Failure Mode Based Optimization of Durability and Reliability Validation Programs

SAE Ground Vehicle Reliability Committee Presentation

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Content

- AVL’s Reliability Engineering Process
- The Load Matrix – Failure Mode based Optimization of Validation Programs
- Conclusions
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- The Load Matrix – Failure Mode based Optimization of Validation Programs
- Conclusions
Who is AVL?

Privately owned company

(Owner: Prof List and family)

Turnover:

1984: ~40 million €
2006: ~500 million €

Staff:

1984: ~560
2006: ~3500

Average R&D spending

10 % of turnover
AVL Establishments

Austria (HQ)
Croatia
Czech Republic
France
Germany
Hungary
Italy
Poland
Russia
Slovenia
Spain
Sweden
Switzerland
Turkey
United Kingdom

Other locations:
California
Michigan
Mexico
Brazil
Argentina
China
Japan
Korea
Thailand
Malaysia
Indonesia
Taiwan
AVL’s Reliability Engineering ...

- Is focused on failure-free products in the field
- Includes a range of methods,
  - Risk management
  - Field and test data analysis
  - Statistical methods
  - Validation optimisation
- Is a comprehensive process throughout product development
The Reliability Engineering Process

Concept Phase
Prototype Development (Gen 1)
Preproduction Development (Gen 2)
Production Validation
Volume Prod.

Development time

Statistical Analysis
Concern System
RA & FMEA
DoE / Robustness
Reliability Allocation
Reliability Charts
Warranty Cost Prediction
Load Matrix
Project Risk Assessment

- To get a quick, clear and unbiased view on project risks
- To be able to act upon critical risks in an appropriate way

**How?**

- The risks not to reach the project targets are rated.
- Assessment is done similar to FMEA. Scoring system, facilitator, interdisciplinary team.
- Technical, organisational, financial, and legal / contractual risks are covered.
- Generation of an action plan.
Robustness / DoE Techniques

- Application of DoE (Design of Experiments) and related statistical methods
- Definition of variants of reference duty cycles
- Derivation of load variations for especially critical components / failure modes

Benefits

- Optimized, robust design and testing
- Reduction of test effort
- Insight into „load space“ and damaging parameters
Reliability Allocation

- The system is modelled reliability-wise as a block diagram
- Reliability values (e.g., $B_{10}$ and RF) are allocated to each subsystem
- Values are derived from similar projects, prototypes, FMEAs and field data.

Benefits

- Gives an instant overview of the whole system and on reliability-critical parts
- Provides reliability targets for as an input for supplier technical specs
- Serves as a basis for life cycle cost models

<table>
<thead>
<tr>
<th>Component</th>
<th>RF Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust system</td>
<td>0.05</td>
</tr>
<tr>
<td>Cylinder head assembly</td>
<td>0.04</td>
</tr>
<tr>
<td>Crank train</td>
<td>0.01</td>
</tr>
<tr>
<td>Crank case</td>
<td>0.01</td>
</tr>
<tr>
<td>Injection system</td>
<td>0.05</td>
</tr>
<tr>
<td>Add-on parts</td>
<td>0.04</td>
</tr>
<tr>
<td>Engine</td>
<td>0.2</td>
</tr>
</tbody>
</table>

(simplified model)
Reliability Charts -
Reliability Improvement Monitoring

- Monitoring technique - shows the durability and reliability status of an engine / powertrain / vehicle during product development
- One chart is made for the system lifetime, another one for Repair Frequency or MTBF value (classical Reliability Growth Testing)

Benefits
- Shows current and historic values of reliability indices
- Illustrates the rate of improvement of these indices
- Provides a basis for prediction of the indices in the future
Warranty Cost Models

- illustrate in which way warranty costs depend on the $B_{10}$ and the MTBF/RF values of the product
- reflect 100%-repair campaigns due to serial defects
- require as input repair costs and subsystem failure distributions (from field data or estimated from protos)

Benefits

- make the costs of unreliability transparent
- show the SOP risk
- can be used as a basis for life cycle cost prediction
Content

- AVL’s Reliability Engineering Process
- The Load Matrix – Failure Mode based Optimization of Validation Programs
- Conclusions
The Load Matrix

The Load Matrix is ...

- a methodology to optimise test & validation programs systematically

The Load Matrix is applied to

- optimise existing „traditional“ durability & reliability validation programs
- design optimal validation programs for new systems (eg, DPF)

- Selection of critical parts and failure modes (based on FMEA, field data analysis, etc.)
- Definition of reliability targets for these critical parts / failure modes
- Collection of tests and test durations as well as acceleration factors
- Evaluation of test programme with respect to reliability (reliability & durability demonstration, weak point analysis, etc.)
Load Matrix Details

The Load Matrix ...

- is based on component and failure mode specific test acceleration factors
- uses these specific acceleration factors as weighting factors to compare test efficiency and life coverage
- uses damage models to calculate acceleration

The Load Matrix is used for ...

- minimising validation costs without jeopardizing product durability & reliability
Load Matrix Process

Selection of critical components and failure modes (basis: FMEA, field data, etc.)

Definition of reliability targets for these critical parts / failure modes

Collection of validation steps, test durations, determination of test acceleration factors

Evaluation of validation program with respect to reliability & durability, weak point analysis
Selection of critical components & failure modes

Existing reliability field data (e.g., from previous engine)

<table>
<thead>
<tr>
<th>Part name</th>
<th>Failure Rate (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pump</td>
<td>2110</td>
</tr>
<tr>
<td>Cylinder head</td>
<td>1690</td>
</tr>
<tr>
<td>Connector 36A</td>
<td>1450</td>
</tr>
<tr>
<td>ECU</td>
<td>1420</td>
</tr>
<tr>
<td>Gasket 145</td>
<td>1350</td>
</tr>
<tr>
<td>T/C</td>
<td>1100</td>
</tr>
<tr>
<td>Exhaust manifold</td>
<td>1040</td>
</tr>
</tbody>
</table>

FMEAs and FP sheets of new subsystems

Result:
List of critical components and failure modes

1. Component / failure mode
2. Piston Ring / wear
3. Cylinder head / valve bridge fracture
4. Cylinder head / valve seat wear
5. Connector / fretting
6. ....
An Important Tool: The FP Sheet

FP (Failure Mode - Parameter) Sheet

= Extended FMEA with emphasis on parameters relevant for damaging and critical operating conditions

Priorisation of critical failure modes

Identification of damage parameters

Selection of damage model

FMEA, Risk Analysis, Field Data, Experience
### Example of an FP Sheet (shortened)

<table>
<thead>
<tr>
<th>Subsystem/Komponente</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Failure effect</th>
<th>Priority</th>
<th>(Sub)System Parameter</th>
<th>Damaging operating condition</th>
<th>Classification model</th>
<th>Damage model</th>
<th>Damage model class</th>
<th>Measurements</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Substrate cracks</td>
<td>Thermal stress</td>
<td>Soot accumulation too low</td>
<td>1</td>
<td>Temperature, -gradient, exhaust gas stream, O2</td>
<td>Regeneration operation, worst case (filter overloading, idle during regeneration), load change (start/stop)</td>
<td>Planflow substrate temperature</td>
<td>Wöhler / Miner</td>
<td>B</td>
<td>Temperature difference sensor, vehicle application</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume reduction</td>
<td>Ash accumulation</td>
<td>Increased regeneration frequency, emissions too high, oil dilution, engine damage</td>
<td>1</td>
<td>Ash in exhaust gas, temperature</td>
<td>High load operation (oil, fuel consumption), ash content in oil, fuel quality</td>
<td>Accumulated oil and fuel consumption</td>
<td>Oil consumption measurement, fuel consumption measurement</td>
<td>B</td>
<td>Durability documentation</td>
<td></td>
</tr>
<tr>
<td>Catalytic coating</td>
<td>Degradation of surface</td>
<td>Ash accumulation</td>
<td>...</td>
<td>1</td>
<td>Ash in exhaust gas</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>B</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Example. Load Matrix Single Sheet for Cylinder Head High Cycle Fatigue

<table>
<thead>
<tr>
<th>Test</th>
<th>Number</th>
<th>Duration / Planned</th>
<th>Defects during tests</th>
<th>Acceleration Factor</th>
<th>Equivalent-km (one repetition)</th>
<th>Equivalent-km (all repetitions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Test 1</td>
<td>1</td>
<td>200 h</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Component Test 2</td>
<td>1</td>
<td>500 h</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Engine Cyclic Load Test</td>
<td>3</td>
<td>750 h</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>67500</td>
</tr>
<tr>
<td>Engine Thermal Cycle Test</td>
<td>2</td>
<td>300 h</td>
<td>3</td>
<td>1</td>
<td>0,5</td>
<td>6750</td>
</tr>
<tr>
<td>Reliability Vehicle - City Cycle</td>
<td>5</td>
<td>100000 km</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>100000</td>
</tr>
<tr>
<td>Reliability Vehicle - Highway Track</td>
<td>10</td>
<td>200000 km</td>
<td>4</td>
<td>1</td>
<td>1,5</td>
<td>300000</td>
</tr>
<tr>
<td>Customer Vehicles</td>
<td>20</td>
<td>150000 km</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>150000</td>
</tr>
</tbody>
</table>

- **Tests**: Component Test 1, Component Test 2, Engine Cyclic Load Test, Engine Thermal Cycle Test, Reliability Vehicle - City Cycle, Reliability Vehicle - Highway Track, Customer Vehicles
- **Number and Duration**: Number of tests and duration in hours or kilometers
- **Acceleration Factors**: Relevant factors for acceleration
- **Equivalent Mileage**: Calculated equivalent mileage based on repetitions
### Example. Load Matrix Summary Sheet

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Crit. Component / Failure Mode</th>
<th>Weibull Parameter Gamma</th>
<th>Weibull Parameter Beta</th>
<th>Reliability Target</th>
<th>Maximum of Equivalent km in one single test</th>
<th>Sum of Equivalent km</th>
<th>Demonstrable Reliability (Weibull Distribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cylinder Head - HCF</td>
<td>0</td>
<td>1,00</td>
<td>0,999</td>
<td>300,000</td>
<td>6,716,000</td>
<td>0,990</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder Head - LCF valve bridge</td>
<td>0</td>
<td>2,50</td>
<td>0,998</td>
<td>240,000</td>
<td>5,957,125</td>
<td>0,996</td>
</tr>
<tr>
<td>3</td>
<td>Piston Ring - Wear</td>
<td>0</td>
<td>2,00</td>
<td>0,995</td>
<td>280,000</td>
<td>6,534,500</td>
<td>0,994</td>
</tr>
<tr>
<td>4</td>
<td>DPF - Substrate Crack (thermal cycling)</td>
<td>0</td>
<td>2,50</td>
<td>0,990</td>
<td>300,000</td>
<td>6,250,000</td>
<td>0,997</td>
</tr>
<tr>
<td>5</td>
<td>Injector joint - wear (engine vibration)</td>
<td>0</td>
<td>1,50</td>
<td>0,999</td>
<td>300,000</td>
<td>6,711,000</td>
<td>0,989</td>
</tr>
</tbody>
</table>

- Highlights existing durability risks of the validation program
- Indicates to what extent the test program is adequate to demonstrate the target reliabilities

Derived actions to reduce risks include higher acceleration, new test procedure, calculation (e.g., FEM analysis), longer test time / mileage, customer fleets)
Calculation of Acceleration Factor (simplified)

Test: Cyclic Load Test

Frequency Plot resulting from test procedure

Damage profile resulting from damage model calculation

Vehicle (duty cycle)

Frequency Plot resulting from statistics and in-vehicle measurements

Damage profile resulting from damage model calculation

Relative damage per hour in Cyclic Load Test:

\[ D_R^{(c)} = \sum h_i^{(c)} d_i \]

Relative damage per hour in vehicle (duty cycle):

\[ D_R^{(v)} = \sum h_i^{(v)} d_i \]

Acceleration Factor = \[ \frac{D_R^{(c)}}{D_R^{(v)}} \]
Data Processing w.r.t. to Damage

Vehicle operation

Acquisition of damage related parameters

Data processing

[Graph showing data processing with respect to damage parameters]
Example of Damage Calculation (Matlab-based)

Wear Rate in Engine Map

Wear Rate per Hour
Duration in Engine Map

Wear LINER total 118.5372nm for total duration 4068.2793h

V_m 68.10km/h, Md_m 2791.25rpm

Wear rate 0.3291nm/h

Calculated by AVL List GmbH, on 02-Nov-2005 17:36:04
### Classes of Damage Models

<table>
<thead>
<tr>
<th>Class</th>
<th>Method</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>empirical model based on general experience</td>
<td>damage is proportional to the number of actuations</td>
</tr>
<tr>
<td>B</td>
<td>simplified physical model</td>
<td>$L = (C/P)^m$ for the lifetime of a ball bearing</td>
</tr>
<tr>
<td>C</td>
<td>full physical model Modell</td>
<td>FE-Analysis + Damage Accumulation Hypothesis + Actual material data</td>
</tr>
</tbody>
</table>
Example. Optimization of an Exhaust Aftertreatment System Validation Plan

Optimization of Reliability and Durability

Original Plan

Plan after Optimization
Load Matrix as Key Element of an Overall Risk Minimisation Process

CONCEPT PHASE
- Risk analysis / System FMEA
- Detailed FMEAs for Hardware
- Detailed FMEAs for Software

DESIGN / DEVELOPMENT PHASE
- DVP for Hardware Functional Checks
- FP Sheets for Hardware Durability & Reliability
- SVP Software Validation Plan
- Software Reliability Methodology

TEST / VALIDATION PHASE
- Hardware Functional Tests
- Load Matrix as Key Element of an Overall Risk Minimisation Process
- Load Matrix Test Program Optimisation
  - (test bed, components and vehicle durability & reliability tests)
- Software Function Tests (SIL, HIL, vehicle testing, etc.)
- Warranty Data Analysis, Early Warning System

PRODUCTION
- Warranty Data Analysis, Early Warning System
Content

- AVL‘s Reliability Engineering Process
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- Conclusions
Load Matrix Benefits

Failure mode based optimization of validation ...

- Generates complete and balanced validation plans, including analysis, component testing, test bed tests, vehicle tests.
- Shows how far durability and reliability targets can be demonstrated.
- Helps to avoid unnecessary testing.
- Supports the exchange and proper use of key information from all involved partners, including suppliers.
- Supports optimised assessment procedures to make full use of all available information.
- Helps in deciding on the benefits of additional validation steps.
## A Selection of Recent Projects

<table>
<thead>
<tr>
<th>Customer</th>
<th>System</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>European OEM</td>
<td>HD Diesel Engine</td>
<td>Setup of a warranty cost prediction model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assessment of Validation Program</td>
</tr>
<tr>
<td>European OEM</td>
<td>HD Diesel Engine</td>
<td>Determination of sub-system specific acceleration factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation program optimisation</td>
</tr>
<tr>
<td>Supplier</td>
<td>Diesel Particle Filter</td>
<td>Definition of a test program</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Definition of the LOAD MATRIX for Substrate, Mat and Canning</td>
</tr>
<tr>
<td>European OEM</td>
<td>DENOX System</td>
<td>Definition and optimisation of a test program</td>
</tr>
<tr>
<td>Japanese OEM</td>
<td>SUV and LCV TCI Diesel Engine</td>
<td>Determination of the effect of a different vehicle application (LCV instead of SUV) on engine life</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Definition of a durability test program</td>
</tr>
<tr>
<td>European OEM</td>
<td>Rear Axle</td>
<td>Setup of Load Matrix</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assessment of current test program</td>
</tr>
<tr>
<td>European OEM</td>
<td>Pass Car Gasoline Engine</td>
<td>Comparison of two different validation programs</td>
</tr>
<tr>
<td>European OEM</td>
<td>LCV and HD TCI Diesel Engine</td>
<td>Assessment of validation program for a DPF application</td>
</tr>
</tbody>
</table>
Thank you for your attention!