VEHICLE PROGNOSTICS: UNDERSTANDING USAGE SEVERITY AND POTENTIAL DAMAGE ACCUMULATION FOR A COMBAT VEHICLE SUSPENSION COMPONENT

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UNCLAS: Dist A. Approved for public release

ABSTRACT

Vehicle prognostics are used to estimate the remaining useful life of components or subsystems, based on measured vehicle parameters. This paper presents an overview of a vehicle prognostic system, including the critical tasks associated with configuring such a system. The end user of a vehicle prognostic system focuses on the reports generated by the system that provide indications of vehicle readiness, condition and remaining useful life. These reports are based on measurements recorded from sensors on the vehicle and analyzed either on the vehicle or remotely by a "back office" information management system; the latter also provides usage severity trends. To implement such a system, an engineer must first define the vehicle components of interest and determine "damage correlates": the relationship between damage occurring on key component(s) and key vehicle parameters that can be obtained from vehicle "bus data". These "damage correlates" and the associated analysis methods are combined with component usage severity information such that the remaining useful life of the component is estimated. One of the most complex steps in this process is calculating "damage correlates" and a specific example is shown for a combat vehicle suspension component. A key suspension component was identified based on maintenance, repair and replacement costs. Measurements were undertaken on durability road surfaces, where loads on the suspension component and vehicle data were measured simultaneously. A damage model for the suspension component was developed based on the measured component loads. This was used to identify key vehicle parameters, establish transfer functions and together with a simple damage model, establish "damage correlates". The key to success is that the vehicle parameters are easily measurable and can be correlated to specific component damage and deterioration. This paper illustrates the challenges and successful implementation of this approach for a suspension component on a combat vehicle.

INTRODUCTION

Vehicle prognostics are the process of estimating the remaining useful life of specific vehicle components or sub-systems by assessing the degradation rate of these components. This involves continuous monitoring of vehicle usage using embedded sensors, an on-board processor and a "back office" application to evaluate the vehicle's actual condition, the rate of damage accumulation and determine the likelihood of failure to diminish risk. In order to provide prognostics estimates, it is important to understand the component of interest in terms of potential failure modes, critical locations, and understanding of damage accumulation. Key factors to be considered include scalability, robustness, cost effectiveness and ease of installation of the sensors and on-board processor plus ease of access to information from multiple operational vehicles for trend analysis and understanding of mission readiness.

This paper describes the components of a vehicle prognostic system, from what the end user sees to the critical tasks associated with configuring such a system. This is followed by an example of one of the most complex parts of the configuration process; how the transfer function and "damage correlates" are calculated for a combat vehicle suspension component.

VEHICLE PROGNOSTIC SYSTEM

From the end-user perspective, a vehicle prognostic system consists of 3 components: sensors on the vehicle, an on-board processor and a "back office" application that are all used to generate reports as shown in Figure 1. The reports allow the end user to monitor trends over the vehicle fleet, identify vehicles of high usage, determine how individual vehicles are being used, and compare vehicle usage with design limits.

Figure 1 - Vehicle prognostic System from the User Perspective

A vehicle prognostic system provides a tremendous amount of information and the benefits of such a system include:

- Service, support and operational cost reductions by reducing unscheduled maintenance and setting maintenance schedules according to severity of usage.
- Actual usage data of fielded vehicles for investigating and analyzing root cause failures and to quickly respond to potential field issues.
- A better understanding of the vehicles actual end use to assist engineers with design life optimization and accelerate deployment.
- Improve mission readiness and reduce logistics footprint.

The steps required to configure a vehicle prognostic system are: identify key components to monitor, establish "damage correlates" (which includes transfer functions) to relate measured parameters to damage at the key components, identify the key sensors and vehicle parameters to be measured, define how the data will be measured on-board the vehicle, stored and off loaded to the "back office" software, establish the design usage specification and define the analysis methods and reports required by the end user as shown in Figure 2. The individual components of the prognostic system are described in the next section.

COMPONENTS OF A VEHICLE PROGNOSTIC SYSTEM

Identify Key Components

There are two fundamental approaches to gathering vehicle data: "bottom-up" and "top-down". "Bottom-up" involves measuring all available data and then trying to sort out meaningful information. This approach suffers from major challenges related to bandwidth, transmission of data, on-board storage, cost and complexity. A more appropriate approach ("top down") is to define the stakeholders that need information and then identify key components and systems to be evaluated. Key components can be identified by examining maintenance and usage trends to determine the cost drivers for scheduled and unscheduled maintenance. In addition to these cost critical items, it is important to monitor high value components or subsystems such as the engine or transmission and components of potential concern.

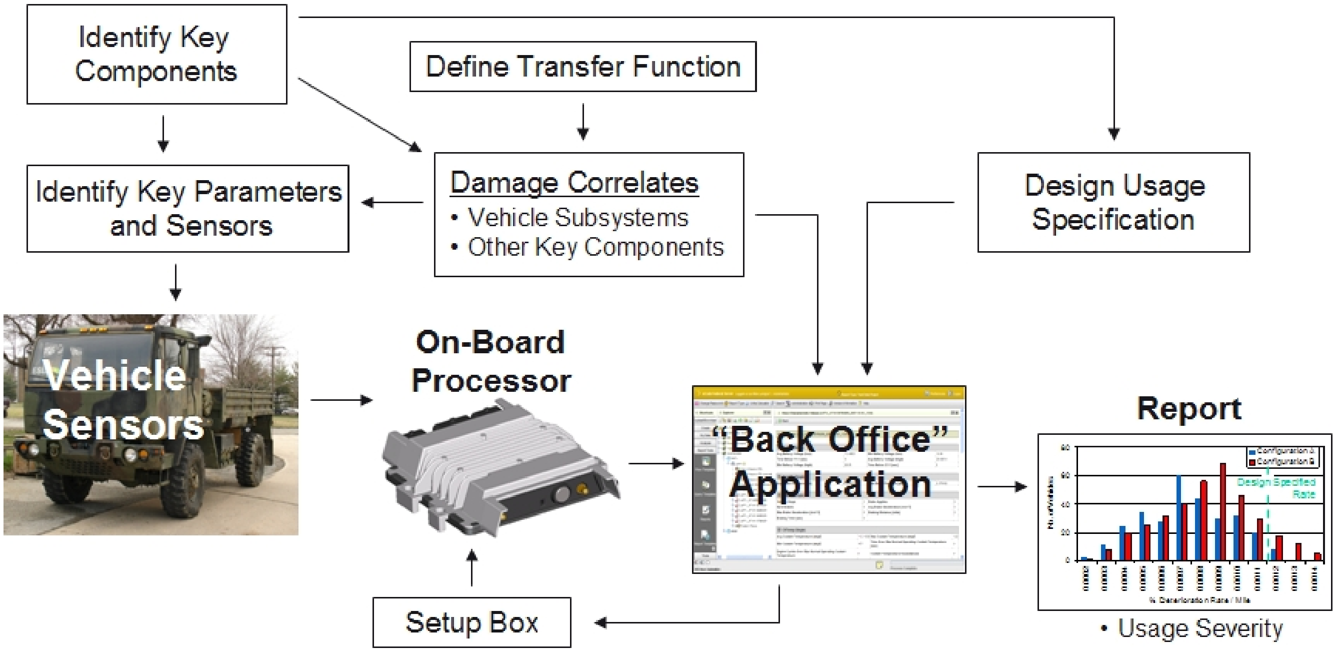

Figure 2 - Configuration of a Vehicle Prognostic System

"Damage Correlates" and Transfer Functions

After the key components have been identified, it is essential to understand the potential failure modes, critical locations and critical loads for each of these components and how these components can be monitored in an effective and practical manner. Ideally, sensors would be available for every component and failure mode of interest, such that accurate data could be measured and used in prognostic estimates. However, this is impractical in terms of the number of sensors required, the costs to install such a system and maintain its integrity. An alternative solution is to relate the loading on a specific component to vehicle behavior, using readily available vehicle data and a limited number of additional sensors. "Damage correlates" are then used to provide the relationship between damage occurring on key component(s) and available data, such as vehicle parameters and vehicle bus data. "Damage correlates" are obtained by understanding the potential failure mode and key loads that influence failure, establishing a transfer function between the loading on the key component and available vehicle data, and creating a fatigue model for damage accumulation. The transfer function can be established using a detailed data acquisition on the proving ground, numerical modeling, laboratory measurements, or seeded fault studies. An example is provided that details how "damage correlates" were established for a suspension component, using proving ground measurements.

Identify Vehicle Parameters and Sensors

The "damage correlates" define what needs to be measured and what needs to be derived as part of the damage determination model. The goal is to use as much vehicle bus data as possible and minimize / avoid additional sensors. A few examples of this approach are: braking can be identified as decreases in vehicle speed coupled with changes in vehicle pitch, lateral loads can be derived from changes in vehicle direction linked with differential wheel speeds or vehicle roll, and driveline torque can be derived from engine load, engine speed, and gear position. The identified parameters and sensors are then monitored using an on-board processor.

Vehicle Sensors and On-board Processor

An on-board processor is placed on the vehicle to store the desired parameters from vehicle bus data or sensors. Data analysis can take place on board the vehicle or in the "back office" application. Any analysis performed on board the vehicle helps reduce the amount of information that needs to be transferred from the vehicle. In addition, some information may constitute an immediate need while other data provides general trending information for improved operational understanding of the vehicle and the fleet. Immediate alerts can be used when an unusual event occurs or a particular measurement exceeds a defined level. The downloading of the majority of information can take place periodically under controlled conditions at the convenience of the vehicle operator. The system can be configured to:

- Identify the key data from the vehicle bus and synchronize this by time stamping.
- Check the data for errors and anomalies
- Identify and combine the key data to calculate "damage correlates" for the key components/systems being considered.
- Identify extreme values that are beyond defined thresholds to send messages to appropriate stakeholders.
- Analyze the "damage correlates" to create damage parameters that can be stored as discrete characteristic values, Rainflow histograms, time-at-level matrices, etc. for download as discussed in next section.

An on-board system needs to have flexibility in the setup of what data to collect, how often to collect it, what algorithms to apply, what statistical manipulations to perform, and how time blocks are stored. With this flexibility, the on-board system can monitor data for usage severity evaluation and to understand specific field failure modes that could come into play when a quality issue is suspected. Field usage data can be quickly collected to better understand the problem and find a solution, thus avoiding the issue of becoming a high cost maintenance or replacement issue.

Design Usage Specification

The design usage specification defines the safe design life of a component and is required in prognostic calculations to estimate the remaining useful life. The design usage specification can be determined from laboratory simulation testing, proving ground testing, numerical simulation, maintenance data or fleet usage. For example, in proving ground tests the component could have either failed or survived. If the component failed, the design usage specification represents failure and is defined by the miles completed on the proving ground before failure. If the component survived, the design usage specification would be defined by the total number of proving ground miles that were completed. In this case the component could continue to be functional beyond the tested miles but it would be operating beyond the known "safe regime". The basic approach is to establish a "stake in the ground" against which severity of usage and deterioration rates can be assessed.

The design usage specification is not necessarily failure of the component, but corresponds to the extent it has been tested and provides a safe limit for prognostic estimates.

"Back Office" Application

A web-enabled "back office" software application contains vehicle operational usage data collected from multiple vehicles. The data is stored in a structure that readily allows query, processing, reporting, storing and downloading of the vehicle information. User defined processes are used to analyze the vehicle information and report vehicle operational parameters describing component and system behavior. Some examples of available analysis methods include: summary information about engine usage, component or system deterioration rates, comparisons between individual vehicles, different vehicle configurations, different operating locations, etc. Comparisons can be made between vehicles and compared to known design specifications, laboratory simulation tests or proving ground tests in terms of deterioration rates to determine if the fielded design life is near the design life limits. By calculating the progressive deterioration, the rate at which "damage" is accumulating can be compared to the safe operating regime to estimate the potential remaining life.

The vehicle parameters calculated and stored in the system capture vehicle usage and form the basis to allow the determination of vehicle severity of use and component wear and deterioration rates relevant for prognostics. Over time, as the usage data continues to be collected and the corresponding vehicle maintenance and repair data becomes available, models can be refined for specific vehicle prognostics and diagnostic issues.

Reports

The "back office" application combines information from multiple vehicles to deliver reports to stakeholders that summarize usage in terms of engineering information that can compare locations, fleets, drivers, potential remaining life, etc. An example is shown in Figure 3 that shows the potential remaining life for 6 vehicles. The potential remaining life is calculated based on accumulated damage from previous usage to determine the deterioration rate, which is divided into the design limit, where the design limit is based on actual performance criteria such as a proving ground specification the vehicle is known to survive (safe regime). This provides guidance to the various "stakeholders" concerning likelihood of failure, time to maintenance and allows fleet and user comparisons, avoidance of potential issues and improved mission readiness.

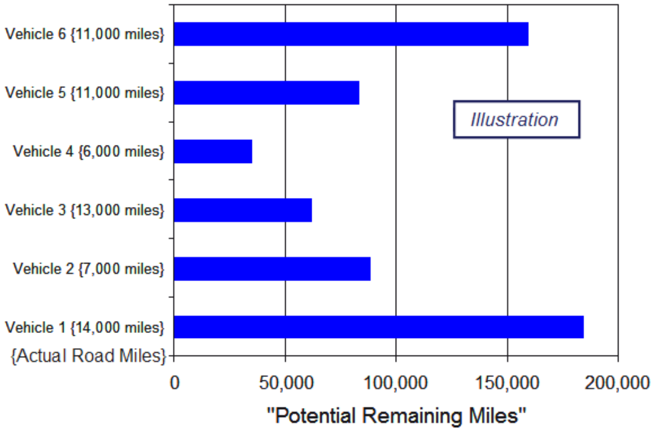

Figure 3 - Potential Remaining Life of Structural Component – Based on PG Specification Testing

EXAMPLE: "DAMAGE CORRELATE" FOR A SUSPENSION COMPONENT

One of the most complex steps in configuring a prognostic system is establishing the "damage correlate" – the relationship between damage occurring on key component(s) and key vehicle operational parameters that can be readily measured. This example provides the details of this process along with a brief explanation of the background.

The operator of a vehicle fleet, in this case the PM for combat vehicles, is well aware of major maintenance and safety critical items on their vehicles. In this study a suspension component was identified as a costly recurring maintenance item. Significant costs are being incurred for regular inspections and replacement of the component in order to keep vehicles operational. In addition, unexpected failures in the field are unacceptable in terms of cost, operator safety and mission readiness. As a result, the PM was motivated to better understand loading on the component with the end goal of developing a monitoring / prognostic system.

To date only the initial part of configuring a complete system installation has been completed. This identified key operating events that cause the most damage to the component and established "damage correlates" using vehicle parameters that could be related to component loading and could be readily monitored in service to estimate remaining life.

In order to measure component loading during operational service, one of two methods can be used: measure the loading with sensors on the component or measure vehicle parameters and calculate component loading based on transfer functions. For this application it was impractical to place sensors on the component in service, due to the complexity of the sensor, difficulty with retrieving the signal, and concerns over the robustness of the sensor over the long term. The adopted approach was to initially measure component loading together with relevant vehicle parameters such that a transfer function could be established under controlled and relevant conditions at the proving ground. These vehicle parameters could then be used long term to estimate loading on the suspension component during operational service.

Data Acquisition

Forensic studies and modeling identified the key loads causing component damage were tension and torque. The component was instrumented using strain gages and calibrated in a laboratory test rig in terms of the two primary loading conditions: tension and torque. The instrumented component was installed on the vehicle together with instrumentation to measure both the strain gage (load) data and vehicle parameters. The later were: GPS (speed heading, altitude, etc), accelerations in 3 directions located at the CG and angular motion in 3 directions (roll, pitch and yaw). All the instrumentation was connected to a data acquisition system to simultaneously capture all channels during the measurement exercise at the proving ground. Video was also captured during some events and proved helpful in verifying high load conditions.

The data acquisition was performed for three types of proving grounds events: fundamental maneuvers, durability circuits and extreme loading. The fundamental maneuvers are simple controlled conditions such as driving straight ahead at various speeds, vehicle acceleration and braking, turning, going over an obstacle and wash board. Durability circuits are the standard durability routes at the proving ground that tend to be much longer events and used to create the vehicle duty cycle. Extreme loading is situations that are not necessarily included in the durability circuit but do occur in service and cause high load levels on the component, such as panic braking, hard turns, pot hole strikes or steep hills. The measured time series data for a fundamental maneuver, straight ahead driving, is shown in Fig 4, with a short turning maneuver at the start of the time series and a braking maneuver at the end. Figure 4 includes, 2 vehicle parameters (speed, heading) and the 2 component loads (tension, torque) that relate to damage on the component. Before the key events can be identified and the transfer function established, a damage model must be created such that the correct combination of component loading is used to develop the transfer function.

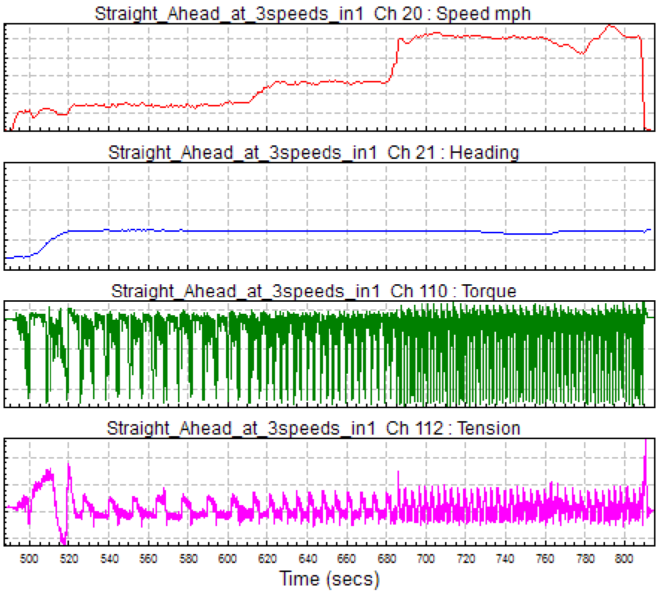

Figure 4 - Straight Ahead Driving

Damage Model – Load Combination

A damage model consists of a number of parts including how the component loads (tension and torque) are combined into a parameter that is appropriate for damage calculations assuming a uniaxial fatigue model is being used. The other relevant segments of the damage model are described later. The component load combination can be determined analytically through finite element analysis or through measuring component strains in laboratory loading tests to determine scale factors that are applied to each component load such that the combination equals the “uniaxial load” at the critical location of interest. This “uniaxial load” could be load, strain or stress depending on the fatigue methodology being used. In this case, the sum of the tension and torque loading was identified as the “uniaxial load” at the critical location on the component and is referred to as the “local load”. The load combination is shown in Figure 5 for the same fundamental maneuver.

Identify Key Events

The first pass in identifying key events is to look at the fundamental maneuvers and determine the points in time at which the highest local load range occurs. The highest local load, shown in Figure 5, occur at the end of the time series (the largest range), at the beginning (the next highest), and in the middle (to a lesser extent), while the remainder is fairly

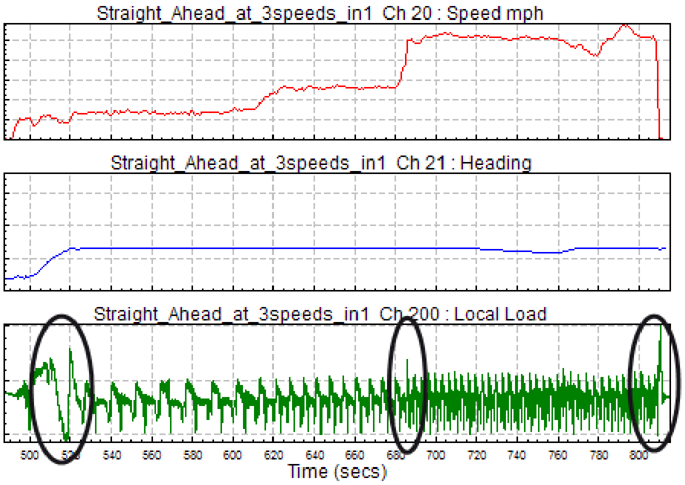

Figure 5 - High Load Occurrences for the Local Load

constant in terms of range. The next step is to determine what the vehicle is doing when these high local loads occur. Starting with the highest local load, which occurred at the end of the sequence at approximately 810 seconds, the speed abruptly decreases representing deceleration of the vehicle. Hence the highest local load occurrence is due to braking. The second largest local load is at the start of the sequence at approximately 520 seconds and shows that the speed is relatively constant but the heading changes. Hence the high local load occurrence at the beginning is due to a turning event. The next highest local load level occurred at approximately 685 seconds and corresponds to a rapid increase in the speed channel. Hence the high local load occurrence in the middle is due to acceleration of the vehicle.

By examining this fundamental maneuver, a number of key events were identified. The other fundamental maneuvers were also examined to determine if vehicle acceleration, braking and turning consistently caused high load levels and this was found to be true. Further examination of the component loads in Figure 4, shows the high local load levels correspond to high transient loads in the tension channel, while the torque channel did not vary significantly in terms of range and could be represented by a constant amplitude cycle. It was found that the frequency of occurrence of the torque cycles was proportional to the speed of the vehicle as was the smaller amplitude cycles in the tension channel. Upon further examination these cycles repeat themselves based on distance travelled, where the period was inversely proportional to vehicle speed.

In parallel, the vehicle parameters were measured for comparison with the local load measurements as the basis for creating the transfer functions and “damage correlates”.

The fundamental maneuvers and extreme loading were examined first, because it is much easier to determine what the vehicle is doing and relate the high local loads to specific vehicle maneuvers. After the key vehicle parameters for the fundamental maneuvers and extreme loading were determined, a preliminary transfer function (as described in the next section) was established. From this a preliminary “damage correlate” was calculated. This was applied to measured vehicle parameter data recorded on the durability circuits and compared to local load data measured on the component in parallel to determine the level of correlation. From this analysis, it was determined that an additional vehicle parameter could help improve correlation. The durability circuits were divided into segments to determine which areas to examine in more detail. It was found that pitching of the vehicle resulted in significant tension loading on the component while driving on some of the off road circuits and a rough correlation was found between component tension load and vehicle pitch as shown in Fig 6 in terms of the overlay of the time series data and as a cross plot between the channels. A principal component analysis could also have been used to identify potential vehicle parameters of interest.

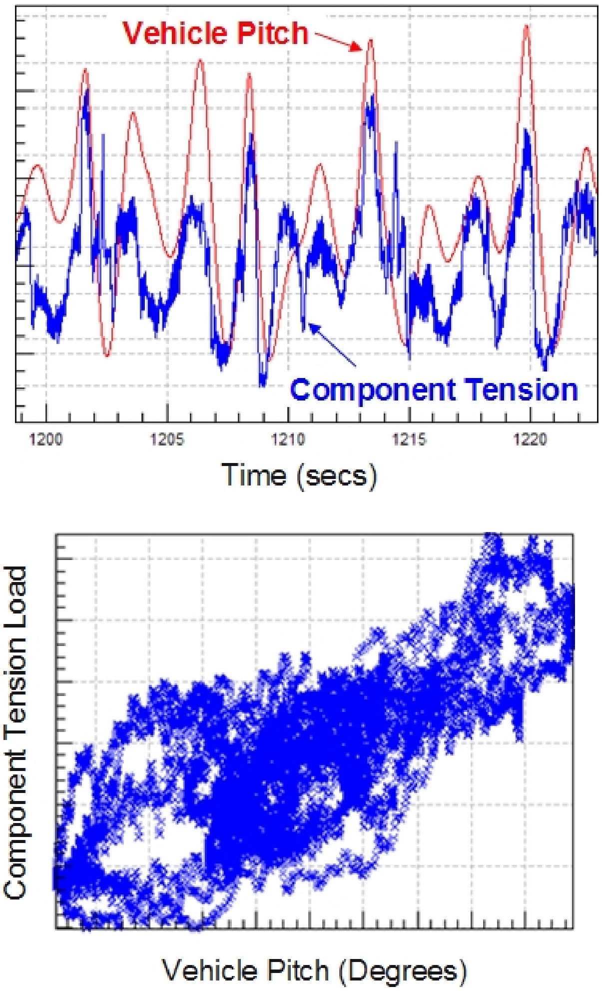

Figure 6 - Vehicle Pitch versus Component Tension

Key Vehicle Parameters

The key events identified from the fundamental maneuvers were vehicle acceleration, braking, turning and distance travelled, while vehicle pitch was identified from the durability circuit. The next step is to identify which vehicle parameters can be used to represent these vehicle characteristics of interest. Vehicle acceleration can be derived from vehicle speed by differentiating the speed channel and taking the positive portion for acceleration and the negative portion for braking. Turning is calculated from the GPS heading channel. The small amplitude cycles are based on distance travelled, which can be determined by integrating the vehicle speed. Vehicle pitch can be measured from a dedicated sensor or may be available from other vehicle systems.

Transfer Function

The transfer function is derived by combining the 5 vehicle parameters: vehicle acceleration, braking, turning, pitch and distance travelled.

The first 4 vehicle parameters can be combined linearly with scale factors applied to each to calculate local loads. The magnitude of the scale factors is determined by independently matching the relative magnitude of the vehicle parameter and the local load over a number of occurrences of the maneuver (to ensure its consistency). The scale factor for vehicle pitch is the slope of the cross plot shown in Figure 6. This method requires that key events are independent, which is another reason to start with the fundamental maneuvers. The time signals of vehicle acceleration, braking, turning and pitch are scaled by the appropriate scale factors and summed to create the estimate tension load time signal. A comparison of tension load for the measured component tension and the tension estimated from vehicles parameters is shown as an exceedance plot in Figure 7, based on Rainflow counting.

The 5th vehicle parameter (distance travelled) is treated differently as it represents the smaller constant amplitude cycles observed on the component torque channel. A repeating waveform is calculated, where the period is based on a fixed distance travelled and the amplitude is the measured component torque, since it was nearly a constant amplitude signal.

The estimated time series for the component torque is summed with the estimated component tension and the result is a time series calculated from all 5 vehicle parameters that represents the local loading conditions and is referred to as the estimated local load time series. It is not necessary to reproduce the local loading signal exactly, but to provide the correct trends in terms of identifying the damaging events and damage accumulation.

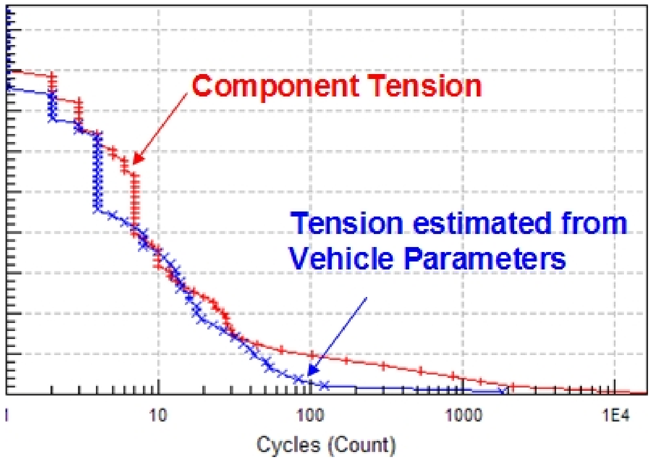

Figure 7 - Exceedance Plot of Component Tension and Estimate Component Tension for Fundamental Maneuver

Damage Model

The damage model used in this example is based on the load-life approach with the material model represented as a load life curve with a slope of -3 to match the material fatigue curve at the critical location. A more complex damage model could easily be used but is not required for this illustrative example. The next step is to perform the fatigue calculations for the local load history (based on actual measured component loads) and for the estimated local load history (based on vehicle parameters) for each run at the proving ground to calculate relative damage numbers. Data was available for 18 different proving ground runs and the damage calculations are shown in Figure 8 and 9. This shows the individual damage numbers for each proving ground run in a tower plot and as a relative comparison where perfect correlation would be a 45 degree line.

"Damage Correlate"

A "damage correlate" is the combination of the key vehicle parameters, the transfer function and the damage model. The results show that the "damage correlates" give good correlation in terms of relative damage over 18 different proving ground runs and demonstrate that easily measurable

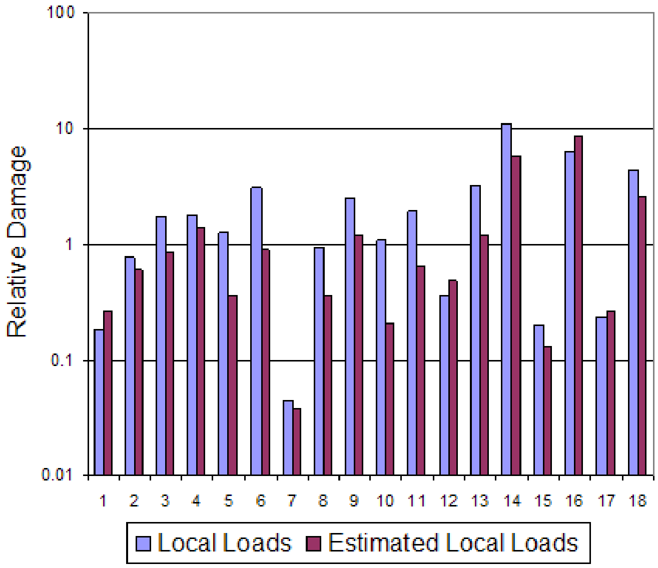

Figure 8 - Damage Comparison – Tower Plots

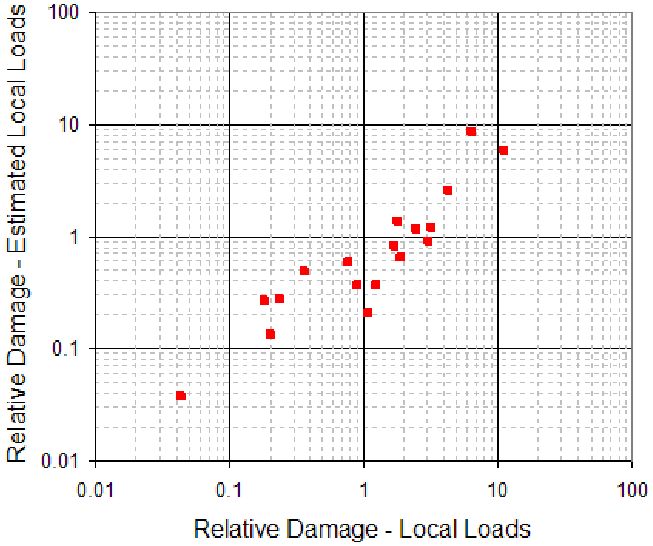

Figure 9 - Damage Comparison – Cross Plot

vehicle parameters (e.g. speed, GPS, pitch, etc.) can be correlated with specific component damage and deterioration rates. This is significantly more effective in terms of scalability, cost, reliability and operational effectiveness than using dedicated sensors on components and systems to understand usage severity for individual vehicles and vehicle fleets.

CONCLUSION

This paper explains each of the components of a vehicle prognostic system, which are used to estimate the remaining useful life of components or subsystems, based on measured vehicle usage data. An example is provided showing how “damage correlates” were successfully developed for a combat vehicle suspension component. The results show that easily measurable vehicle parameters can be used to estimate component damage and deterioration rates, which is a cost effective, scalable and reliable solution for determining usage severity for prognostic estimates. This provides vehicle fleet information that improves decisions on deployment and mission readiness. In addition, understanding operational usage severity provides valuable input for future designs and design improvements plus the development of realistic accelerated test and evaluation schedules.

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ACKNOWLEDGEMENT

This material is partially based upon work supported by the U.S. Army TACOM Life Cycle Command under Contract No. W56HZV-08-C-0236, through a subcontract with Mississippi State University under the Simulation Based Reliability and Safety (SimBRS) research program.

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