2018 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) TECHNICAL SESSION
AUGUST 7-9, 2018 – NOVI, MICHIGAN

MODERNIZING MILITARY GROUND VEHICLE RELIABILITY TESTING

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ABSTRACT

The durability and reliability of military vehicle systems are traditionally tested at Aberdeen Proving Ground by driving vehicles on a set of paved roads, secondary roads, trails, and cross-country terrains. However, driving mile-for-mile over the proving ground test courses is very time-consuming and costly. The U.S. Army Aberdeen Test Center (ATC) has recently conducted accelerated durability tests of wheeled vehicles using two different methods: accelerated hardware-in-the-loop simulation and accelerated field testing. This paper discusses the methods used to date and associated technical details to highlight options for future accelerated testing.

INTRODUCTION

The durability and reliability of military vehicle systems are traditionally tested at the proving grounds by driving vehicles on a set of paved roads, secondary roads, trails, and cross-country terrains. The combination of terrain types that a military vehicle is expected to traverse is determined by the test vehicle's specific Operational Mode Summary/Mission Profile (OMS/MP), a unique combination of paved, secondary and off-road terrain that defines its expected life-cycle usage. The proving ground test courses are designed to replicate terrains historically encountered around the world. However, driving mile-for-mile over the proving ground test courses is very time-consuming and costly. For example, a 20,000-mi wheeled vehicle Reliability, Availability, Maintainability-Durability (RAM-D) test can take a year or more to complete. As a result, test distance is often reduced to accommodate acquisition milestones. The distance reductions can result in inaccurate reliability estimates or prevent a critical failure mode from surfacing during testing. Even if full-length or extended testing is conducted, the process may take too long to identify potential failures. Consequently, acquisition decisions may be made without all the key information. The automobile industry recognized these challenges decades ago and pioneered the use of laboratory-based accelerated durability test methods.

The U.S. Army Aberdeen Test Center (ATC) has recently conducted accelerated durability tests of wheeled vehicles using two different methods: accelerated hardware-in-the-loop (HITL) simulation and accelerated field testing. Test durations have been accelerated from 1.8 to 5 times, depending on the specific test. In all cases, instrumented vehicles were initially operated using the OMS/MP over the courses to characterize the terrain loads to the vehicle during normal use. Measurements included wheel forces, displacements, velocities, accelerations, sprung mass motions, steering forces, and component strain data. OMS/MP-derived course data were then used to develop and execute accelerated tests.

Although differences exist regarding how reliability and durability estimates are computed post-testing, both estimates are generated from essentially the same set of driving data. This paper describes the methods and processes used to prepare and execute accelerated testing with emphasis on high-risk failure modes such as chassis structure fatigue. Both laboratory HITL and field-based methods are discussed.

DATA COLLECTION

Terrain Selection and Payload Configuration

The first step in the process is to develop a matrix of test course and payload configurations for testing. The matrix is influenced by a candidate test vehicle's Life Cycle Environmental Profile (LCEP), which describes the expected environmental conditions experienced by a vehicle over its normal life. The LCEP usually defines the vehicle's OMS/MP, providing a percentage breakdown of usage on paved, secondary road, trail, and cross-county terrains. Each terrain type is described by a range of vertical amplitude root mean square (RMS) values or a wave number spectrum (WNS), as a measure of roughness. Aberdeen Test Center's test courses are aligned with the OMS/MP breakdown, based on roughness, to establish the number of miles driven over different test courses at different payloads.

Field Data Collection

Terrain-induced load data is then collected while driving over the selected test courses with the appropriate payloads. The test vehicle is instrumented with a digital data acquisition system and sensors to measure wheel forces, wheel hub and chassis accelerations, chassis angular rates, wheel displacements and velocities, and suspension and chassis strain. Data channel lists vary across vehicles, but in general the use of wheel force transducers at each wheel position provides the best data for analysis, drive file development, and simulation. The data collection process typically takes one to two weeks, and includes multiple test runs on each course to ensure data integrity and statistical variation. Field data collection is required for accelerated laboratory and field testing.

ACCELERATED HARDWARE-IN-THE-LOOP DURABILITY SIMULATION

For laboratory HITL durability testing, ATC uses the spindle-coupled Vehicle Durability Simulator (VDS) shown in Figure 1. The initial terrain data are analyzed to identify benign activity, which is deleted from the time histories. The resulting data are then spliced back together with special algorithms, producing time acceleration. A system identification and actuator drive file development process known as Remote Parameter Control (RPC) is utilized to prepare the test inputs. The actuator drive files are then repeated for each test course in a sequence that mimics the traditional OMS/MP-based RAM-D operations, but at a much faster pace. Accelerated testing, as applied by ATC to date, has been achieved solely by removal of benign load data time from the laboratory simulations. Exaggeration of load amplitudes has not been attempted to avoid concerns of over-testing.

Figure 1. Up-armored HMMWV testing on the ATC VDS.

Source Drive File Selection

After the field data have been reviewed and analyzed for anomalies or irregularities, a validated set of test files are compiled, with one test file for each test course and payload condition. As a conservative measure, the most apparently "damaging" run for each test condition is generally selected for the final data set. These data files become the source data used to create the desired response files for simulation, as described below.

Identification and Removal of Benign Activity

Three methods have been used to screen and edit the source data files to remove benign activity: Fatigue Damage Editing, Relative Damage Estimate, and Statistical Region Selection. The decision as to which method to use depends on the purpose of the test and any specific durability concerns of the test item. A combination of the three methods is often used for data editing. When using multiple methods, overlaps of selected sections from each method are combined.

A. Fatigue Damage Editing

Fatigue Damage Editing is used when strain and/or force-based sensors are applied on the test specimen. Strain sensors are the most direct method for correlating vehicle response to structural stress and damage. Force and strain data time histories are analyzed to identify and eliminate sections of data that have minimal contribution to structural damage. The goal is to retain at least 90 percent of the fatigue damage as compared to the field test data.

The relation of fatigue damage and time occurrence is required to effectively remove benign portions of the data. Rainflow cycle counting is conducted on selected data channels, as described in American Society for Testing and Materials (ASTM) E1049-85[1]. Figures 2 through 4 show examples of Rainflow analysis results for vertical wheel force, steering tie rod force, and wheel torque, using test file repeats to account for 10 miles of operation. The VDS analysis software generates a Damage Time History (DTH) which identifies points in time where each fatigue half-cycle occurs. The value of damage of each half-cycle is established based on a comparison of the magnitude of the strain cycle to material fatigue properties. Figure 5 shows an example of data processed using this method, with damaging sections of data highlighted in blue.

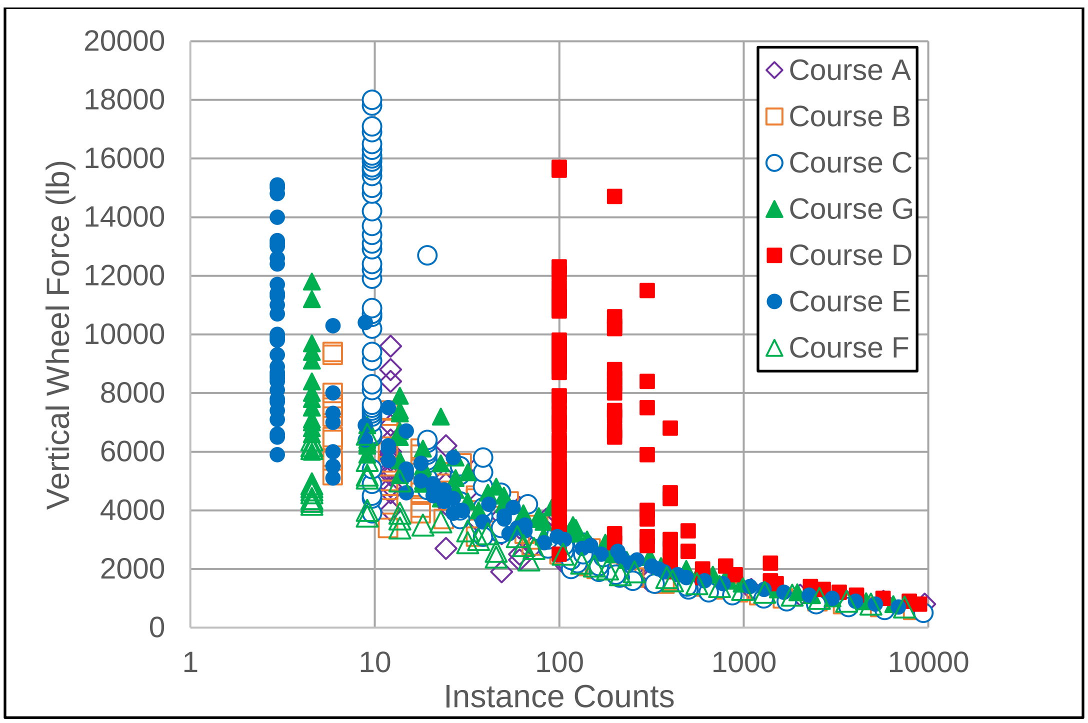

Figure 2. Rainflow analysis example of vertical wheel force data, for 10 miles on each test course.

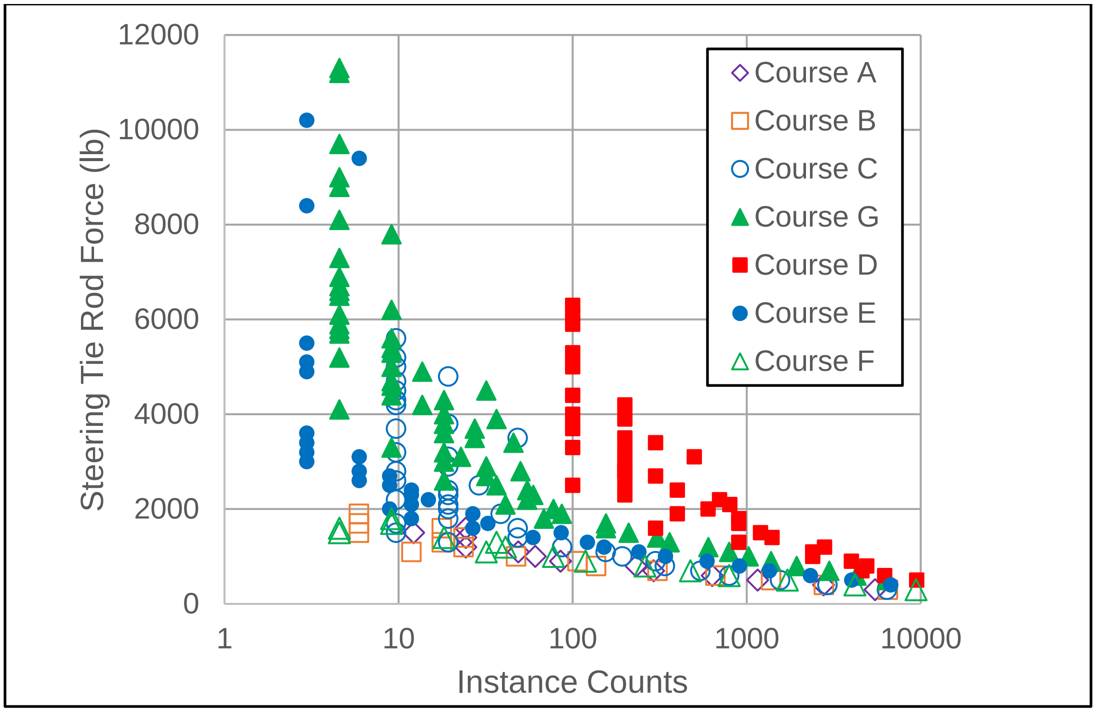

Figure 3. Rainflow analysis example of steering tie rod force data, for 10 miles on each test course.

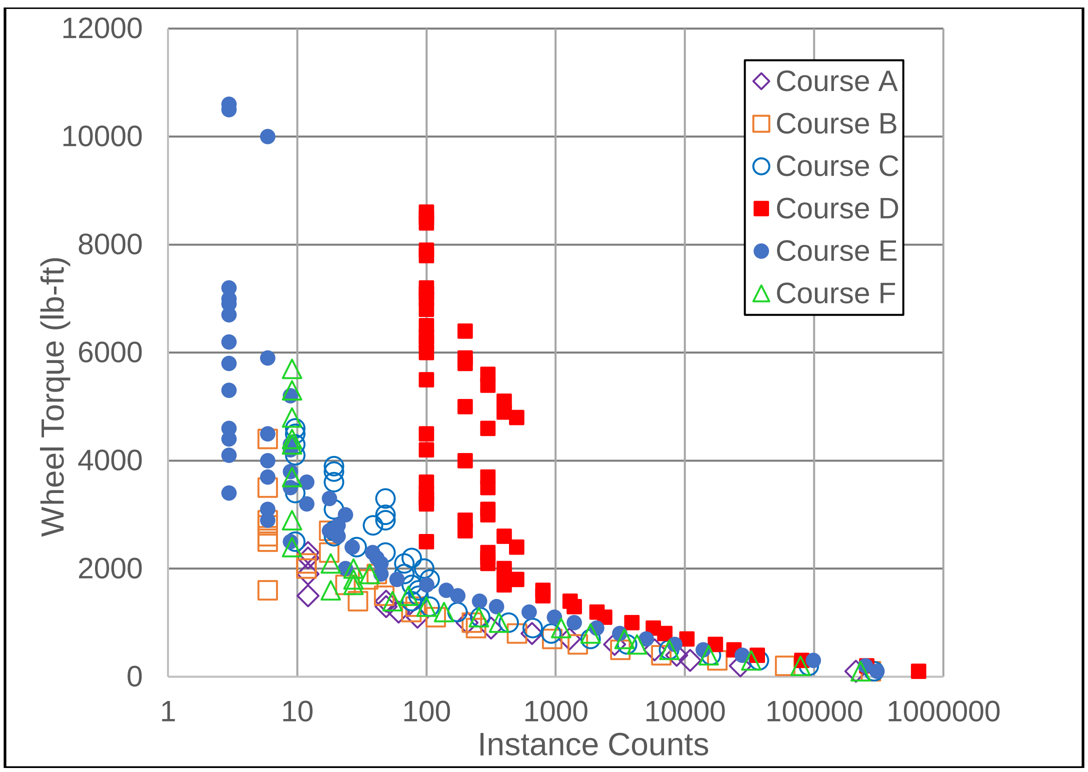

Figure 4. Rainflow analysis example of wheel torque data, for 10 miles on each test course.

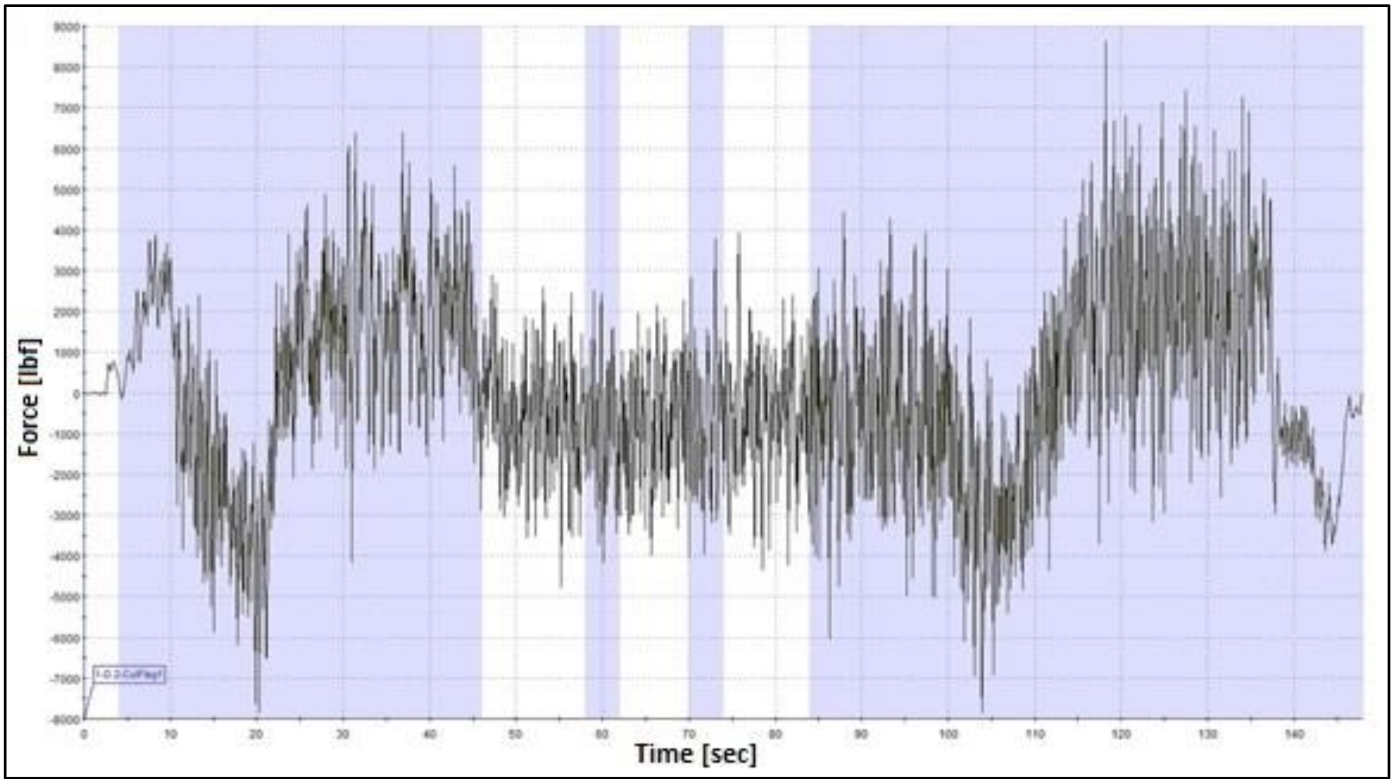

Figure 5. Example of file region selection based on fatigue damage.

B. Relative Damage Estimate

Relative Damage Estimate (RDE), sometimes called the "Pseudo-fatigue Damage", is an analysis technique intended to enable relative severity comparisons between different time segments of a response channel. The time segments under comparison can be within the same data run, or within separate time histories. The technique is also called pseudo-fatigue damage because it is often used with sensors that are not appropriate for assessing material damage (such as accelerometers), rather than strain gages or force sensors. The implication is that the analysis results are not a correct estimate of fatigue damage, though it is recognized that the results could be used to assess relative severity[2]. The method is based on traditional fatigue damage estimates relying on strain measurements, knowledge of material properties, Rainflow cycle counting, assumptions of Miner's Rule, and a presumed fatigue-damage model.

Most structural components of military vehicles are made of low-carbon steels. Therefore, the material properties of low-carbon steel are often used for performing the pseudo-fatigue damage calculations. Steel materials have an endurance limit threshold level below which it is presumed failure will never occur, regardless of how many cycles are applied. A load-life curve consists of two distinct regions. The lower cycle count region is dominated by plastic strain-inducing loads, while the higher cycle count region is dominated by elastic strain-inducing loads. Applying a larger scale factor will raise the pseudo-loading past the elastic region, into the plastic region. The transition from elastic- to plastic-dominated strain life is non-linear, therefore this method is sensitive to larger amplitude signals.

When performing RDE, a scale factor is applied to a data channel to produce pseudo-load ranges large enough to be considered cyclic fatigue-inducing. This is especially important with a sensor such as an accelerometer which typically measures values on a scale of 10 g's, as opposed to strain gauges which measure hundreds of microstrain. The scale factor can be different for two different channels, but the scale factor for a given channel must be consistent across all data runs to provide valid relative comparisons. The analysis of the overall distributions of signal amplitudes amongst all data runs should be calculated to determine the appropriate scale factor to use for each data channel. The scale factors chosen should be low enough that the cyclic load-life models do not imply failure at extremely low cycle counts.

After selection of the scale factor for each channel, the analysis process outlined in the fatigue damage editing process is used to remove the "non-damaging" regions of data.

C. Statistical Region Selection

A final method used to reduce test time from the raw field data is known as Statistical Region Selection. Statistics calculations are performed over moving windows in the file to identify non-damaging regions. Correlation exists between the standard deviation of forces measured by wheel force transducers and structural fatigue on the vehicle. Since force typically has a linear correlation to strain on a structure, the use of force data may be substituted for strain data. Often, a four second window is used with wheel force transducer vertical and lateral force data for assessment. Typically, the standard deviation of vertical force over the 4 second window is set to 20% of the wheel weight as a starting point. The value is then adjusted based on the results to provide a conservative reduction of the simulation file time.

D. Rebuilding Compressed Time Histories.

The last step in the process is to remove the benign sections of data and then splice the remaining portions of the time history data together. The process uses a smooth taper over a 0.5 to 1 second window to align sections of data. The tapering ensures that the signal does not jump discontinuously and smoothly merges at each time history splice location. The splice is done by a graduated method of averaging the data on each side of the merge. An example of a tapered versus non-tapered splice of a time history file is presented in Figure 6.

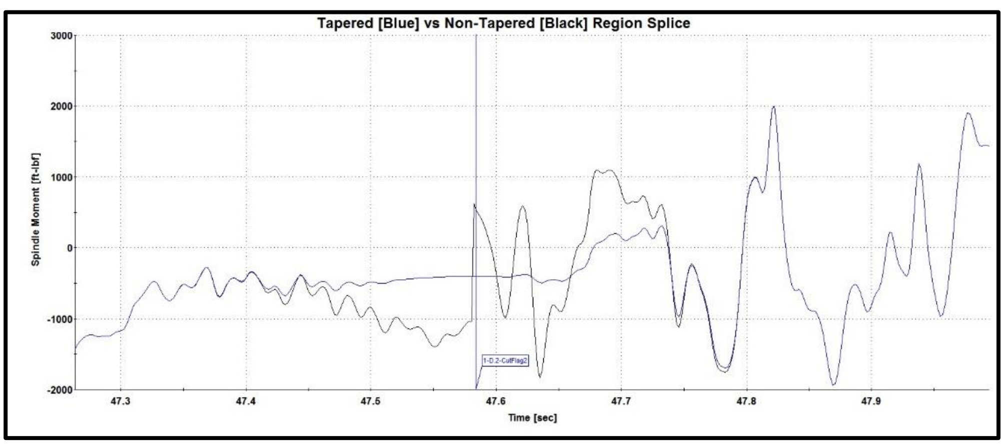

Figure 6. Example of tapering splices of a time history.

Drive File Creation

After the desired response files have been edited to remove benign portions of the data, the next step is to filter the files to remove data content that cannot be physically simulated. The VDS is an inertia-reacted simulator, which means that all forces are created by actuator inputs to the vehicle wheels. The problem is most pronounced for force and acceleration measurements made in the horizontal plane. Typically, a high-pass filter is applied to all the data channels to remove any frequency content below 0.5 Hz. A process known as signal decomposition is used to retain some of the low frequency content that would be otherwise be removed from the simulation, thus improving simulation integrity as compared to actual field operation.

To further illustrate the signal decomposition process, two front lateral wheel force channels, F_{y1} and F_{y2} (corresponding to the two front wheels), are decomposed into lateral compressive and lateral translational forces, F_{fC} and F_{fT}. A compressive force is internally reacted by the vehicle structure, whereas a translational force causes a free-body acceleration. After decomposing the lateral force, a high pass filter is applied to F_{fT}, resulting in F_{fT_hp}. A frequency-based high-pass filter is typically used. The filter works by computing a Fast Fourier Transform (FFT) and then zeroing out the FFT bins below the cut-off frequency. After zeroing out the low frequency content, an inverse FFT (iFFT) is applied to reconstruct the time history signal. The filter cut off frequency is set high enough so that the final actuator drive translational forces will not be commanded to push the test item farther than the displacement constraints of the rig, when trying to replicate near-static force events such as turns or driving on laterally sloped surfaces. If compressive forces acting on the front axle do not result in the hardware limits being exceeded, then F_{fC} should remain unfiltered to retain any effects those forces have on the test item. F_{fC} and F_{fT_hp} are then recombined (“recomposed”), resulting in a modified time history of the lateral wheel forces, F'_{y1} and F'_{y2}. The modified channels are used in subsequent analysis and drive file development. Signal decomposition is an important step, because simply high pass-filtering the unmodified F_{y1} and F_{y2} results in removing actual compressive forces.

The signal decomposition approach for handling translational and compressive forces is further applied to other data channel combinations, such as the rear axle lateral forces and the longitudinal forces acting on the left and right sides of a vehicle. The matrix-based relationships between spindle forces and the control channels are presented in Equations 1 through 4. Once this work is completed, the final desired response files are ready for use in creating the actuator drive files.

$$\begin{bmatrix} Lateral\ Translation \\ Front\ Lateral\ Compression \\ Rear\ Lateral\ Compression \\ Shear \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ -1 & -1 & 1 & 1 \end{bmatrix} * \begin{bmatrix} LF\ Fy \\ RF\ Fy \\ LR\ Fy \\ RR\ Fy \end{bmatrix} \qquad \textit{(Equation1)}$$

$$\begin{bmatrix} .25 & -.5 & 0 & -.25 \\ .25 & .5 & 0 & -.25 \\ .25 & 0 & -.5 & .25 \\ .25 & 0 & .5 & .25 \end{bmatrix} * \begin{bmatrix} Lateral\ Translation \\ Front\ Lateral\ Compression \\ Rear\ Lateral\ Compression \\ Shear \end{bmatrix} = \begin{bmatrix} LF\ Fy \\ RF\ Fy \\ LR\ Fy \\ RR\ Fy \end{bmatrix} \qquad \textit{(Equation 2)}$$

$$\begin{bmatrix} Longitudinal\ Translation \\ Left\ Longitudinal\ Compression \\ Right\ Longitudinal\ Compression \\ Shear \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} * \begin{bmatrix} LF\ Fx \\ RF\ Fx \\ LR\ Fx \\ RR\ Fx \end{bmatrix} \quad \textit{(Equation 3)}$$

$$\begin{bmatrix} .25 & -.5 & 0 & .25 \\ .25 & 0 & -.5 & -.25 \\ .25 & .5 & 0 & .25 \\ .25 & 0 & .5 & -.25 \end{bmatrix} * \begin{bmatrix} Lateral\ Translation \\ Front\ Lateral\ Compression \\ Rear\ Lateral\ Compression \\ Shear \end{bmatrix} = \begin{bmatrix} LF\ Fx \\ RF\ Fx \\ LR\ Fx \\ RR\ Fx \end{bmatrix} \quad \textit{(Equation 4)}$$

Next, the test vehicle is mounted onto the VDS with the same test sensors in place that were used during field data collection. The vehicle is attached to wheel-end actuator sets that affix to the vehicle wheel hubs. Six actuators are used on each actuator set to provide terrain loads to the vehicle that simulate the field inputs.

RPC is used to create the VDS actuator drive command files needed for simulation. System identification is performed by sending white noise signals to all simulator actuators, then measuring the vehicle sensor responses. Inverse FFTs are developed for each drive command file. An iterative process follows where the sensor response data files are multiplied by the iFFT to create new drive commands. Iteration continues until the observed RMS errors between the actual and desired response files are within 5-10%. This process requires engineering discretion, because with typically more than 24 response files to evaluate, it's very difficult to get all the channels converging perfectly. Therefore, the test engineer usually focuses on important responses, based on experience and judgement.

Life Cycle Testing

Before starting accelerated test operations, an ensemble of drive files is developed to replicate the typical OMS/MP test sequence and mission blocks. Note that each accelerated (or time shortened) drive file represents the same vehicle mileage accumulated when the field data was recorded, but requires less time to execute. The drive files are repeated in sets, as necessary, to produce the mileage required for each block of the OMS/MP missions.

The VDS drive inputs and test item responses are continually monitored for validity throughout testing. The response of the test item will change throughout testing due to mechanical compliances, internal coupling, and nonlinearity as components degrade due to wear. The first run of each unique course and payload combination after drive file development has been completed should be recorded as reference files. The reference files are then used for comparison throughout the life cycle simulation. Trend monitoring is used to automatically stop the simulation and warn the operator if the RMS, maximum, or minimum of the acceleration, force and/or strain channels, between the current run and reference file, exceed the selected limits. The limits are typically set at 10 percent variation from the reference files.

Vehicle inspections are performed every 4-6 hours of simulation to note potential failures and observe fatigue crack growth, if observed. A drive file run log is maintained beginning with the first drive iteration, with each record containing the following: date and time of the drive initiation, name of the represented terrain, drive file iteration number, frequency response function (FRF) reference name, and distance represented by the drive file. Test sequences are repeated until the target test mileage is achieved or critical failures are experienced.

ACCELERATED FIELD-BASED DURABILITY TESTING

An accelerated reliability/durability test of a military wheeled vehicle was recently conducted at ATC, where the vehicle mission objectives were very specific and the fielding schedule was very short. Furthermore, the number of test/operation miles was planned to be approximately 2000 miles per vehicle, with two vehicles. An accelerated field test was chosen as the best course of action, with a primary focus on revealing any potential high risk failure modes as quickly as possible.

The test methodology closely followed the initial HITL simulation methodology described previously. The OMS/MP breakdown of terrains was identified, which included approximately two-thirds paved operations and one-third cross-country. Field data collection was conducted to measure terrain load forces and accelerations on the various cross-country test courses normally associated with the OMS/MP terrains. The miles accumulated during data collection were counted towards the target mileage.

The highway component of paved operations was accelerated by operating the vehicle at 60 mph (96 kph), rather than at the 50 mph (80 kph) normally used for reliability testing of this particular vehicle. Checks were made to ensure cooling issues were not encountered during sustained operations. The intent was to accelerate the accumulation of fatigue loading on the powertrain.

Rainflow analyses were conducted on the wheel force and acceleration data collected on the cross-country courses, which included some trail operations. A graphical review of the data very clearly showed which courses imparted the most fatigue damage to the vehicle in terms of chassis loads, which courses actually had similar content, and which courses were benign. The benign courses were viewed from a chassis, steering, and driveline loading perspective as likely producing loads below the endurance limits of the materials.

After data collection and analysis were complete, approximately 600-650 miles of cross-country operation remained for reliability/durability testing, per vehicle. To accelerate testing, the benign courses were replaced with the more aggressive courses in the test course usage matrix. To illustrate the acceleration breakdown, a simplistic hypothetical example is shown in Table 1. In effect, use of the more aggressive courses was doubled up. The notional concept was that operation for only 600 miles on the more aggressive courses was equivalent to 1200 miles of operation if the normal OMS/MP percentages had been used. Realizing that revealing potentially high risk failure modes (chassis structure, etc) was the objective, not low risk failure modes such as seal wear, this seemed like a logical and traceable approach. Consequently, the estimated acceleration factor for cross-country usage was two to one.

TABLE 1. HYPOTHETICAL CROSS-COUNTRY COURSE SELECTION PROCESS

Test Course	Rainflow Result	OMS/MP Planned Mileage (mi)	Executed Mileage (mi)
Course 1	More aggressive	150	300
Course 2	Benign	100	0
Course 3	More aggressive	50	100
Course 4	More aggressive	100	200
Course 5	Benign	150	0
Course 6	Benign	50	0
Actual Total (mi)		600	600
Equivalent Total (mi)		600	1200

SUMMARY AND CONCLUSIONS

Two recent approaches to accelerated reliability/durability testing of military wheeled vehicles were presented. The first approach was laboratory HITL testing, and the second approach was field-based testing. Both methodologies required instrumented field testing to identify test course operations that produced the most fatigue damage. Benefits of the laboratory-based HITL approach include opportunities to precisely control the load inputs in a repeatable manner and to witness/observe material crack initiation and growth, since the vehicle stays clean throughout testing. Acceleration factors up to 5 times faster than the pace of a traditional field test have been demonstrated, with observed failure modes consistent with field testing and finite element analysis results. Accelerated field testing may be more beneficial when potential failure modes are unknown, or the vehicle is not able to be mounted on the laboratory test rig. Acceleration factors of 2 times faster than traditional field testing have been estimated, but correlation to traditional field test failure mode observations have not yet been verified.

REFERENCES

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2. Brudnak, M., Walsh, J., Baseski, I., and LaRose, B., "Durability Test Time Reduction Methods," SAE International Journal of Commercial. Vehicles. 10(1):113-121, 2017, doi:10.4271/2017-01-0258.