride quality [29]. This is logical since human subjects will perceive ride quality based on the frequency of vibration of the sprung mass. International standards suggest filtering the sprung mass acceleration using a band-pass filter that is representative of human sensitivity to vertical accelerations. Section 2.2.5 covers this topic.

2.2.1 Pavement Condition Index

A most basic method for surveying the condition of pavement is described in ASTM D6433-03 [23]. This method outlines a matrix which reviews segments of roadway or parking lots. The pavement to be reviewed is divided into 25 foot slabs. Then the condition of each partition is rated based on the types of defects and the degree of severity of the particular defects. Types of defects noted include alligator cracking, bleeding, bumps, sags, corrugation, potholes, etc. The defects are generally rated as low, medium, or high, which are separated by the size and number of defects per partition. Once the matrix has every type of defect noted, a deduct value is given. The deduct value is subtracted from 100 to give the Pavement Condition Index (PCI). The lower the PCI, the more severe are the deformities in the pavement and repair is recommended.

2.2.2 International Roughness Index

IRI is a metric based on the response of a quarter-car model to a single profile. The calculation accumulates the relative velocity of the sprung and unsprung masses and normalizes by the profile length. This concept was standardized in the 1982 experiment in Brazil known as the International Road Roughness Experiment (IRRE) [63, 64]. Once a profile is measured, the output is processed through several steps to obtain IRI. First the profile is smoothed with a 9.8425 in (250 mm) moving average filter which is defined as [24, 25]:

$$h_{ps}(i) = \frac{1}{k} \sum_{j=i}^{i+k-1} h_p(j)$$

Equation 2.1: Moving Average Filter

$$k = \max[1, \text{round}(L_B/\Delta)]$$

h_p = profile height

h_{ps} = smoothed profile height

$\max$ = maximum of two arguments

round = MATLAB command to find the nearest integer,

L_B = moving average base length, 9.8425 in

Following the moving average filter, the profile is again filtered by using a quarter-car model.

c_s = suspension damping rate

k_s = suspension spring rate

k_t = tire spring rate

m_s = sprung mass

m_u = unsprung mass

h_{ps} = smoothed profile elevation

z_s = sprung mass height

z_u = unsprung mass height

Figure 2.1: Quarter-Car Model and System Parameters

The state space equations for the system are:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}h_{ps}$$

$$c = c_s/m_s = 6.0$$

$$\mathbf{x} = [z_s, \dot{z}_s, z_u, \dot{z}_u]^T$$

$$k_1 = k_t/m_2 = 653$$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_2 & -c & k_2 & c \\ 0 & 0 & 1 & 0 \\ \frac{k_2}{\mu} & \frac{c}{\mu} & -\frac{k_1 + k_2}{\mu} & -\frac{c}{\mu} \end{bmatrix}$$

$$k_2 = k_s/m_s = 63.3$$

$$\mu = m_u/m_s = 0.15$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & \frac{k_1}{\mu} \end{bmatrix}^T$$

Equation 2.2: State Space Equations and Parameters for the Quarter-Car Model

These standard parameters for the quarter-car are based on the suspension of the BPR Roughometer, known as the “Golden Car” [3, 35]. This was set as the standard for IRI during the IRRE.

To solve the ordinary differential equations, IRRE recommends using a state transition matrix with partial responses:

$$\mathbf{x}_i = e^{\mathbf{A}\Delta/V} \mathbf{x}_{i-1} + \mathbf{A}^{-1}(e^{\mathbf{A}\Delta/V} - \mathbf{I})\mathbf{B}u$$

Equation 2.3: Solution to ODE of Quarter-Car Model

where the state transition matrix, $e^{\mathbf{A}\Delta/V}$, can be solved by:

$$e^{\mathbf{A}\Delta/V} = \mathbf{I} + \sum_{i=1}^N \frac{\mathbf{A}^i (\Delta/V)^i}{i!}$$

Equation 2.4: State Transition Matrix

Once the response is found by solution of this ODE, then IRI may be found as:

$$IRI = \frac{1}{L} \int_0^T |\dot{z}_s - \dot{z}_u| dt$$

Equation 2.5: International Roughness Index (IRI)

This is further defined by Sayers [25] and a standard is given in ASTM E1926-98 [24]. Both of these references also give a FORTRAN code to make the calculations. The University of Michigan's Transportation Research Institute (UMTRI) has contributed much to the research of terrain roughness characterization for highway applications. They also provide several free downloads on their website (the main page is: <http://www.umtri.umich.edu/> and the free downloads are available at <http://www.umtri.umich.edu/erd/roughness/index.html>). A download of interest is the

RoadRuf program which computes a profile's IRI and overall RN. They also have made available FORTRAN code to compute IRI and RN.

To gain familiarity for the range of outputs and the subjective interpretation of IRI for unpaved measurements, Table 2.1 is provided [24].

IRI [m/km]	IRI [in/mi]	Description
0	0	Recently bladed surface of fine gravel, or soil surface with excellent longitudinal profile
2	126.7	
4	253.4	Ride is comfortable up to 80-100 km/h with perception of gentle undulations, and no severe bumps or potholes
6	380.2	
8	506.9	Ride comfortable up to 80km/h. There may also be shallow potholes and some wheel bounce
10	633.6	
12	760.3	Ride comfortable at 50km/h with frequent depressions, occasional deep potholes, and possibly strong wash board
14	887.0	
16	1014	Ride comfortable 30-40km/h with frequent deep depressions or potholes. It is not possible to avoid all depressions
18	1141	
20	1267	Ride comfortable at 20-30km/h. Speeds higher than 40km/h would cause extreme discomfort and may damage the vehicle. Frequent deep depressions (40-80mm with 10-15 per 50m)
24	1394	

Table 2.1: IRI Scale for Gravel or Other Unpaved Roads

2.2.3 Ride Number

RN is based upon studies of a subjective nature. Two studies by the Ohio Department of Transportation, in 1983 and 1988, focused on the subjective response of 36 panel members [5]. The panel members were instructed to rate the ride comfort based on the guidelines listed in of Table 2.2 and further defined in ASTM E1927-98 [26]. These ratings were then used to find a Mean Panel Rating (MPR). The results of these two tests were then used to define RN as a transformation to convert a measured profile to a value between zero and five that correlates to subjective ride quality. The calculations are as follows:

$$RN = 5e^{-160(PI)}$$

Equation 2.6: Ride Number (RN)

$$PI = \sqrt{\frac{PI_L^2 + PI_R^2}{2}}$$

Equation 2.7: Profile Index

Description	RN
Perfect	5.0
Very Good	4.5
	4.0
Good	3.5
	3.0
Fair	2.5
	2.0
Poor	1.5
	1.0
Very Poor	0.5
Impassable	0.0

Table 2.2: RN Scale Description

$$c = c_s/m_s = 17$$

$$k_1 = k_l/m_2 = 5120$$

$$k_2 = k_s/m_s = 390$$

$$\mu = m_w/m_s = 0.036$$

Table 2.3: RN ¼ Car Parameters

Profile Index (PI) is found by filtering the left and right profiles with a quarter-car model similar to that of IRI. The exception is in the parameters, as shown in Table 2.3, and results in the filter shown in Figure 2.2. PI_L and PI_R are defined as the RMS of the filtered slopes of the measured elevation. So, it is essentially the same concept as IRI, only the gain on the filter has an emphasis on a different range of wave numbers, and the final value is logarithmically transformed to fall on a scale of zero to five [5, 39, 40, 41]. The most detailed description of RN may be found in NCHRP 275, though some details are still missing [42]. A FORTRAN code may be found at UMTRI's website to run the calculation.

Using Table 2.2, it is important to define the extremes. Perfect is a road so smooth that it seems unlikely to create a smoother ride. The passenger can hardly tell they are traveling on a road at all. Impassable is a road so harsh that the speed must be drastically reduced to avoid discomfort or even damage to the vehicle and/or passengers [39]. Note that this scale is also intended for the highway community in an average highway vehicle. Thus, the comfort level would have to be adjusted for larger off-road vehicles that inherently have a rougher ride, and are capable of comfortably traversing far more severe terrain.

Figure 2.2: Wave number response of the quarter-car filter used in RN

2.2.4 Power Spectral Density

The PSD function was previously used in analysis for the ATC Profilometer. The profilometer would define the spatial coordinates of the profile, and then calculate the PSD. The PSD of the terrain may be proportional to the energy absorbed by a vehicle traveling over the profile, thus giving a good measure of the roughness [19]. General trends of the PSD plot lead to a perception of the roughness of the profile. The total area under the curve can be used to find the elevation RMS and will give an idea of the overall course roughness. A steep slope will indicate that the lower frequencies are exerting much more energy. A shallow slope will indicate the higher frequencies are contributing more [27].

For ground surfaces, the PSD can be described as the Fourier transform of the autocovariance function. [27]. The autocovariance function is defined as:

$$R(x') = \lim_{s \rightarrow \infty} \left[\frac{1}{2X} \int_{-X}^X z(x)z(x+x')dx \right]$$

Equation 2.8: Autocovariance Function

and the Fourier transform and thus PSD is:

$$S_g(\Omega) = \frac{2}{\pi} \int_0^\infty R(x') \cos(\Omega x') dx$$

Equation 2.9: PSD Estimation

where x is the longitudinal distance, z is the profile elevation, and Ω is wave number in units of cycles/ft [22, 28].

It is possible to find the elevation's RMS value from the PSD:

$$RMS = \left[\int_{\nu_1}^{\nu_2} PSD d\nu \right]^{\frac{1}{2}}$$

Equation 2.10: RMS from Elevation PSD

where PSD is in ft^3 and $d\nu$ is the incremental wave number. The integral is taken from 1 to 60 feet since these are the wavelengths of greatest concern to vehicle dynamics. This converts to wave numbers of 0.0167 to 1 cycles/ft [19].

In MATLAB, the function ' $[Pxx, w] = pwelch(z, window, noverlap, nfft, fs)$ ' may be used to approximate the PSD. This function breaks the data up into segments to find

average values for the total PSD. The segments may be windowed using a Hamming window with the number of points defined by *window*. Windowing eliminates effects of leakage, which can cause resonant peaks to become attenuated. The data windows may overlap by *noverlap* sample points. The overlap will allow for more averaging, and provides the benefit of more of a sliding window. To determine the number of points of the FFT, *nfft* is specified. Finally, the sampling frequency is f_s , and is determined from the inverse of the profiling systems sampling period. The averaging technique is similar to that used in the ATC Profilometer. Windowing and averaging the data will increase the usefulness of the results of the PSD, given the data is stationary [22].

The PSD was found for some data given from YPG in Figure 2.3. The course was profiled using the ATC Profilometer before and after the course was graded. Courses at YPG may be groomed if undesirable trends appear, such as wash boarding. The PSD clearly shows attenuation in amplitude at the wave numbers where wash boarding is most significant.

Figure 2.3: Demonstration of Change in PSD after Grading a Course

One caution with use of PSD is these average values hide deviations in the true data in the presence of non-stationary data [22, 45]. Data may be wide sense stationary if the mean is constant and the covariance is shift invariant. It is recommended to keep the data as stationary as possible when collecting. This can be done in two ways. The speed of travel should be kept nearly constant, and the data should be broken up by sections of similar terrain. It should be noted that these two concepts tend to coincide. For instance, on the test course, there may be a straightaway where it is easy to maintain a constant velocity. This section would be analyzed separately. Then, following the straightaway, there may be an area where the terrain becomes more severe and thus speed must be

reduced. This section should again be analyzed separately. So by observing the speed data, the entire course can be broken into areas of similar speed, which can correlate to areas that have similar statistics, and similar levels of severity, therefore increasing the relevance of the PSD.

As an example, a particular course at YPG known as Desert March consists of numerous sections of similar terrain. There are multiple lengths that are known as relic beach terraces, which consist of a fine, sandy soil. This is broken up by sections through washes, which are dried up streams that consist of deep gravel. There are also hills that climb in and out of the wash, and between terraces. When traversing this course, it is easy to notice that speed is highly dependent on the section. The wash only allows a moderate speed due to the excessive amount of slip at the tires. The terraces allow much more traction and thus a higher velocity is attainable. Riding these courses also will give a sense for the similarity in roughness of these different sections. The terraces all feel very similar, as do the washes. It would be a fairly simple task to divide the course into appropriate sections when calculating the PSD. So for Desert March, the course would be broken into three class sections: beach terrace, hills, and washes. Each class could then have the PSD found by simply adding the similar sections together as if it were a continuous profile.

Breaking the course into sections based on speed is viable for the OSU-TSMS since the data collected will include a speed measurement. However, if the course is already profiled, such as with the data discussed in Chapter 4 from YPG, then the entire course may be assumed to have constant speed in analysis, though sections of varying

severity could be averaged together. Breaking the course into like sections is only a suggestion to improve the analysis results.

2.2.4.1 Waterfall Plots

Another approach to avoiding averaging an entire course is to use a waterfall plot to show the PSD over smaller sections. Figure 2.4 shows a waterfall plot for the YPG course Laguna Level Trails East. This course is five miles long, so a PSD of the entire course that uses averaging will eliminate a lot of information. By breaking the course into smaller sections, the averaging may be reduced. This could prove useful, but care must be taken in breaking the course up, and in presentation of the plot. It is easy to make the plot far too congested to even decipher between sections. This type of plot leads to the possibility for several other concepts. For instance, the course could be divided into mile long sections. Then, each mile long section could have a waterfall plot divided into fifths. This would still allow enough data to use averaging. Of course, when it comes to data presentation of this nature, it is up to personal preference to decide the final analysis provided. The methodology for TSC provided only recommends using PSD, and if possible, dividing a course into similar sections.

Figure 2.4: Waterfall Plot for Laguna Level Trails East

2.2.4.2 Wavelet Analysis

Wavelet analysis presents another frequency domain method of viewing time data. The advantage to wavelet analysis is it allows for simultaneous adjustments of frequency and time resolution. It is similar to Fourier series analysis. Fourier series analysis describes a time signal as a summation of an infinite number of sinusoids. Wavelet analysis tweaks this concept by describing the time signal by a series of wave-like functions that may be stretched or compressed as needed to describe the data.

The equations will not be divulged, as there is an adequate toolbox in MATLAB which may be used for 1-D and 2-D analysis. The study of wavelets in the field of road roughness found it is very useful in identifying the locations and relative frequencies of surface bumps and distress [66]. However, the method developed in Chapter 4 is able to identify the locations of surface bumps and more. Thus, this analysis tool is not recommended for off-road use.

2.2.5 Frequency Weighted Root-Mean-Square Vertical Acceleration

There have been several methods developed that analyze a profile based on the response that an average human body would experience during travel [29, 30, 31]. This type of analysis requires a frequency weighting function to represent the human response. The International Organization for Standardization (ISO) standard number 2631-1 gives several weighting functions based on the orientation of the human with respect to the vibration direction. For this analysis, the type of vibration of concern is whole-body vibration in the vertical direction while a person is in a standard automotive seat. The band-limited weighting function shows sensitivity between 0.5 Hz and 80 Hz. It is represented by four transfer functions in the frequency domain such that the total weighting function is:

$$H(p) = H_h(p)H_l(p)H_t(p)H_s(p);$$

where the individual components are defined as:

$$H_h(p) = \frac{s^2}{s^2 + \sqrt{2}\omega_1 s + \omega_1^2}; \quad H_l(p) = \frac{1}{\frac{s^2}{\omega_2^2} + \frac{\sqrt{2}}{\omega_2} s + 1};$$

$$H_t(p) = \frac{\frac{s}{\omega_3} + 1}{\frac{s^2}{\omega_4^2} + \frac{s}{Q_4 \omega_4} + 1}; \quad H_s(p) = \frac{\frac{s^2}{\omega_5^2} + \frac{s}{Q_5 \omega_5} + 1}{\frac{s^2}{\omega_6^2} + \frac{s}{Q_6 \omega_6} + 1}$$

Equation 2.11: Frequency Weighting Function

For a human subject sitting in a vehicle's seat and being exposed to whole body vibration in the vertical direction, the parameters are given in Table 2.4, and the filter is seen in Figure 2.5.

ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	Q_4	Q_5	Q_6
[rad/sec]	[rad/sec]	[rad/sec]	[rad/sec]	[rad/sec]	[rad/sec]			
0.8π	200π	25π	25π	4.74π	6.7π	0.63	0.91	0.91

Table 2.4: Parameters for the Frequency Weighting Transfer Functions

The weighting is applied to an acceleration signal, which may be the acceleration of the sprung mass, as measured from accelerometers on the vehicle, or calculated from a vehicle model. This is known as the Frequency Weighted Acceleration (FWA). Once the acceleration is filtered, then the RMS of the acceleration is calculated over a running window of duration τ :

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)]^2 dt \right\}^{\frac{1}{2}}$$

Equation 2.12: Running RMS Acceleration

RMS for the entire profile, known as the Root-Mean-Square Vertical Acceleration (RMSVA), may be found by setting τ to the total length of time being analyzed, T .

$$a_{w,RMS} = \left\{ \frac{1}{T} \int_0^T [a_w(t)]^2 dt \right\}^{\frac{1}{2}}$$

Equation 2.13: RMSVA

Figure 2.5: Frequency Weighting Curve from ISO 2631-1

Using some energy concepts, two different exposures to vibration may be related by:

$$a_{w,1}T_1^{1/2} = a_{w,2}T_2^{1/2}$$

Equation 2.14: Equating Two Different Vibration Exposures

where $a_{w,1}$ is the vibration exposure and T_1 is the time duration of exposure.

To find an equivalent acceleration based on multiple acceleration magnitudes and on the length of time exposed to the vibration use Equation 2.15 [29].

$$a_{w,e} = \left[\frac{\sum a_{wi}^2 T_i}{\sum T_i} \right]^{1/2}$$

Equation 2.15: Equivalent Acceleration

Similarly, from TRR 774, the acceleration limits listed in Table 2.5 were found for a human subject in a vehicle's seat, facing forward, with a footrest, and with the seat pan at different tilt angles [32]. The seat back was set to 97° from the seat pan.

Seat Tilt [°]	Corrected Deceleration Levels [g]			
	Without Footrest		With Footrest	
	50% Retention	84% Retention	50% Retention	84% Retention
0	0.35	0.30	0.38	0.33
3	0.34	0.28	0.41	0.31
9	0.38	0.31	0.41	0.36
12	0.43	0.33	0.46	0.36

Table 2.5: Acceleration Limits for a Human Subject

The columns of Table 2.5 give the percent of passengers that remained fully retained for the given acceleration level. The footrest was bolted to the floor in front of the seat.

Figure 2.6: Health Caution Zones for Vibration Exposure.

The TSC method suggests accumulating accelerations above 0.28 g, (84% retention, 3° seat tilt) and calculating the equivalent acceleration using Equation 2.15. This procedure will be explored in detail in Chapter 4. Using concepts associated with RMSVA, health guidelines may be administered. Knowing the duration of vibration exposure, and the equivalent acceleration, Figure 2.6 may be accessed to determine if

there is potential for health hazards or fatigue. The main concept is to avoid allowing personnel to exceed these limits.

2.3 Off-Road Considerations

Sections 2.3.1 through 2.3.4 provide some new metrics for potential use in off-road systems, and for severity determination in the OSU-TSMS. These metrics were decided upon after much contemplation as metrics that may give a new look at the profile data. Furthermore, the remainder of Chapter 2 reviews the limited availability of current off-road systems, and covers the recommended procedure for off-road TSC for the OSU-TSMS.

2.3.1 Arc Length

For spatial data, it is easy to visualize the profile roughness as a function of arc length. Arc length is defined as [33]:

$$s(t) = \int_a^b \left| \frac{d\vec{R}}{dt} \right| dt$$

Equation 2.16: Arc Length

where $\vec{R}$ is the profile as a function of longitudinal distance and time.

For smooth profiles, the arc length will be nearly equivalent to the longitudinal distance traveled. For rough, off-road terrain, it is easy to see that the arc length will increase as the profile becomes more sporadic over a certain span.

For the discrete profile obtained by profilometers, the arc length may be defined as:

$$s(k) = \sum_{n=1}^{n=k} \sqrt{\Delta x_n^2 + \Delta z_n^2}$$

Equation 2.17: Arc Length for Discrete System

where k is the discrete index, x is the longitudinal distance traveled and z is the profile elevation.

2.3.2 Crest Factor

Crest factor is a metric used in the machining industry and in electronics to assess large spikes above the RMS value. It is defined as the peak value in a span divided by the span's RMS value [31]:

$$CF = \frac{Peak}{RMS}$$

Equation 2.18: Crest Factor

This metric is convenient in situations where there is a very stable RMS value occasioned by a large disturbance, and may be helpful in analysis of large profile deformations.

2.3.3 Spatial Derivatives

In reviewing profile terrain, it may prove useful to examine the derivatives of the profile in the spatial domain. The first derivative is the profile slope, and the second derivative is the rate of change of the slope.

$$\dot{z}(k) = \frac{z(k+1) - z(k)}{\Delta x} ; \quad \ddot{z}(k) = \frac{z(k+2) - 2z(k+1) + z(k)}{\Delta x^2}$$

Equation 2.19: Profile 1st and 2nd Derivatives

Profile slope gives the rate of change of the profile elevation, thus a sense of the dynamic input seen by the tire. This type of measurement was used by profilometers like CHLOE to give a roughness metric. Mathematically, zero crossings of the first derivative also show maxima in the profile, thus points where the suspension could change from compression to extension, and vice versa.

2.3.4 Suspension Forces

Using vehicle dynamics models it is possible to examine estimates of the forces seen in the suspension system. ASTM E1170-97 provides 3 vehicle models (quarter-car, half-car, and full-car) and explains that they are commonly used to find IRI, RN and RMSVA [20]. ASTM E1170-97 suggests using the relative motion between the sprung and unsprung masses from the 1/4- or 1/2-car models as a roughness indicator, thus finding either IRI or RN. If the full-car model is used, it is suggested to analyze the sprung mass acceleration, and therefore RMSVA as the indicator of overall roughness. The 7 Degree of Freedom (DOF) full vehicle model discussed in section 3.2 provides an adequate

model to evaluate suspension forces considering the profile input and the effects of pitch and roll [34]. A simulation model was developed in MATLAB/Simulink, and details of this model are given in Appendix A. This model is used to find the suspension's forces and relative motion.

The relative force of the suspension gives the compressive forces between the axle and chassis. Using a detailed model, such as the 7-DOF model, it is simple to extract the relative force data along with the relative displacement. The relative displacement may be differentiated to find the relative velocity. This leads to two simple calculations to find the work done by the suspension and the associated power [67]:

$$Work = \vec{F} \cdot \vec{d} = \vec{F} \cdot (\vec{z}_s - \vec{z}_u)$$

Equation 2.20: Suspension Work

$$Power = \vec{F} \cdot \vec{v} = \vec{F} \cdot (\dot{\vec{z}}_s - \dot{\vec{z}}_u)$$

Equation 2.21: Suspension Power

Figures 2.7 and 2.8 show the relative motion and force as predicted by a 7-DOF model in response to a highway profile. Only a 100-ft window is shown so the relationship between force and velocity may be easily seen: they are always out of phase. The profile, known in this report as ProRuts section 6, is further discussed in Chapter 4.5. The usefulness of the interpretation of the work and power calculations is discussed in conjunction with examples in Chapter 4.

Figure 2.7: Relative Suspension Displacement and Velocity from 7-DOF Model

Figure 2.8: Example of Relative Suspension Force from 7-DOF Model

2.4 ATC Profilometer

This system was discussed in section 1.2.1. This section will review the metrics calculated. There are two methods used by the U.S. military to quantify their courses' roughness. One approach used is the passengers of an High Mobility Mult-Wheeled Vehicle (HMMWV) are suited with accelerometers on their chests. A trained driver will navigate the courses, and the passengers will note when, where, and how frequently they are subjected to accelerations over 0.5, 1.0 and 2.0 g's. This is a straightforward approach to a subjective concept. Since the courses at APG and YPG are used for durability testing, it is desirable to keep them at a known level of severity. Each course has upper and lower limits for the number of times the passengers may breach the three specified acceleration values. To control some of the variables, routine is incorporated in the test runs: the same driver is to be used, as is the same vehicle, with the same tire pressure, shock absorber pressure, and the same passengers, or at least passengers of similar stature [19].

The second method utilized by the military is to actually measure the course profiles with the ATC Profilometer. From the measured profile, several steps may be taken. One use of the measured data is to simply map the coordinates of the measured elevation. More desirable is the PSD computation. Before the PSD is calculated, the profile is detrended by a high pass filter. It is again noted that the profile must be measured at low speeds to avoid adding dynamics to the tow arm. This means the courses can only be profiled at speeds of less than 10 mph. Military Test Operations Procedure (TOP) 1-1-010 also gives some PSD plots from the APG courses.

2.5 OSU-TSMS Severity

This section details the ambitions of the OSU-TSMS research effort. The actual measurement system and the methodology for producing a profile from the sensor outputs are described in detail in Chapter 3.

Though the research project has a wide variety of overall goals, the area of research that this paper focuses on is giving OSU-TSMS a method to determine comparative roughness of military test courses at the various military proving grounds (APG, YPG, Cold Regions Test Center (CRTC), Tropic Regions Test Center (TRTC)). Also, if possible, the method defined by this paper should provide data for correlation to other roughness calculations for comparison.

In light of the statement of work's deliverables, this paper used available profile data of the YPG test courses obtained from the ATC Profilometer. This data was analyzed using all known roughness metrics. Further, an in-depth literature review provided the background necessary to determine which metrics, or combinations thereof, that provide the clearest definition of the level of terrain severity. Special care needs to be taken to emphasize that the courses that will utilize this system are far more severe than any paved-roadway that most previous systems have measured. Many assumptions utilized in paved-road systems no longer apply, such as constant speed, linear models, and small pitch and roll angles.

2.6 Conclusion

This paper concludes with a complete methodology for reporting the severity of the terrain. Though highway roughness measuring systems tend to produce a single metric that is used to determine the pavement condition, this research has found that a single metric will prove insufficient to completely characterize off-road terrain. Instead, the off-road TSC report will focus on three main factors of terrain severity: profile frequency content, sprung mass contribution to ride comfort, and action of the suspension system. It is postulated here, that reporting on these three factors gives a complete understanding of off-road course condition. Reporting guidelines will be discussed further in Chapter 4, and will be accompanied by seven sample courses from YPG and RPUG that will be characterized.

CHAPTER 3

TERRAIN SEVERITY MEASUREMENT SYSTEM

3.1 Introduction

Before going into further detail about the analysis of off-road terrain profile data, some time must be spent describing the vehicle platform, the sensors, and the data acquisition used to measure the terrain profile. Also, the post processing to obtain a profile from the sensors is only referenced since other papers are being written concurrently. This section provides an overview of the type of hardware, software, and ATV required to produce an effective off-road profiler. An important consideration is durability of all equipment since this system is intended for use in deserts, tropical regions, and polar regions.

3.2 Hardware and Vehicle Platform

The OSU-TSMS is the basis for the prototype outlined in this section. The vehicle platform used is the Polaris® Ranger 6x6. This ATV has 3 axles with all-wheel-drive traction control that can engage the front axle when the two rear axles slip. It has an open payload, which will provide ample room for mounting all enclosures that house the

necessary electronic equipment. Additionally, the frame allows for easy mounting of sensors with minor modifications. The baseline vehicle is shown in Figure 3.1.

Figure 3.1: Baseline Polaris 6x6 ATV

The instrumentation used in this system must all be capable of withstanding some extreme conditions, especially on a vehicle with such an open-air design. The most important sensors for an inertial profilometer are the displacement sensors and the accelerometers. The displacement sensors chosen were the LMI Selcom[®] laser sensors, model number SLS 6725/1000. The mandatory standoff for the sensors is 39 in and the measurement range is 29 in. Paved-road systems generally have significantly lower standoff. The reason for a high standoff is to avoid damaging the equipment while

crossing large bumps and being subjected to times of extreme pitching. The lasers also have a resolution of 0.007 in at worst, with a typical resolution of 0.0007 in. The benefit of these laser sensors lies in their sampling frequency of 16 kHz, which gives flexibility in the speed the vehicle is traveling, and at low enough speeds could allow for averaging to down-sample to the desired sample frequency which is 1-3 in. Furthermore, the sensors are packaged in either IP64 or IP65 cases to protect against all dust and moist moisture with exception to submersion or powerful jets. The Ingress Protection (IP) scale denotes protection from solid and liquid intrusion. The first number represents resistance to dust, and is scaled from zero to six, six being impenetrable. Similarly, the second number represents resistance to dust, and is scaled from zero to eight.

The four accelerometers used in the OSU-TSMS are the Endevco[®] model 7290A-50. They have a range of $\pm 50g$ and sensitivity at 100Hz of 40 mV/g. From the perspective of durability, these accelerometers may withstand a static acceleration of 20,000 g, a sinusoidal excitation of 100g peak from 20-2,000Hz, and a random vibration of 40g RMS from 20-2,000Hz. They also only exhibit a $\pm 2.0\%$ shift in full scale output over a temperature range of -13°F to 167°F, and are rated to operate from -65°F to 250°F.

Another sensor of importance is the inclinometer. The OSU-TSMS uses the MicroStrain[®] 3DM-GX1-SK gyro enhanced 3-axis orientation system. This is used to gather vehicle pitch, roll, and yaw data. The mounting of the inclinometer, accelerometers, and lasers is illustrated in Figures 3.3 and 3.4.

Figure 3.2: LMI Selcom® Laser Dimensions and Illustration of Triangulation

Figure 3.3: Sensors Mounting Locations (Side View)

The last sensor required is a speed sensor, which is shown in Figure 3.5. Speed data may be obtained in a variety of different ways. For the OSU-TSMS, a Doppler radar speed sensor, the ADAT[®] DRS-6, is used. This sensor may be mounted on any side of the vehicle. Speed data is necessary to convert between temporal and spatial domains.

Figure 3.4: Sensors Mounting Locations (Top View)

Figure 3.5: ADAT DRS-6 Speed Sensor and Mounting Location on Side of Vehicle

The data acquisition system used consists of a laptop equipped with LabVIEW[®] software and a National Instruments[®] Data Acquisition (DAQ) card. The laptop is the rugged Panasonic[®] TB-29, which is moisture/dust resistant, and has an anti-glare screen. The sensors require a DC power supply, so EaglePicher[®] 12V batteries were used. In order to recharge the batteries and run the AC equipment, a power inverter/charger was used. These pieces of electrical equipment needed to be protected from the environment, since they would be housed in the ATV's open-air truck bed. To protect the batteries, a battery box from Todd Marine Products[®] was used. It provides protection from the ambient environment and ventilation. For the inverter and other electrical equipment, a Hoffman[®] type 4x corrosion resistant solid-door fiberglass enclosure was used. This is rated at IP67, but the box had to be modified to include fans for ventilation. The fans chosen were Hoffman filter fans, which reduce the rating to IP 54.

For highway measurement systems, there are levels of classification based on stationary sensor accuracy in place. This may be reviewed in ASTM E1656-94 [44]. This guideline gives ranges of measurement accuracy for vertical measurement, longitudinal sampling rate, and transverse sampling. Transverse sampling is simply the number of profiles collected. A number is given to define the profilometer accuracy, and for longitudinal profilometers looks like: $LX_1X_2X_3$, where L indicates it is a longitudinal profilometer, and X_1, X_2, X_3 , are defined in Table 3.1.

X_1	Vertical Measurement	<i>Stationary Repeatability Precision</i>	
		1	Less than or equal to 0.004 in
		2	Greater than 0.004 in to 0.008 in
		3	Greater than 0.008 in to 0.020 in
		4	Greater than 0.020 in
X_2	Longitudinal Sampling	<i>Sampling Interval</i>	
		1	Less than or equal to 1 in
		2	Greater than 1 in to 6 in
		3	Greater than 6 in to 12 in
		4	Greater than 12 in
X_3	Transverse Sampling	<i>Number of Profiles per Pass</i>	
		1	3 or more profiles
		2	2 profiles
		3	1 profile

Table 3.1: Labeling Nomenclature for Systems Measuring Longitudinal Profile

From this standard, OSU-TSMS may be classified as a L111 profiler in normal conditions or L211 in the worst case scenario.

3.3 Profile Measurement

The measured output will be used to provide an approximation of the profile. The vehicle may be modeled as a transfer function between the road input and the measured displacement, acceleration, and angle outputs. Using a 7-DOF model, an inverse function

was developed to convert the measured values to the profile. This paper does not focus on this process; rather this paper assumes there are two main sets of data: the calculated profile, and the measured data directly from the instrumentation.

The 7-DOF used in the inversion procedure is also useful in post-processing, much as the quarter-car model is useful in IRI and RN. The 7-DOF model is given in Figure 3.6.

Figure 3.6: 7-DOF Model

Next, the equations of motion are developed. Define:

$z_w = \begin{bmatrix} z_{w1} \\ z_{w2} \\ z_{w3} \\ z_{w4} \end{bmatrix}$	z_w = Wheel Displacement 1 = Front Left 2 = Front Right 3 = Rear Left 4 = Rear Right	
$q = \begin{bmatrix} h \\ r \\ p \end{bmatrix}$	h = heave r = roll p = pitch	
$z_b = \begin{bmatrix} z_{b1} \\ z_{b2} \\ z_{b3} \\ z_{b4} \end{bmatrix}$	z_b = body displacement at the corners	
$H = \begin{bmatrix} 1 & l_{y1f} & -l_{x1f} \\ 1 & -l_{y1f} & -l_{x1f} \\ 1 & l_{y1r} & l_{x1r} \\ 1 & -l_{y1r} & l_{x1r} \end{bmatrix}$	Transformation matrix to relate the body motion to the corner position	$l_{x1f} = 3.762$ ft $l_{x1r} = 4.697$ ft $l_{y1f} = 2.413$ ft $l_{y1r} = 2.421$ ft
$z_{rp} = z_b - z_w$	Relative displacement of the suspension	
$S(z_{rp}, \dot{z}_{rp}) = K_s \cdot z_{rp} + C_s \cdot \dot{z}_{rp}$	K_s = Suspension Stiffness	1371 lb/ft
	C_s = Suspension Damping	(Fig 3.7)
$z_b = Hq$		
M_s = Sprung Mass		3,030.9 lb
I_{xx} = Roll moment of inertia		377.8 slugs-ft ²
I_{yy} = Pitch moment of inertia		1,995.9 slugs-ft ²
$M_w = \text{diag}(M_{w1}, M_{w2}, M_{w3}, M_{w4})$	Unsprung Mass	636.2 lb (Total)
$K_t = \text{diag}(K_{t1}, K_{t2}, K_{t3}, K_{t4})$	Tire Stiffness	13,713 lb/ft
$M_b = \text{diag}(M_s, I_{xx}, I_{yy})$	Sprung mass inertia matrix	

Table 3.2: 7-DOF System Matrices and Model Parameters Defined

$$\begin{aligned}
M_s \ddot{h} &= \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} S(z_{rp}, \dot{z}_{rp}) \\
I_{xx} \ddot{r} &= \begin{bmatrix} l_{ylf} & -l_{ylf} & l_{ylr} & -l_{ylr} \end{bmatrix} S(z_{rp}, \dot{z}_{rp}) \\
I_{yy} \ddot{p} &= \begin{bmatrix} -l_{xf} & -l_{xf} & l_{xr} & l_{xr} \end{bmatrix} S(z_{rp}, \dot{z}_{rp})
\end{aligned}$$

Equation 3.1: Equations of Motion for the 7-DOF Vehicle Body

$$M_b \ddot{q} = H^T S(z_{rp}, \dot{z}_{rp})$$

Equation 3.2: Rewriting Equation 3.1

and finally:

$$M_w \ddot{z}_w = -S(z_{rp}, \dot{z}_{rp}) - K_t(z_w - w)$$

Equation 3.3: 7-DOF Wheel Equations of Motion

Figure 3.7: Nonlinear Damping, C_s , from 2000 Jeep Grand Cherokee

These equations will be utilized in the final algorithm for the OSU-TSMS to find the terrain profile. For this paper, these equations are used to simulate vehicle response assuming a known profile. The parameters for the vehicle model are given in Table 3.2 and the nonlinear damping used is shown in Figure 3.7. A sample Simulink model is given in Appendix A. Note that the vehicle model is representative of a 2000 Jeep Grand Cherokee, and the parameters were provided to OSU in the winter of 2005 for the course ME 794G: *Vehicle Dynamics Modeling and Simulation* and also used in the Society of Automotive Engineers (SAE) paper 2006-01-0563 [68].

3.4 Conclusion

With the raw data measured during the test procedure, and the profile calculated from the system outputs, there is a vast amount of data available for defining the statistics and severity of the traversed terrain. Chapter 4 definitively develops the methodology for off-road TSC.

CHAPTER 4

REPORTING TERRAIN SEVERITY

4.1 Introduction

Severity is defined, similar to roughness, to represent the variation in terrain elevation that will elicit suspension forces and dynamics in the sprung mass. The methodology to describe the severity of off-road terrain is termed off-road TSC, and is detailed in this chapter.

4.2 Off-Road Terrain Severity Characterization

Once an accurate profile is obtained, any number of calculations may be found with the profile data. The goal here is to focus on metrics that will give a sense for the roughness of the terrain. Section 2.2 delved into many of the metrics used in quantifying paved-road roughness. Section 2.3 presented some new conceptual metrics. These may provide further insight for complete characterization and assessment of the actual terrain and how the terrain and vehicle interact. After much literature review, and experimenting with the calculations of multiple metrics, a system for characterizing off-road terrain severity has been developed.

Off-road TSC will look at three major issues: the actual makeup of the measured profile, the vehicle response as felt by human subjects, and the action of the suspension. These factors are assessed by profile PSD, RMSVA of the frequency weighted sprung mass acceleration, and relative work done by the suspension, respectively. Individually, these three factors show a small portion of the bigger picture. It is difficult to summarize a smooth, paved-road with one number, but it has been done with satisfying results for several decades now. However, it is not possible to summarize the complexity of an off-road course with a single metric. On the other hand, a simple report of these three metrics provides a very good sense of the severity of the terrain. This methodology provides a much needed means of tracking course degradation for the off-road community.

Before exploring some examples to illustrate the adequacy of this system, some time is first spent discussing shortcomings of other methods, and why they were not selected. The three major issues in terrain severity that were noted above provide the guideline for what is expected of the roughness calculations. First off, the main goal of the OSU-TSMS is to profile off-road terrain using a highly mobile device, at velocities greater than that of the previous system, the ATC Profilometer. This immediately eliminates methods such as PCI from ASTM D6433-03 which rely on observing the condition of the pavement. Something more systematic and automated is required.

PSD, Arc Length, Crest Factor, and spatial derivatives all may give useful information about the actual makeup of the measured profiles. Only one statistical reference is desired, so PSD was selected since it is already proven to be effective at giving good statistical inferences about the actual elevation versus longitudinal distance

data [18, 19]. As discussed in section 2.2.4, there are other variations of the PSD, such as Waterfall Plots and Wavelet analysis. The recommended procedure is to use a normal PSD, but divide the course profile into sections of similar roughness, as discussed in section 2.2.4.

Next, a method to assess ride quality had to be determined. The choices were between IRI, RN, RMSVA, Arc Length, and Crest Factor. Crest Factor is not sensitive to human response. Studies have shown that a high crest factor does not correlate to what is considered uncomfortable [31]. Arc Length proved to be very similar to IRI and RN, only without filtering, so it is only representative of the profile, not the sprung mass response. IRI is widely used in paved-road applications, but it has also been proven to be uncorrelated to ride quality as felt by passengers [35]. RN was designed to represent subjective response to traveled profiles [5]. However, when choosing between RN and RMSVA, the preferred method is to use the FWA and RMSVA. This international standard has been used widely, and has far more literature published than RN. Also, RN is specified by standard parameters that make the calculation vehicle specific, and the method to obtain RMSVA is open-ended; it may be found from a measured sprung mass acceleration, or from any acceptable vehicle model. Here the 7-DOF model is used as it presents a convenient system which may be easily adapted to more suitably represent any desired 2-axle vehicle. The main changes involve the spring stiffness and vehicle mass, which both may be determined rather easily [37]. Clearly, more complicated models could also be used, and the acceleration must simply be representative of what the operators or passengers would experience.

Another advantage of assessing the acceleration data, is that large spikes may be reviewed to find the equivalent acceleration ($a_{w,e}$) which gives an estimation of operator fatigue. Acceleration data has also proven useful in accelerated fatigue tests [36]. So, the profile is first statistically reviewed by the PSD, and then ride quality is characterized by the FWA and RMSVA. Last, the method to explore suspension motion was developed.

IRI and RN, by definition, look at the relative motion of the suspension. Yet, they both are highly vehicle dependent. IRI uses a quarter-car model representative of the rather old BPR Roughometer, and is said to be a poor indicator of the suspension motion of modern vehicles. Also, the resonances of the 'Golden Car' are very different than that of a truck, so IRI is also a poor indicator of roughness as seen by trucks [35]. RN uses a model similar to the 'Golden Car', only with slightly different parameters. So both IRI and RN, by their definitions, are specific to their models.

To describe suspension motion, the 7-DOF model presented in this paper is preferred. The 7-DOF model may be adapted to represent any 2-axle vehicle to give a sense of specific vehicle reactions. From this model, it is very simple to find the suspension work done and instantaneous power at each corner of the vehicle. Thus, effects of pitch and roll, which are significant in off-road durability courses, are considered. It is suggested to examine work and power, though a caution about the instantaneous power is that it uses the relative suspension velocity, which is a derivative of the relative displacement, and thus subject to large spikes which may be in excess of reasonable velocities. Using work and power to describe the road vehicle interaction is the last variable to consider for the off-road TSC.

Next, off-road data samples provided from YPG are reviewed and subjected to the TSC using the following guideline:

1. Find the PSD of the profile in the spatial domain. This gives an overview of the amount of energy that can be expected at each wave number.
2. Filter the data with a band pass-filter so only the wavelengths from 9 in to 100 ft are relevant. In an actual vehicle, short wavelengths are eliminated by the tire footprint, and long wavelengths are not noticed simply due to vehicle dynamics [3]. This study used a moving average filter for the low-pass filtering, like in the IRI calculation. The high-pass filter was built in MATLAB using a first order high-pass Butterworth filter. For this study, the YPG data is only low-pass filtered since it has already been detrended.
3. Calculate the FWA. Use this to find spikes in acceleration, $a_{w,e}$, and calculate a sliding window RMSVA and overall RMSVA. This will give a feel for the ride quality and help locate local bumps.
4. Find the work and instantaneous power using a 7-DOF vehicle model. This illustrates the action in the suspension components and could be useful in designing suitable suspensions for the vehicle given the profile, and for determining structural damage.

4.3 Off-Road Data Samples

In order to prove the usefulness of the TSC process, several profiles taken from YPG were fully analyzed. These profiles were given to OSU-CAR as examples of the profiles extracted from the ATC Profilometer, and to give an idea of the type of terrain seen on a regular basis. The five courses are listed here. The courses were recently renamed, so the new names are given in parenthesis.

1. **Old Highway 95 (aka Laguna Level Gravel)** – A straight stretch of state route 95 that was abandoned and is now a gravel road. There are loops at each end to give the course a total length of 8.4 miles. The data given to OSU-CAR is a 5.1 mile stretch.
2. **Level Cross Country East and West (aka Laguna Level Trails East and West) (2 files)** - These trails consist of predominantly relic beach terrace, with occasional gravel wash areas. The course is considered analogous to unkempt roads in the Middle East. The west course is considered less severe and is 6.1 miles long. The data file associated with the west section is 4.8 miles long. The east course is 3.2 miles long, and the data file is 2.3 miles.
3. **Truck Gravel Loop (aka Kofa Level Gravel)** – This is a 3.1 mile oval course composed of gravel ranging in diameter from 0.5 in to 3 in. It is designed to mimic a secondary gravel road. The data file accounts for 2.6 miles of the course.

4. **Paved Dynamometer Course (aka Laguna Paved)** – The Dynamometer course is an asphalt course with a maximum grade of 0.8% used for mobile field dynamometer testing. The course is a two-mile straightaway with turnarounds at the ends. The data file accounts for 4.1 miles, thus two passes.

4.4 Sample Calculations Using YPG Data

The guidelines set forth were used to evaluate TSC of the five YPG courses. Only the left track will be examined, though reporting both tracks will be necessary for complete course severity evaluation. The courses are considered one at a time, and the detailed analysis given for each course may be used as an example for future reporting expectations. The first course is given in extra detail to explain some intricacies of the data analysis. The remaining four are then reported as would be expected in actual use.

The first course considered is Old 95. First, the PSD, shown in Figure 4.1, is evaluated. The wave numbers are set to focus on the range of 0.01 to 2 cycles per feet. This corresponds to a wavelength range of 6 in to 100 ft. These wavelengths will also correspond to frequencies of 0.73 to 146 Hz since speed used in simulation was 73 ft/sec (50 mph). This frequency range well encompasses the main range of interest for vehicle dynamics [3, 19, 37, 27]. The PSD shows a rise in amplitude just before 0.02 ft^{-1} , 0.3 ft^{-1} , and 0.8 ft^{-1} . These resonant wave numbers are common for YPG courses, as is seen in the remaining profiles' analyses. These common frequencies arise from the same vehicles repeatedly traversing the course, which signifies wash boarding of different wavelengths. Another important factor to note is the magnitude at the noted resonances. Respectively,

they are¹ 0.002 ft^3 , $5\text{E-}4 \text{ ft}^3$, and $2\text{E-}4 \text{ ft}^3$. These values will play an important role in determining relative roughness, based on PSD, for the same course over time. The final values to report are the starting and ending power magnitudes of the PSD over the range of wave numbers. For instance, the Old 95 PSD starts at $1.5\text{E-}3 \text{ ft}^3$ and ends at approximately $5\text{E-}5 \text{ ft}^3$.

Figure 4.1: PSD, Course: Old 95

¹ The amplitude may be reported as ft^3 or to show the dependence on wave number as $\text{ft}^2/\text{cycle}/\text{ft}$

Figure 4.2: FWA, Course: Old 95

The next calculation made is the FWA, shown in Figure 4.2. This calculation was used to find excessive sprung mass accelerations that may cause severe discomfort and health hazards in accordance with ISO 2631-1 and TRR 774 [29, 32]. In this study, no accelerometer data was available, so the sprung mass acceleration was found using the 7-DOF model. In practice, the accelerometer outputs would be preferred. The model response was then filtered in the frequency domain using Equation 2.11. Next, in accordance with TRR 774, any acceleration levels above 0.28 g are found. In this case, there are no excessive accelerations found by the model, thus this subject is revisited later in this section during the review of Laguna Level Trails, which does have excessive accelerations predicted.

Figure 4.3: Sliding Window RMSVA, Course: Old 95

The FWA is next used to find the sliding window RMSVA and the overall RMSVA, both shown in Figure 4.3. The sliding window uses a 100-ft window length. This length has been set for several reasons. First, using a sliding window keeps the RMSVA calculation from averaging too much data at once, thus giving a more localized view of the data. Also, as noted earlier in the PSD discussion, a vehicle traveling at 73 ft/sec is generally most concerned with dynamics for wavelengths of 6 in to 100 feet. Most vehicles subjected to an impulse will see complete vibration decay within 2 seconds. Thus, a 100-ft window provides a length that is sufficiently long to represent all of the vehicle dynamics. Also, 100-ft windows are in use by the RoadRuf program provided by UMTRI in the calculation of sliding window IRI values. This will provide a measure for comparison in section 4.5, which is a brief analysis of highway profile

roughness and TSC. Again, ride quality analysis from acceleration is revisited when the Laguna Level Trails are reviewed.

Figure 4.4: Simulated Work, Course: Old 95

Following the sprung mass acceleration analysis for ride quality considerations is the energy analysis for suspension motion and handling considerations. Figure 4.4 shows the suspension work for Old 95, and Figure 4.5 shows the power dissipated in the suspension. For this paper, the plots focus on the front-left corner, though a complete report should include all corners/wheels of the vehicle. Figure 4.6 shows the small difference between front and rear values in a power calculation, with the main difference being the time delay. Similar to the RMSVA acceleration, these plots are used to find peak levels and RMS values. Since the power is predominantly negative, calculating the mean power is sufficient, as opposed to finding RMS. The power is negative because the

relative force and velocity vectors are always out of phase, which was shown in Figures 2.7 and 2.8.

Figure 4.5: Simulated Power, Course: Old 95

Old 95 has maximum work and power at a distance of 22,000 feet. The work is 27 ft-lb, and the power is -3.45 hp. These maximum levels can be used to infer approximate design specifications for the suspension springs and dampers. The 27 ft-lb of work may be used to approximate the desired minimum suspension spring rate. First, the amount of displacement to correspond to 27ft-lb must be set. If it is 6 in, then the force at 6 in is $27\text{ft-lb}/0.5\text{ft} = 54$ lb. This also corresponds to $54\text{lb} / 0.5 \text{ ft} = 108$ lb/ft, which could be used as the spring rate. Note that this is a small value. This course is not very severe, so the predicted spring rate is fairly low. Many vehicles have spring rates at least 10 times larger than 108 lb/ft.

Figure 4.6: Work Comparison of Front and Rear Corners, Course: Old 95

Similarly, the damper could be set by providing a desired velocity given the peak power. For instance, a peak relative suspension velocity of 100 ft/sec for the peak power of 3.45 hp (1900 $\text{lb}_f\text{-ft/sec}$) will yield 19 lb_f and a damping coefficient of 0.19 lb-sec/ft . Again, this is not a reasonable value for an actual suspension, but may provide a means of comparison between courses, and a design guideline for very rough courses.

Figure 4.7 shows the work as a sliding window RMS. Figure 4.8 shows the power as a moving average. These calculations are similar to that used for the sliding window RMSVA of the RMSVA in Figure 4.3. The window length is again 100 ft. Looking at the work and power using this approach will eliminate some of the large spikes so the data may be reviewed to find areas of general smoothness or roughness.

Figure 4.7: Sliding Window RMS of Simulated Work, Course: Old 95

Figure 4.8 Moving Average of Simulated Power, Course: Old 95

Now that an in-depth look at the severity analysis has been conducted for the course Old 95, the remaining 4 courses will be characterized. The plots are shown in Figures 4.9 through 4.28. Three tables (4.1, 4.2 and 4.3) provide an overview of the key metrics for quick comparison.

First, the PSD for each course is considered. Each plot has the same wave number range plotted, but the magnitude scales vary to highlight the individual course resonances. The column of Table 4.1 labeled “Magnitude at Beginning and End” is listed to show the general trend of the PSD, and highlight the relative magnitudes for the courses. It is important to note that all these YPG courses have resonances around the same general wave numbers. Next looking at magnitude, Laguna Level East and West have generally higher PSD magnitudes. This is expected as they are considered to be the two roughest courses of the data sets provided. Old 95, Gravel Loop, and the Dynamometer Course are relatively smooth. The Dynamometer Course has the lowest overall magnitude, which is expected since it is a paved course. PSD is not alone sufficient for a complete description of roughness. Next, ride quality is reviewed.

Figure	Course	PSD		
		Resonance Magnitude [ft ³]	Resonance Wave numbers [ft ⁻¹]	Magnitude at Beginning and End [ft ³]
4.1	Old 95	2E-3, 5E-4, 2E-4	0.02, 0.3 , 0.8	2E-3 , 5E-5
4.9	Laguna Level -East	0.3, 9E-4, 5E-4	0.01, 0.25, 0.8	0.3 , 5E-4
4.10	Laguna Level - West	0.2, 1E-3, 4E-4	0.01, 0.25, 0.8	0.2 ,1E-4
4.11	Gravel Loop	6E-4, 1E-4, 1E-3	0.01, 0.3, 0.7	6E-4 , 3E-5
4.12	Dyno Course	1E-3, 4E-5, 1E-4	0.01, 0.3, 0.8	1E-3 , 1.5E-5

Table 4.1: YPG Key PSD Values

Figure 4.9: PSD, Course: Laguna Level Trails East

Figure 4.10: PSD, Course: Laguna Level Trails West

Figure 4.11: PSD, Course: Gravel Loop

Figure 4.12: PSD, Course: Dynamometer Course

Figure	Course	RMSVA [g]	$a_{w,e}$ [g]	$t(a_{w,e})$ [sec]
4.2, 4.3	Old 95	0.0241	NA	NA
4.13, 4.14	Laguna Level -East	0.0503	0.525	0.1818
4.15, 4.16	Laguna Level - West	0.0469	0.3714	0.4116
4.17, 4.18	Gravel Loop	0.0113	NA	NA
4.19, 4.20	Dyno Course	0.0097	NA	NA

Table 4.2: YPG FWA Values of Interest

The FWA is evaluated to give a description of ride quality. As is seen in section 4.5, RMSVA correlates well to IRI and RN. For the YPG courses, Laguna Level East has the highest RMSVA at 0.05 g. This is appropriate since a subjective course description labels the eastern portion as more severe. Also, as should be expected, the Dynamometer Course, which is the only paved course considered, has the lowest value. This gives a

good sense of the overall course roughness, but alone is not enough. There needs to be a measure of local ride quality. This is done by examining acceleration spikes in the FWA.

Both of the Laguna Level Trails courses have significant acceleration spikes. The program developed to analyze these profiles marks each acceleration point above 0.28 g and records the amount of time above 0.28 g. The equivalent acceleration ($a_{w,e}$) is then found, which gives a sense for the mean acceleration that is sustained over the total time above 0.28 g. The last column of Table 4.2, $t(a_{w,e})$, is the total time above 0.28 g. Looking back at Table 4.2, Laguna Level Trails East has a shorter time, but higher equivalent acceleration. This signifies that the spikes are more severe in nature; reaching higher peaks and not lasting as long. Also, both show only a fraction of a second above 0.28 g. This means these accelerations are very impulsive jolts. The Laguna Level Trails courses were the only courses, of those provided, that had significant localized acceleration.

Figure 4.13: FWA, Course: Laguna Level Trails East

Figure 4.14: Sliding Window RMSVA, Course: Laguna Level Trails East

Figure 4.15: FWA, Course: Laguna Level Trails West

Figure 4.16: Sliding Window RMSVA, Course: Laguna Level Trails West

Figure 4.17: FWA, Course: Gravel Loop

Figure 4.18: Sliding Window RMSVA, Course: Gravel Loop

Figure 4.19: FWA, Course: Dynamometer Course

Figure 4.20: Sliding Window RMSVA, Course: Dynamometer Course

Figure	Course	Work - Peak, RMS [ft-lb]	Power - Peak, Mean [hp]
4.4, 4.5	Old 95	[27.1, 1.1]	[-3.45, 5.56E-2]
4.21, 4.22	Laguna Level -East	[-887, 14.9]	[-70.3, 0.220]
4.23, 4.24	Laguna Level - West	[-433, 9.9]	[-28.8, 0.208]
4.25, 4.26	Gravel Loop	[-11.7, 0.1989]	[-1.45, 1.50E-2]
4.27 4.28	Dyno Course	[-20.3, 0.2669]	[-0.900, 6.33E-3]

Table 4.3: YPG Energy Values

The last consideration is to evaluate the suspension energy. Table 4.3 gives a summary of the findings from Figures 4.21 through 4.28. Again note that Laguna Level Trails East has the largest values, thus it may be considered the most severe. This concludes the off-road TSC procedure. Of the five YPG courses, all three of the phases of the TSC process found Laguna Level Trails East to be most severe, with Laguna Level Trails West a near second. In terms of ride quality, Old 95 then Gravel Loop are next in roughness, with the Dynamometer course the least severe, which is expected since it is the only paved course.

A last note is that the RMS work does not necessarily give the same rank order of roughness for the five courses. It shows the Gravel Loop as the smoothest road. As is shown in Chapter 4.6, RMS work also doesn't correlate well to any previous metrics. Thus, more focus should be given to the mean power and RMSVA for the suspension motion and ride quality considerations. Yet, peak work may still prove useful in suspension design considerations.

Figure 4.21: Simulated Work, Course: Laguna Level Trails East

Figure 4.22: Simulated Power, Course: Laguna Level Trails East

Figure 4.23: Simulated Work, Course: Laguna Level Trails West

Figure 4.24: Simulated Power, Course: Laguna Level Trails West

Figure 4.25: Simulated Work, Course: Gravel Loop

Figure 4.26: Simulated Power, Course: Gravel Loop

Figure 4.27: Simulated Work, Course: Dynamometer Course

Figure 4.28: Simulated Power, Course: Dynamometer Course

4.5 Comparative Analysis of Highway Data

In order to gain a better understanding of the severity calculations, some highway profiles have also been characterized. UMTRI and RPUG have provided some sample profiles over the internet. They are available when the RoadRuf program is downloaded from UMTRI's website. The data is from a study by RPUG in which they profiled the same eight sections of highway with four different systems: ProRuts, ICC, K. J. Law, and Dipstick. The two profiles of interest for this discussion are the profiles found with ProRuts for highway sections 2 and 6. Based on the RoadRuf analysis, these two profiles are the smoothest and roughest, respectively. The RoadRuf analysis is summarized in Table 4.4 and Figures 4.29 and 4.30.

Value		Section 2 (Smooth)	Mean Value	Section 6 (Rough)	Mean Value
IRI [in/mi]	Left	64.07	68.7	221.99	215.44
	Right	73.33		208.89	
RN [Dimensionless]	Left	4.14	4.17	1.99	1.98
	Right	4.20		1.97	

Table 4.4: Highway Profile Properties from RoadRuf

Looking at the IRI plots in Figures 4.29 and 4.30, it is clear that the IRI is significantly higher in section 6. ASTM E1926-98 describes an IRI of 215 in/mi as [24]:

“Moderately perceptible movements or large undulations may be felt. Defective surface; occasional depressions or patches (e.g. 0.2-0.6 in/10 ft or 0.4-0.8 in/16 ft with frequency 2-1 per 160 ft, or many shallow potholes (e.g. on surface treatment showing extensive raveling). Surface without defects; moderate corrugations or large undulations”

Similarly section 2, with an overall IRI of 68.7 in/mi may be described as:

“Ride comfortable over 75 mph... No depressions, potholes or corrugations are noticeable; depressions <0.1in/10ft.”

Now the two profiles will be analyzed with the TSC methodology. First, the PSD plots are analyzed in Table 4.5. It must be noted that since these profiles are rather short (3227 data points) they do not use any windowing in the PSD. Unlike the YPG courses, neither PSD has any noticeable resonances. They both appear generally to be straight lines in these logarithmic plots. It is easy to tell the difference between the smoother section and the rougher section. Section 2 has a far smoother PSD, with a greater overall change in magnitude, meaning the power is predominantly in the smaller wave numbers, or longer wavelengths. Section 6 has a turbulent PSD, and a less pronounced change in power from 0.01 ft^{-1} to 2 ft^{-1} .

Figure	Section	PSD		
		Resonance Magnitude [ft^3]	Resonance Frequencies [ft^{-1}]	General Change in Magnitude [ft^3]
4.29	2	NA	NA	0.04 , 7E-5
4.30	6	NA	NA	6E-3, 3E-7

Table 4.5: Highway Examples Key PSD Values

Figure 4.29: Sliding Window IRI for Smooth Highway (Section 2)

Figure 4.30: Sliding Window IRI for Rough Highway (Section 6)

Figure 4.31: Profile PSD for Smooth Highway (Section 2)

Figure 4.32: Profile PSD for Rough Highway (Section 6)

Next, the RMSVA is found, with details given in Table 4.6. RMSVA is clearly lower for the smoother section 2. Also, predictably, there is no acceleration above 0.28 g's so the equivalent acceleration, $a_{w,e}$, and the time above 0.28 g, $t(a_{w,e})$, are not available. An important relation is the general trends for the IRI plots and the RMSVA plots are similar, with the main difference being the end values, which could be from the manner in which the sliding window is implemented. For the smooth section they both are generally increasing between longitudinal distances of 100 and 450 feet. The rough section has a drop around 150 feet, then steadily rises.

Figure	Course	RMSVA [g]	$a_{w,e}$ [g]	$t(a_{w,e})$ [sec]
4.33, 4.34	2	0.00591	NA	NA
4.35, 4.36	6	0.0299	NA	NA

Table 4.6: Highway Examples Weighted Acceleration Values of Interest

Figure 4.33: FWA for Smooth Highway (Section 2)

Figure 4.34: FWA for Rough Highway (Section 6)

Figure 4.35: Sliding Window RMSVA for Smooth Highway (Section 2)

Figure 4.36: Sliding Window RMSVA for Rough Highway (Section 6)

Figure	Course	Work [Peak, RMS] [ft-lb]	Power [Peak, RMS] [hp]
4.37, 4.39	2	[0.536, 0.1443]	[-4.24E-2, 1.68E-3]
4.38, 4.40	6	[-8.7, 1.165]	[-0.711, 3.60E-2]

Table 4.7: Highway Examples Energy Values, Front Left Corner

The last point of analysis is the suspension energy analysis. Table 4.7 and Figures 4.37 through 4.40 summarize these findings. Notice that a relatively large spike is predicted for the smooth section around 450 feet for the work and power. Looking back, this is also noticed in the sliding window RMSVA and the sprung mass acceleration. This highlights the efficiency of the energy analysis in finding bumps in the road that will excite suspension motion, even on a generally smooth road.

Figure 4.37: Simulated Work for Smooth Highway (Section 2)

Figure 4.38: Simulated Work for Rough Highway (Section 6)

Figure 4.39: Simulated Power for Smooth Highway (Section 2)

Figure 4.40: Simulated Power for Rough Highway (Section 6)

4.6 Correlation to IRI and RN

A deliverable, as stated by the U.S. Army, was to determine a possible correlation to previous standards. Since IRI and RN are widely used, they will be compared to the RMSVA values and the RMS work and power values for the highway profiles. A complete table of the results of a study using the various metrics and the MATLAB Curve Fitting Toolbox is given in Appendix B. In short, there is agreeable correlation between the following pairs: $a_{w,RMS}$ and RN, $a_{w,RMS}$ and IRI, mean power and RN, and mean power and IRI. These are illustrated for the ProRuts system for all eight RPUG highway sections in Figures 4.41 through 4.44, along with their goodness of fit values. It is interesting to note that the mean power is better related to IRI and RN by a quadratic polynomial. This could be because power is generally defined by a squared dimension, such as Volts squared in electronics or Feet squared in this instance.

The main conclusion to draw from this correlation study is that the parameters detailed in this research effort can be related to the existing metrics of IRI and RN. However, the correlation is dependent upon the profilometer. Thus, if a true correlation is desired, it would be necessary to calibrate the OSU-TSMS first. This would have to be done by measuring multiple profiles of varying degrees of roughness and calculating their RN, IRI, and TSC metrics, and then a calibration curve could be calculated.

Figure 4.45 shows the different correlation curves for the different profiles. This is presented to show that in order to make a correlation, the individual profiler must be calibrated. Another way to illustrate this profiler variation is by simply looking at the

calculated values for each profiled section of road. This is shown in Figures 4.46 through 4.50. Clearly, each profiler has slightly different values, with occasional extremes.

Figure 4.41: ProRuts Correlation between RN and RMSVA

Figure 4.42: ProRuts Correlation between IRI and RMSVA

Figure 4.43: ProRuts Correlation between RN and Mean Power

Figure 4.44: ProRuts Correlation between IRI and Mean Power

Figure 4.45: Correlation between RN and Mean Power to Show Variation in Profilers

Figure 4.46: Profiler Variation in RN Calculation

Figure 4.47: Profiler Variation in IRI Calculation

Figure 4.48: Profiler Variation in RMSVA Calculation

Figure 4.49: Profiler Variation in Mean Power Calculation

Figure 4.50: Profiler Variation in Work Calculation

4.7 Conclusion

An appropriate means of describing off-road roughness is now available. The off-road TSC methodology has been outlined and could be immediately implemented in any profiling system. To prove its usefulness, five YPG courses were characterized as were 2 highway profiles. The examples provided clearly show the large disparity between the roughness of highways and modest off-road courses. The procedure used to discuss the examples is representative of what could be used in practice for tracking course wear for maintenance purposes. Last, a correlation was found between the TSC metrics and previous roughness indices. It was found that the RMSVA and mean power both correlated to IRI and RN. Thus OSU-TSMS may eventually be calibrated to not only calculate the TSC metrics but also output IRI or RN.

CHAPTER 5

CLOSING REMARKS

5.1 Conclusions

This research provided a vast and in depth look into the world of road profiling and roughness measuring systems. By looking at numerous research projects to determine which paved-road systems are the best, a methodology for off-road systems was defined. A prototype ATV inertial profilometer termed OSU-TSMS was designed with the most severe operating conditions in mind. This off-road profilometer provides a system that may collect data at speeds of up to 50 mph, given the terrain is not excessively severe. Also, the OSU-TSMS is capable of profiling terrain that the ATC Profilometer could not measure because of limitations of the trailer when traversing rough terrain.

The off-road TSC methodology looks at three aspects of the vehicle-road interaction: profile elevation statistics, passenger ride quality, and suspension reaction. The methodology uses several readily available techniques, along with innovative approaches to fully define the more complex off-road environment. The process is defined as follows:

1. Find the PSD of the profile in the spatial domain from 0.01 ft^{-1} to 2 ft^{-1} . This will give an overview of the amount of energy that can be expected at each wave number. Then, note the wave numbers where resonances occur, and the resonance magnitudes. Also, it is beneficial to take notice of the initial and end magnitude in the defined wave number span.
2. Filter the data with a band pass-filter so only the wavelengths from 9 in to 100 ft are relevant. In an actual vehicle, short wavelengths are eliminated by the tire footprint, and long wavelengths are not noticed simply due to vehicle dynamics [3]. This study used a moving average filter for the low-pass filtering, like in the IRI calculation. The high-pass filter was built in MATLAB using a first order high-pass Butterworth filter.
3. Calculate the FWA. Use this to find spikes in acceleration, $a_{w,e}$, and calculate a running RMSVA and overall RMSVA. Use of a model will provide enhanced repeatability provided an accurate profile is being measured. However, measured data is preferred to avoid inexact model errors.
4. Find the work and instantaneous power using a 7-DOF vehicle model. This will illustrate the action in the suspension components and could be useful in designing suitable suspensions for the vehicle given the profile, and for determining structural damage. Also calculate the mean power.

With the courses at YPG as a benchmark, the system was evaluated to show the type of responses typical for off-road scenarios. Then as a compliment to the study,

highway profiles were evaluated with the TSC technique and compared to the common paved-road metrics IRI, and RN. These highway profiles were also used to show it is possible to define a correlation between the TSC metrics, IRI, and RN.

5.2 Future Work

The research effort for the OSU-TSMS is still in a preliminary stage. Once the ATV prototype has proven its ability to obtain accurate profiles, then an effort should be made to implement the methodology outlined in this paper. This should be coupled with field tests at the various U.S. Army proving grounds to begin compiling records of each courses' TSC reports. This section will also briefly reviews other areas that may require further investigation

During the early stages of testing it is suggested that the test engineer driving the OSU-TSMS should be accompanied by an assistant to take subjective ride quality notes. This should be used to ensure the methods used are predicting severe terrain where the passengers feel discomfort. This could be done by simply making note of the longitudinal distance at which large bumps occur.

Also strongly recommended is the standardization of the entire TSC process. This paper suggests certain parameters for the 7-DOF model that may be subject to change, such as spring and damping stiffness and a simulated velocity of 73 ft/sec. But, changing parameters will alter the model response, and thus the output severity calculated. Therefore, with this paper as a guideline, it is suggested to standardize the off-road TSC methodology.

Once standardization is accomplished, another research effort should investigate combining the TSC calculations into one index. With the limited data available this could not yet be done. However, a suggestion is to first profile numerous courses. Then define each index from one to ten using ranges of the RMSVA and mean power calculations. Then specific vehicles can be described based on their performance on courses of each index number. If one is smooth and ten is extremely harsh, the military could test each of their vehicles abilities on courses that cover the entire scale. For instance, an Abrams Tank should be able to cross nearly any terrain. So, its mobility rating should be for indices from one to nine, if ten is simply impassable. After further testing, each vehicle could be defined for its ability on each index level. As another example, perhaps a HMMWV may pass freely and comfortably without fear of vehicle damage on courses of index one to five. Above five, speed must be reduced. Then at some index, say 8, the HMMWV simply may not be able to cross. Again, this is only a suggestion that will require extensive data collection. In the future, this may provide a valuable tool to assess a vehicle's mobility when crossing new terrain that has only been profiled by an autonomous version of the OSU-TSMS.

As just intimated, there are numerous future applications of the OSU-TSMS and the off-road TSC methodology. From crossing the gap between terrain characterization and vehicle specific mobility prediction, to creating an autonomous version of the OSU-TSMS that could profile terrain and assess which vehicles may experience mobility problems; this young research project has great potential for interesting research for years to come.

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APPENDIX A

7-DOF MODEL DETAILS

The Simulink Model in Figure A.1 was used as the basis for the 7-DOF simulation. System equations were discussed in Section 3.2, and the parameters used were given in Table 3.2

The front wheel inputs are the merely left and right profiles. The rear wheel inputs are time delayed according to the distance between axles and the speed of travel. It should be noted that the profiles are converted from spatial domain to the temporal domain by dividing by a constant velocity. Velocity could be made variable by dividing the longitudinal distance traveled array by the instantaneous velocity array.

APPENDIX B

CORRELATION STUDY

		SSE	R-Square	Adj R-sq	RMSE
a_w vs IRI	ProRuts	0.204	0.858	0.852	0.096
	Dipstick	0.164	0.886	0.881	0.086
	ICC	0.285	0.850	0.844	0.114
	KJ Law	0.221	0.857	0.851	0.100
a_w vs RN	ProRuts	0.185	0.872	0.866	0.092
	Dipstick	0.214	0.852	0.845	0.099
	ICC	0.429	0.775	0.764	0.140
	KJ Law	0.322	0.793	0.783	0.121
IRI vs RN	ProRuts	13465.362	0.719	0.706	24.740
	Dipstick	11744.477	0.739	0.728	23.105
	ICC	11811.203	0.851	0.844	23.171
	KJ Law	23130.775	0.572	0.552	32.425
Power vs IRI *	Dipstick	41.965	0.896	0.880	1.797
	ProRuts	53.912	0.899	0.884	2.036
	KJ Law	48.721	0.917	0.904	1.936
	ICC	108.549	0.788	0.756	2.890
Power vs RN *	ProRuts	32.382	0.939	0.930	1.578
	Dipstick	13.935	0.965	0.960	1.035
	ICC	108.387	0.789	0.756	2.887
	KJ Law	119.785	0.796	0.764	3.035
Power vs Work	ProRuts	196.264	0.633	0.607	3.744
	Dipstick	121.931	0.697	0.675	2.951
	ICC	195.068	0.620	0.593	3.733
	KJ Law	212.779	0.637	0.611	3.899

* - This data was fit with a quadratic polynomial

Continued

Table B. 1: Correlation Study Values

Table B.1 continued

Work vs IRI	ProRuts	1.417	0.626	0.600	0.318
	Dipstick	1.390	0.634	0.608	0.315
	ICC	2.878	0.546	0.514	0.453
	KJ Law	2.399	0.591	0.562	0.414
Work vs RN	ProRuts	1.507	0.603	0.574	0.328
	Dipstick	1.004	0.736	0.717	0.268
	ICC	3.367	0.469	0.431	0.490
	KJ Law	3.073	0.476	0.439	0.468