INVESTIGATION OF THE DURABILITY TRANSFER CONCEPT FOR VEHICLE PROGNOSTIC APPLICATIONS

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The Durability Transfer Concept Premise

“Fatigue damage under operational loading conditions in different areas of a vehicle can be determined by the accelerations measured on the suspension.”*

* Rupp, et al. “Durability Transfer Concept for the Monitoring of the Load and Stress on Vehicles.” Innovative Automotive Technology Conf., Bled, Slovenia. 21-22 April 2005.

Measure accelerations here

Estimate damage here, or here, or here, or …

Benefits

- Onboard data storage significantly reduced – from large time histories to compact damage histograms.
- Eliminates having to strain gage multiple components on entire fleet for the life of all vehicles.
- Field personnel better able to monitor vehicle health and usage, leading to more informed decisions about mission readiness.

Objectives

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

1. Assess accuracy of the Rupp Durability Transfer Concept for damage correlation of automotive components based on nominal vehicle acceleration measurements.
2. Create a software platform on which to validate the method. **CREATE MODEL**
3. Process measured acceleration data and strain data from a vehicle traversing a proving ground and attempt to model the transfer function between acceleration and strain-based fatigue. **TRAIN MODEL**
4. Apply the model to a mix of measured data and determine the goodness of fit between the transfer function approach and the measured strain approach. **APPLY MODEL**

The Durability Transfer Concept Process

- Step 1 – **COLLECT** representative accelerations on the suspension. Collect strains at key components on the vehicle for correlation. Derive damage vs frequency from accelerations.

- Step 2 – **TRAIN** the system using proving ground data. Derive transfer functions that allow suspension accelerations to describe the damage at key components on the vehicle.

- Step 3 – **APPLY** derived transfer functions to predict accumulated damage over long periods of time.

Durability Transfer Concept – Step 1 of 3

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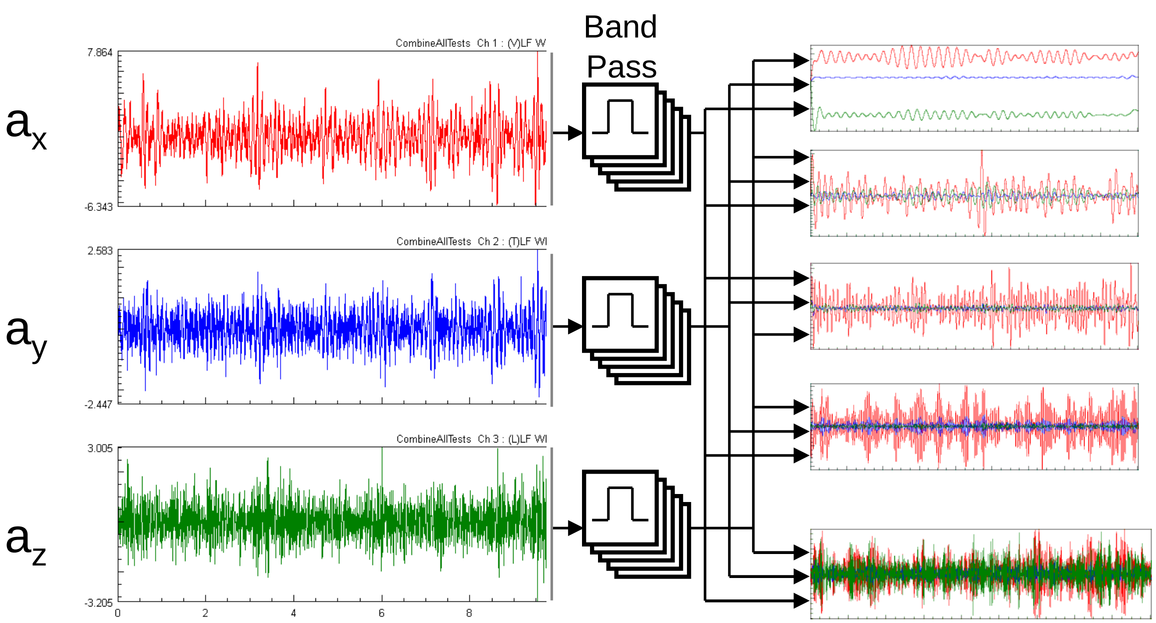
Step 1 – Collect representative accelerations on the suspension.
Collect strains at key components on the vehicle for correlation.
Derive damage vs frequency from accelerations.



$a_{x,y,z}$ for 0-2 Hz

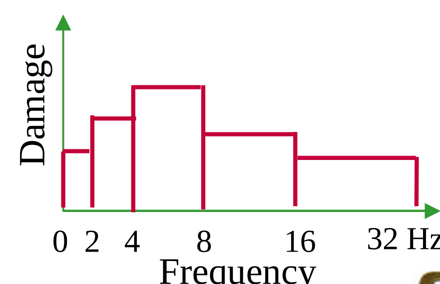
$a_{x,y,z}$ for 2-4 Hz

$a_{x,y,z}$ for 4-8 Hz

$a_{x,y,z}$ for 8-16 Hz

$a_{x,y,z}$ for 16-32 Hz

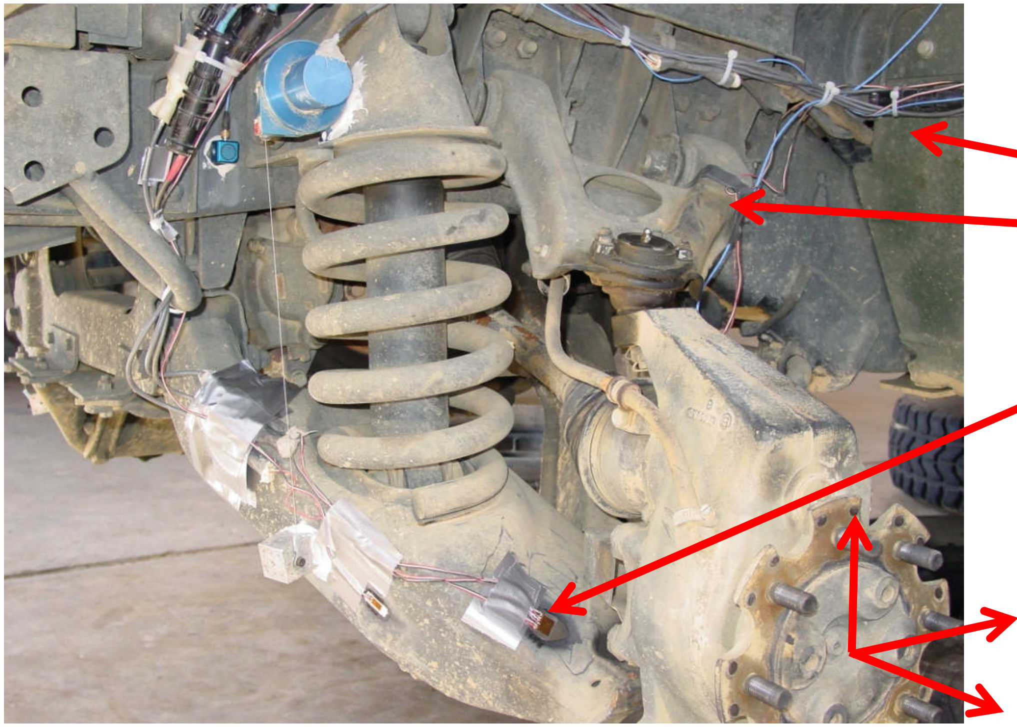
Rainflow cycle count the filtered acceleration data to yield 3 damage vs frequency plots for x,y,z:



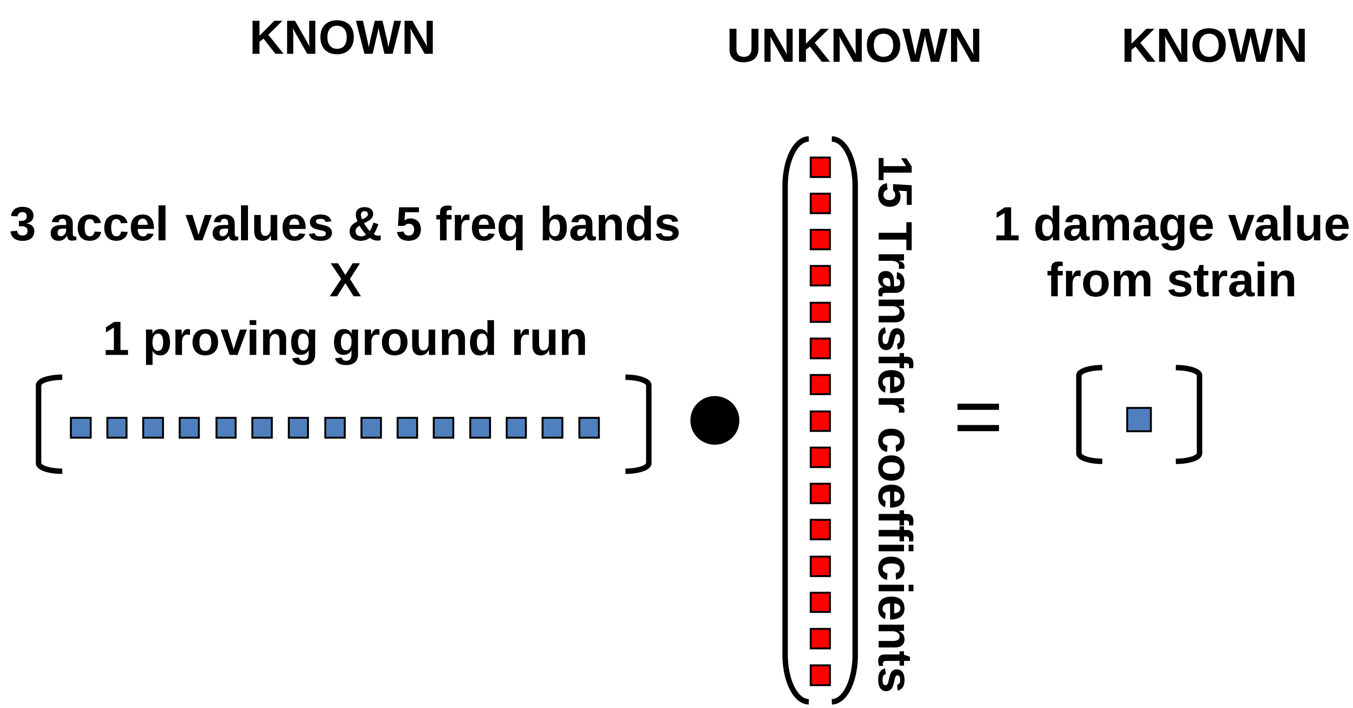
Durability Transfer Concept – Step 2 of 3

The key to this approach is the transfer function:

Knowing x,y,z accelerations at a suspension point, what is the function that allows the user to predict damage at other points on the suspension, chassis, or body?



Durability Transfer Concept – Step 2 of 3 (cont.)



Cannot solve for 15 unknown coefficients with only 1 known damage result

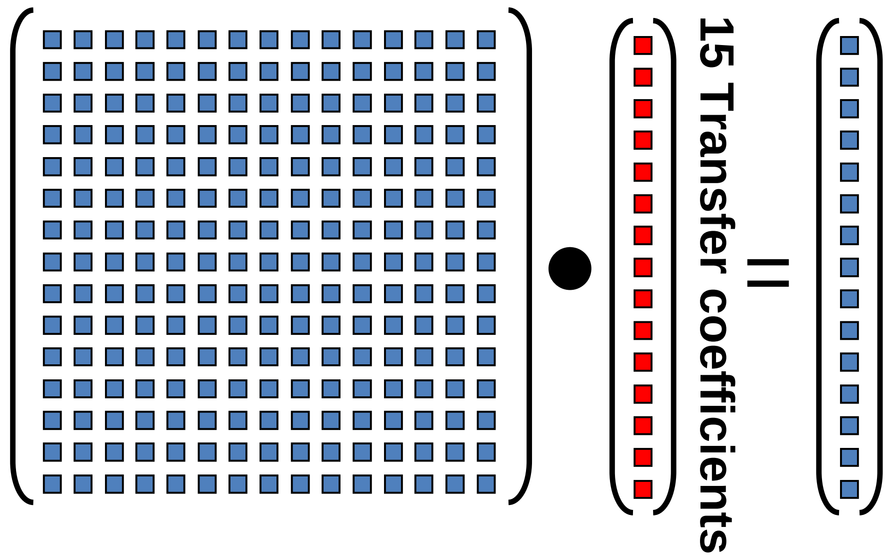
Therefore perform at least 15 measurements under different PG surfaces, weight conditions and speed conditions to create a solvable case. This is the RDS matrix to the right – “Relative Damage Spectrum”.

KNOWN

3 accel values & 5 freq bands
X
15 proving ground runs

KNOWN

15 damage values from strains



UNKNOWN

$$RDS \cdot C = D$$

Durability Transfer Concept - Step 2 of 3 (cont.)

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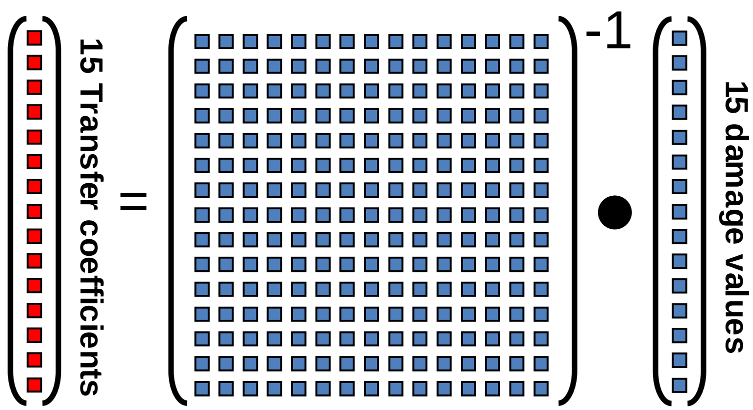

$$C = RDS^{-1} \cdot D$$

- Linear matrix inversion is inadequate
  - Prone to ill-conditioning
  - Negative damage contribution
  - Restricted number of PG passes (RDS must be a square matrix)
- Use non-linear optimization solutions based on minimizing a given error function *err(C)*
- Optimization can be based on neural network solution or classical algorithms such as non-linear simplex, Quasi-Newton, etc.

Given $RDS \cdot C = D$

and $C \geq 0$

and $err(C) = \sum \{\log(RDS \cdot C) - \log(D)\}^2$

Optimize to find C based on minimizing error function

← Error function based on sum of the square of the deviation

← Quasi-Newton optimization algorithm used in this case study

Test Vehicles/Conditions

- Two HMMWVs at two test weights – curb and GVW
- 7 Aberdeen Proving Ground test surfaces; 240 datasets
- Speeds ranged from 15-88mph

Comparable vehicle used to generate dataset 1151 (HMMWV M1151P1):

Curb Wt. = 10,350 lb GVW = 12,100 lb

Vehicle used to generate dataset 1152 (HMMWV M1152):

Curb Wt. = 6,400 lb GVW = 11,500 lb

DTC Process – Step 3 of 3
Predict Long Term Damage

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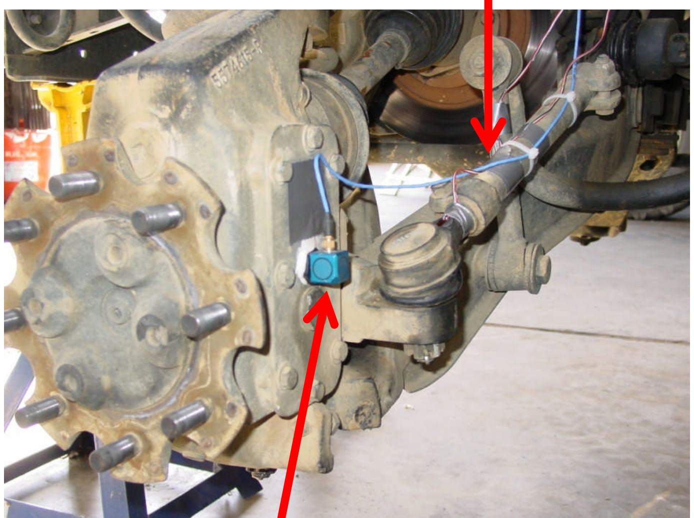
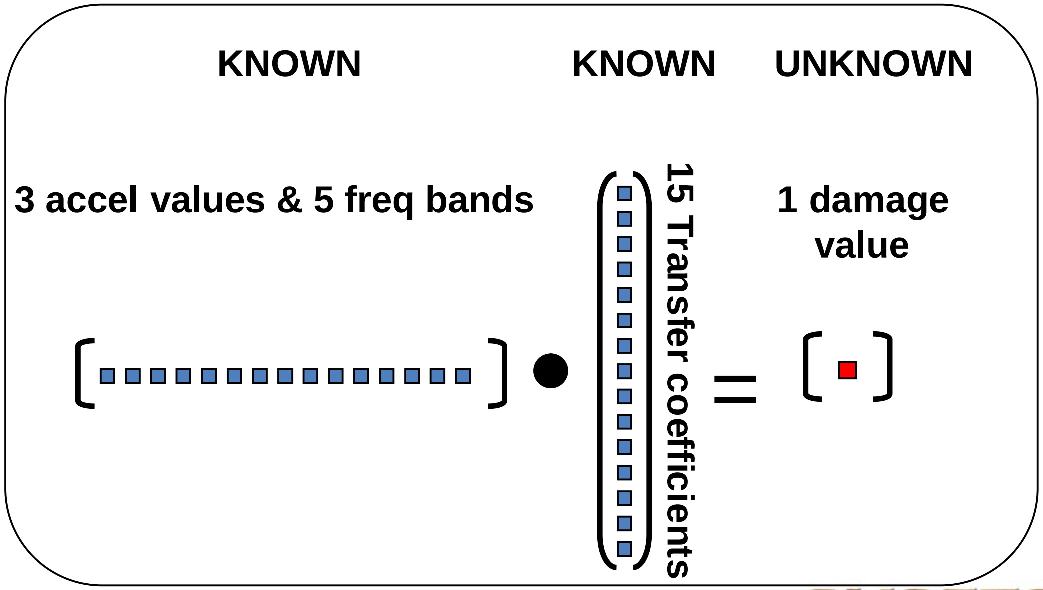
Strain gage located at left front tie rod



Triaxial accelerometer located at left front wheel

- Simulate long-term usage by concatenating multiple datasets in various combinations of vehicle weight, speed and road surface.
- This work examined one component – the left front tie rod.



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Trends in Results

- Accuracy of long-term damage prediction goes up as more usage conditions are included in the transfer function derivation. This includes:
  - Various vehicle weights
  - Various vehicle speeds
  - Various terrain roughness
- Predictions are as likely to be optimistic as conservative. Indicates the Gaussian nature of a random population.
- Most predictions were within a factor of 2 – well within the acceptable range for prognostic analysis and condition based maintenance.

Experiment Objectives

Exp. #

1. Compare random samples; weight condition same as xfer function (curb)
2. Show tolerance in method when vehicle weight changed to GVW
3. Show performance under a mix of vehicle weights
4. Show reliability under a skewed speed profile
5. Show reliability under a skewed vibration amplitude profile
6. Show improvement in prediction if xfer function includes range of weights
7. Show degradation if xfer function ignores a range of possible speeds
8. Show performance when accels and component are far apart
   (lower compliance)

Experiment Results

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	Transfer Function Definition				Verification Events				Maximum Error Factor
Exp.	Vehicle	Weight	Events	# of Tests	Vehicle	Weight	Events*	Speed	
1	1151	Curb	Random	6	Both	Curb	TF, Random, All	Mix	1.4
2	1151	Curb	Random	5	Both	GVW	TF, Random, All	Mix	1.9
3	1151	Curb	Random	4	Both	Mix	Random, All	Mix	1.5
4a	1151	Curb	Random	2	Both	Mix	Be, Bu, Ch, Gr	<30mph	1.3
4b	1151	Curb	Random	2	Both	Mix	Pa, Ro	>30mph	1.8
5a	1151	Curb	Random	2	Both	Mix	Pe, Ro	Mix	1.6
5b	1151	Curb	Random	2	Both	Mix	Be, Bu	Mix	1.3
6	1151	Mix	Random	5	Both	Mix	TF, All	Mix	1.1
7	1151	Mix	<30mph	4	Both	Curb	Pa, Ro	>30mph	4.2
8	1151	Mix	Random	5	Both	Mix	TF, Random, All	Mix	2.2
	Accels @ Left Rear Wheel Component: Left Front Tie Rod								

* Event Descriptions: TF – same as Transfer Function definition, Be – Belgium blocks, Bu – Bumps
Ch – Churchville, Gr – Gravel, Pa – Paved, Pe – Perryman, Ro - Rounds

Conclusions

- These experiments demonstrate the possibility for good correlation between measured acceleration on a vehicle and damage at remote locations.
- On-board data storage and upload requirements greatly reduced as compared to traditional time histories.
- For best results, the transfer function requires a good range of usage conditions – i.e. representative terrain roughness, speed profile and vehicle weight conditions.

Possible Future Efforts:

- Extensible – use CAN bus & GPS data instead of accelerations.
- Use FE models for correlation instead of strain gaged vehicles.

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