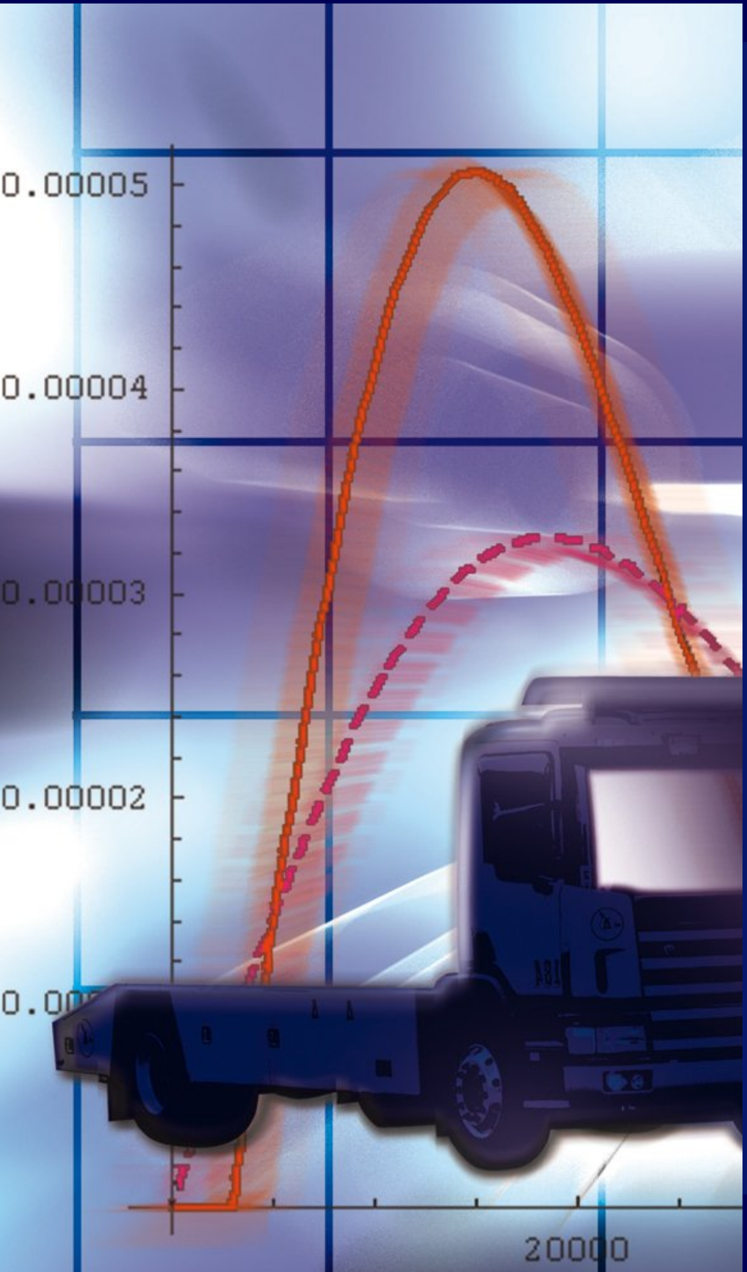


Failure Mode Based Optimization of Durability and Reliability Validation Programs

SAE Ground Vehicle Reliability Committee Presentation

Dr. Klaus Denkmayr

Reno, October 23rd, 2006

Content

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

Content

- **AVL‘s Reliability Engineering Process**
- **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

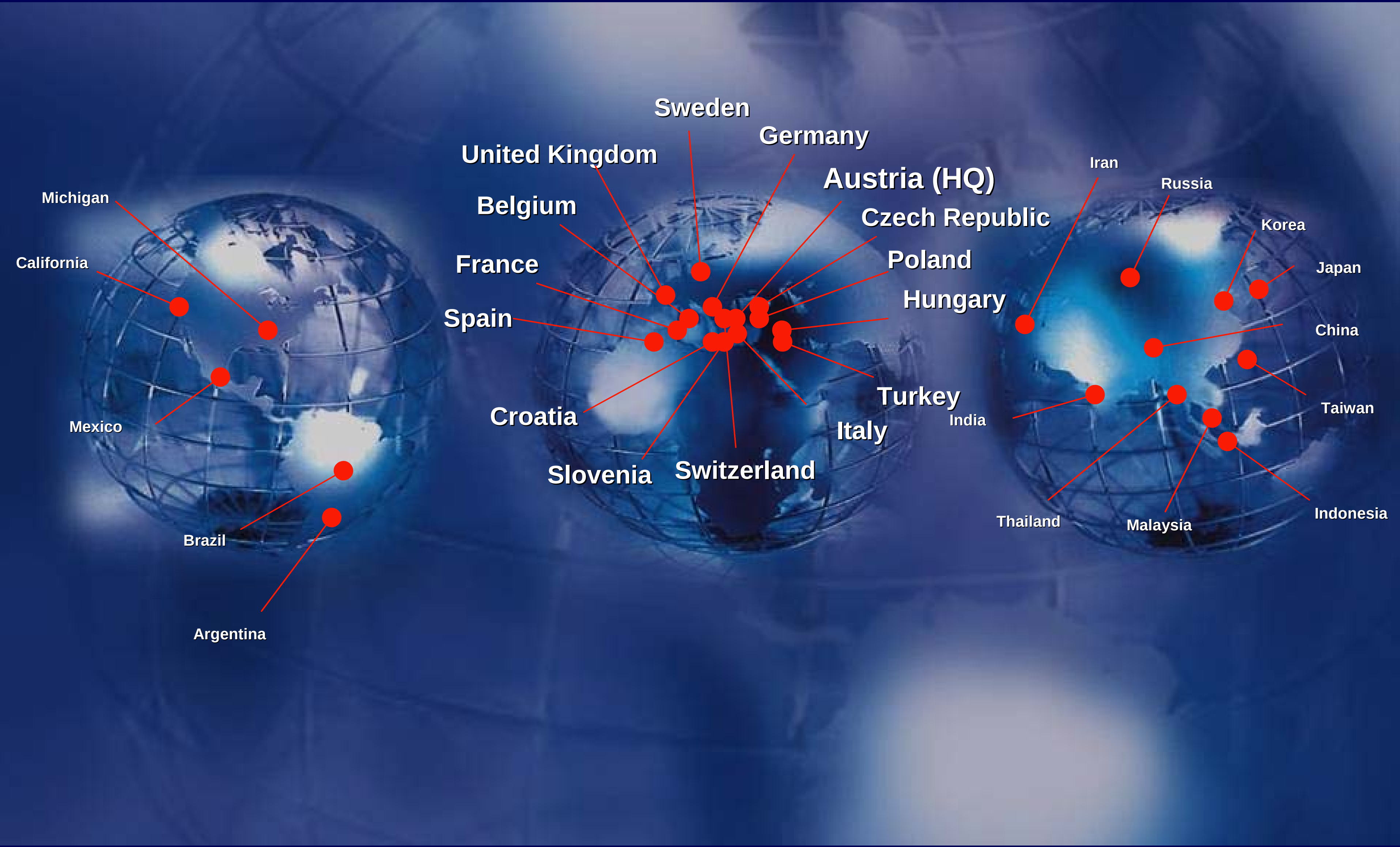
10 % of turnover

AVL Powertrain Engineering

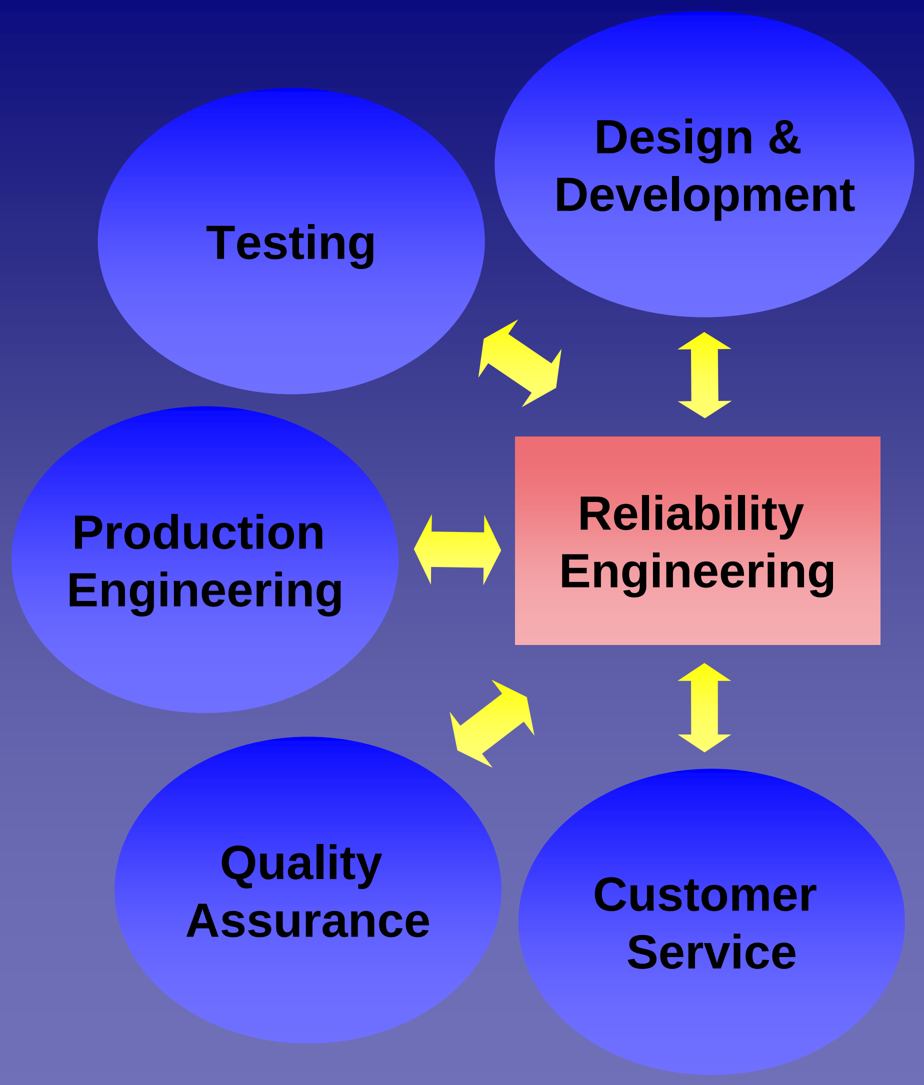
AVL Advanced Simulation Technologies

AVL Instrumentation and Test Systems

AVL Establishments



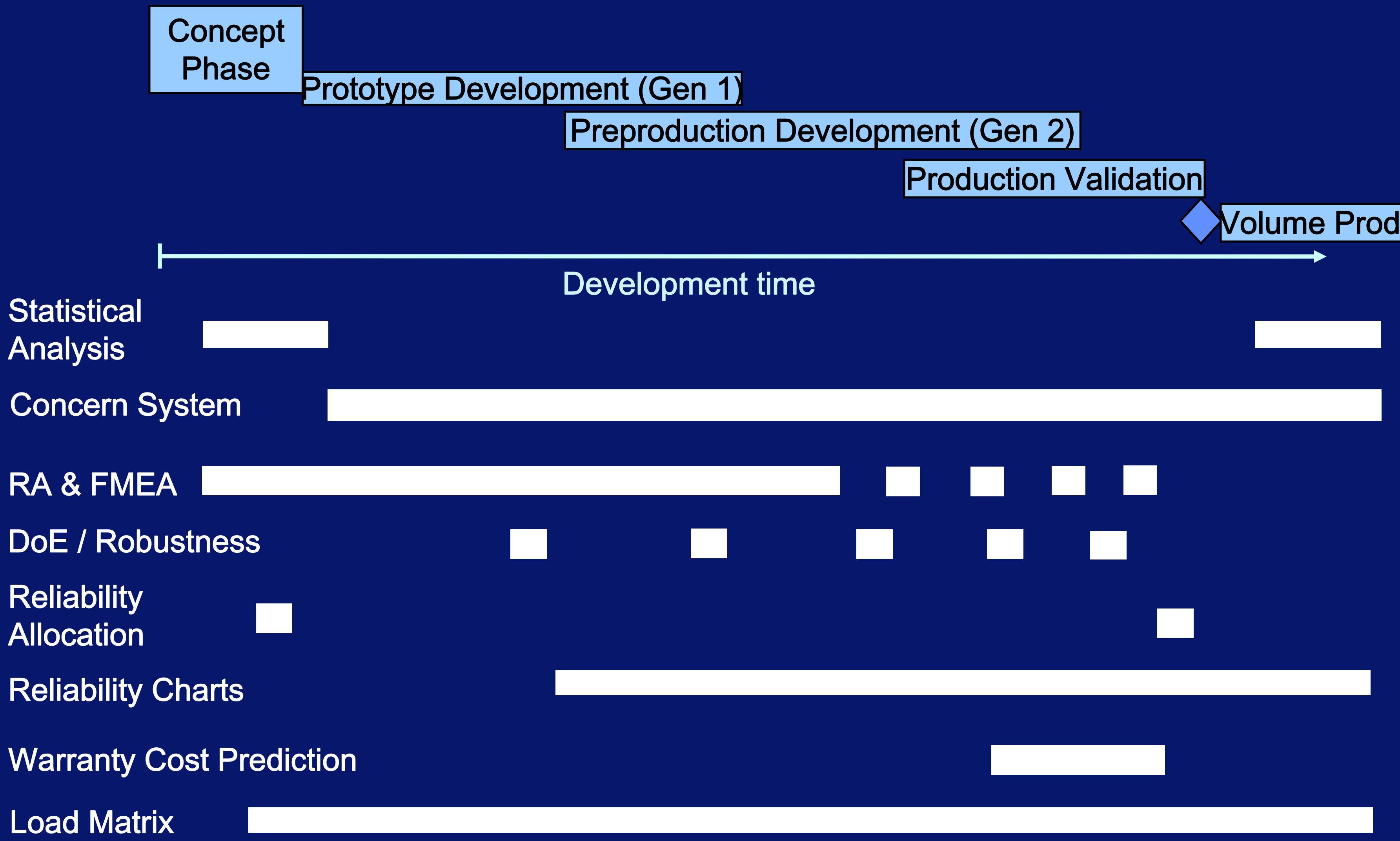
A Reliability Engineering Approach for Powertrain Development



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

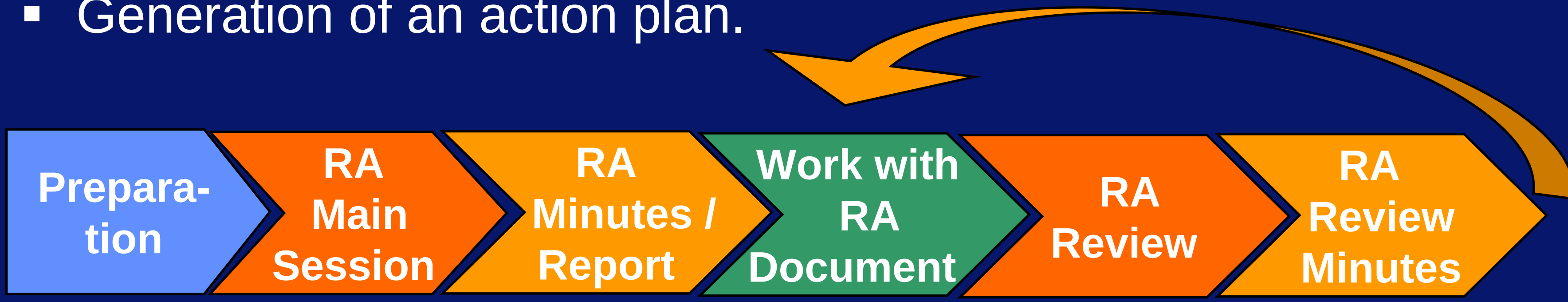


Project Risk Assessment

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

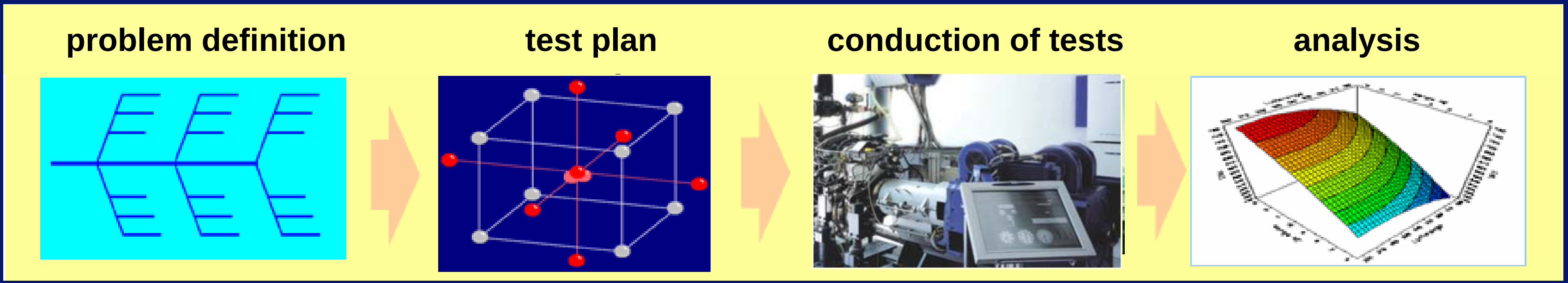
How?

- 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

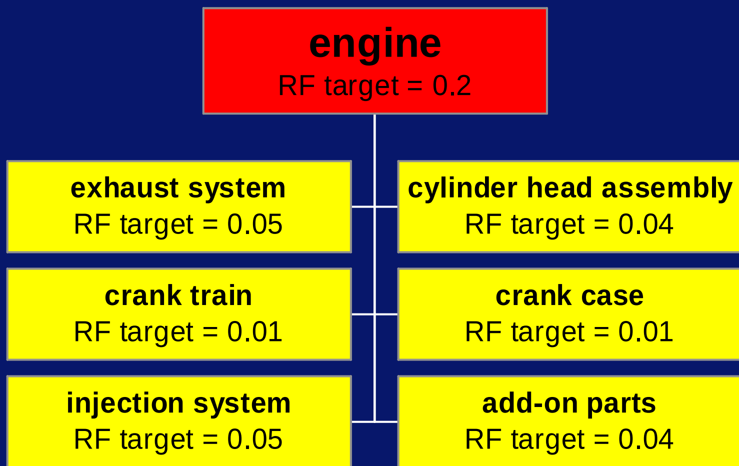
- Application of DoE (Design of Experiments) and related statistical methods
- Definition of variants of reference duty cycles
- Derivation of load variations for especially critical components / failure modes



Benefits

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

Reliability Allocation



(simplified model)

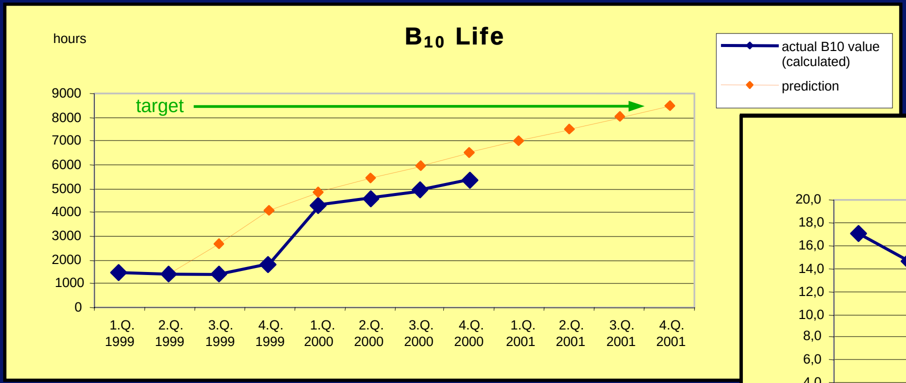
- The system is modelled reliability-wise as a block diagram
- Reliability values (eg, B_{10} and RF) are allocated to each subsystem
- Values are derived from similar projects, prototypes, FMEAs and field data.

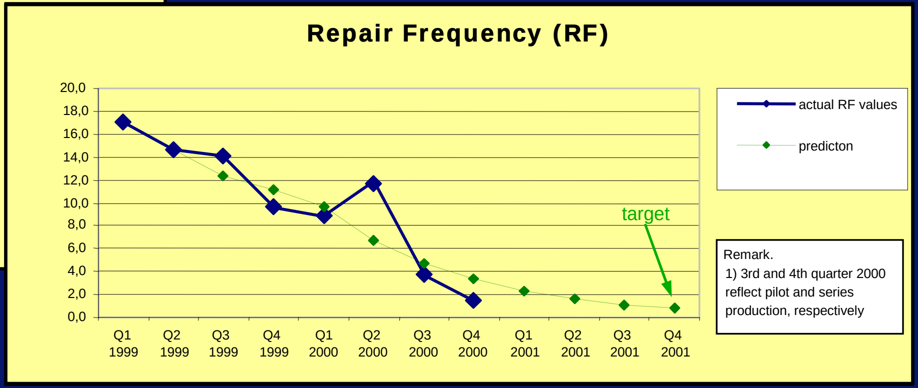
Benefits

- 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

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)





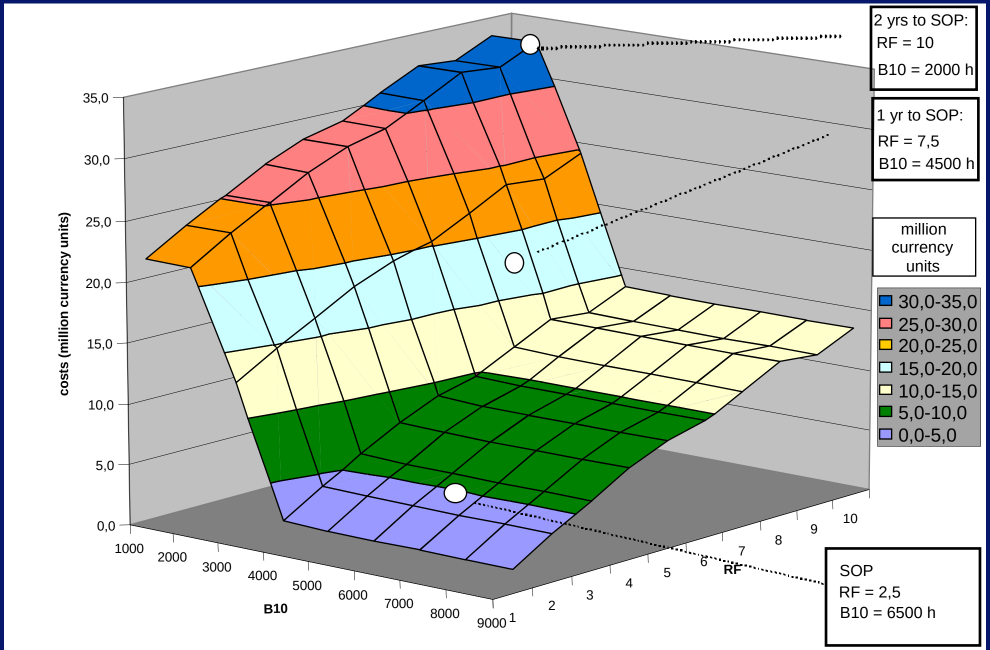
Benefits

- 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

Warranty Cost Models

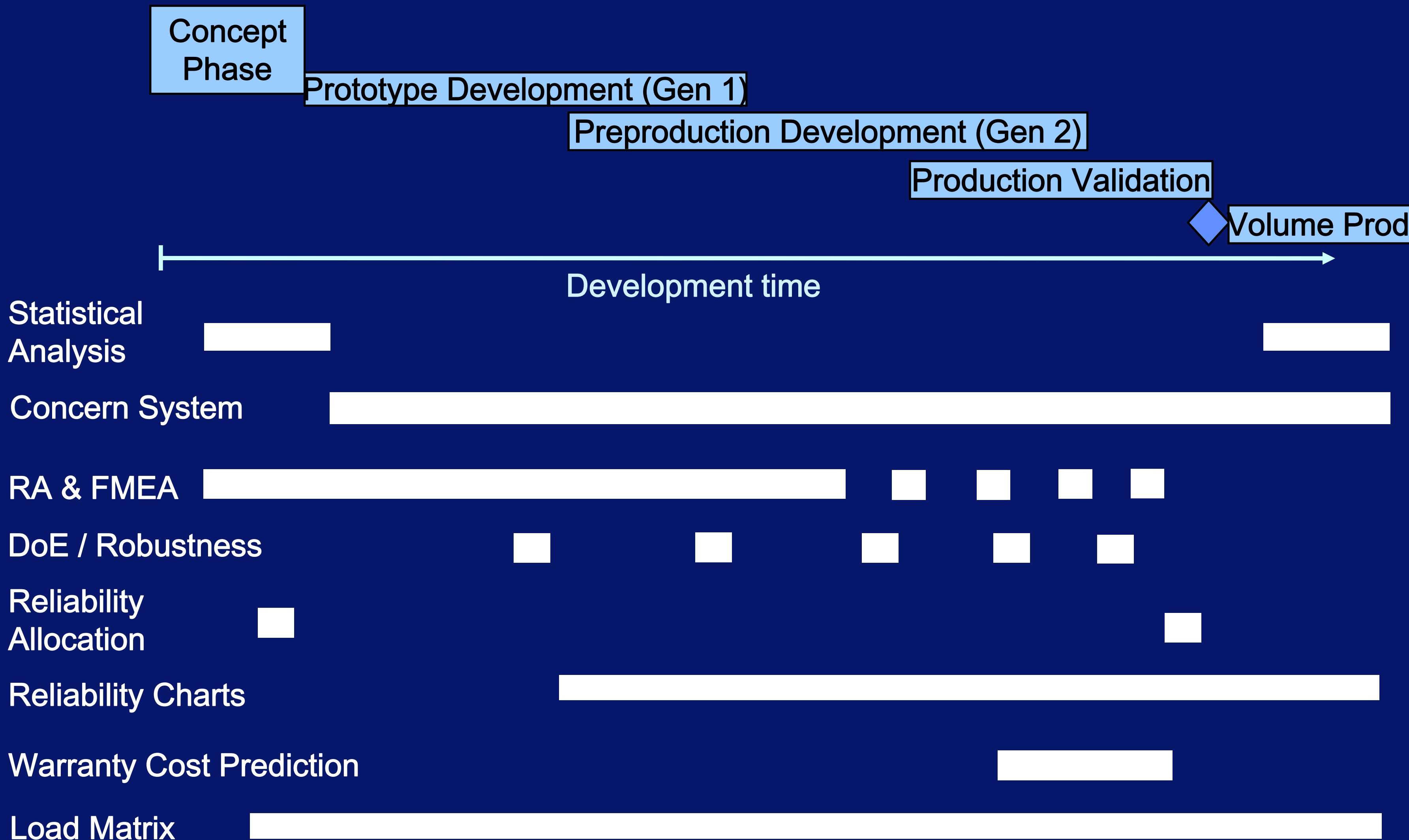
- illustrate in which way warranty costs depend on the B_{10} and the MTBF/RF values of the product
- reflect 100%-repair campaigns due to serial defects
- require as input repair costs and subsystem failure distributions (from field data or estimated from protos)



Benefits

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

The Reliability Engineering Process



Content

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

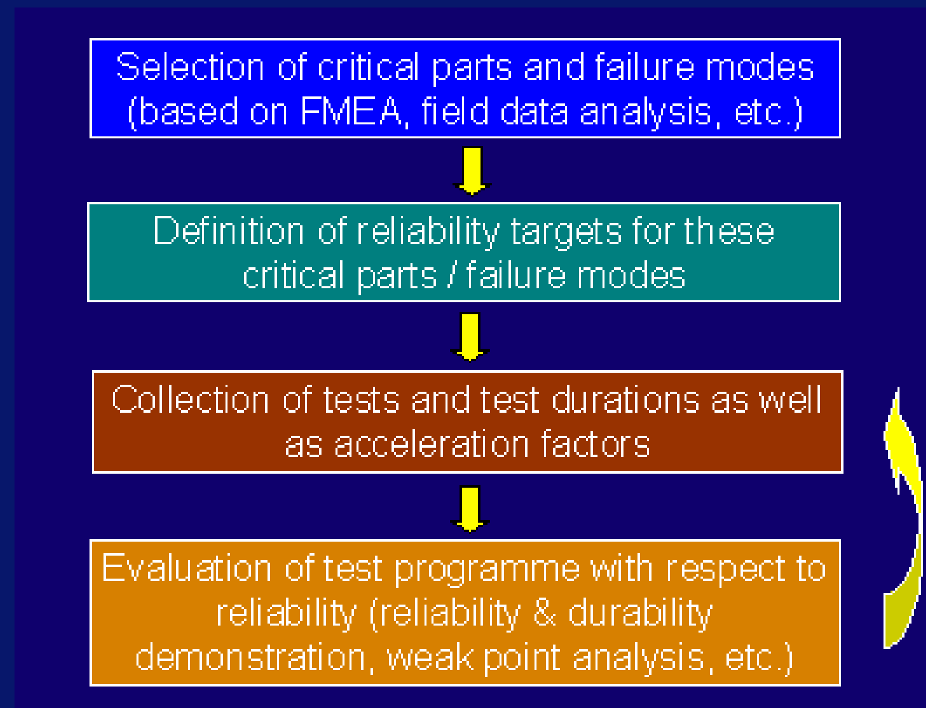
The Load Matrix

The Load Matrix is ...

- a methodology to optimise test & validation programs systematically

The Load Matrix is applied to

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



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

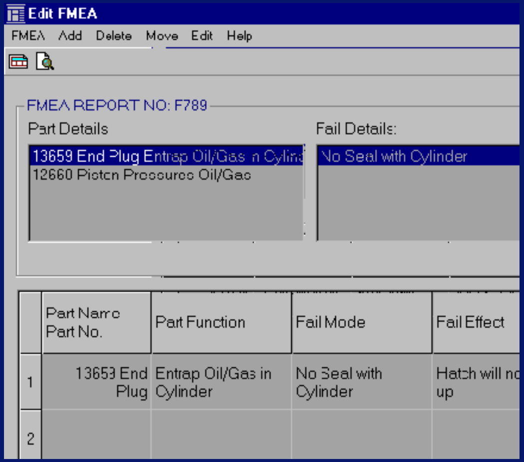
Selection of critical components & failure modes

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

TOP FIELD PROBLEMS OF ENGI

Part name	Failure Rate (ppm)
Injection pump	2110
Cylinder head	1690
Connector 36A	1450
ECU	1420
Gasket 145	1350
T/C	1100
Exhaust manifold	1040

FMEAs and FP sheets of new subsystems



1	**Component / failure mode**
2	Piston Ring / wear
3	Cylinder head / valve bridge fracture
4	Cylinder head / valve seat wear
5	Connector / Fretting
6	**....**

<u>Result</u>:
List of critical components and failure modes

An Important Tool: The FP Sheet

FMEA, Risk Analysis, Field Data, Experience

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

Example of an FP Sheet (shortened)

FP sheet											
Subsystem/ Komponente	**Failure Mode**	**Failure Cause**	**Failure effect**	**Priority**	**(Sub)System-parameter**	**Damaging operating condition**	**Classification model**	**Damage model**	**Damage model class**	**measurements**	**rema acce**
Substrate	substrate cracks	thermal stress	soot accumulation too low	1	Temperature, -gradient, exhaust gas stream, O2	Regeneration operation, worst case (= filter overloading, idle during regeneration), load change (start/stop)	Rainflow substrate temperatur	Wöhler / Miner	**B**	Temperature difference sensor vehicle application	
	Volume reduction	ash accumulation	increased regeneration frequency >> emissions too high, oil dilution >> engine damage	1	Ash in exhaust gas, temperature	high load operation (oil, fuel cunsumption), ash content in oil, fuel quality	accumulated oil and fuel consumption	oil consumption measurement, fuel consumption measurement	**B**	durability documentation	
Catalytic coating	dagradation of surface	ash accumulation	...	1	ash in exhaust gas	...	...	...	**B**	...	

Example. Load Matrix Single Sheet for Cylinder Head High Cycle Fatigue

A	B	F	G	H	K	L	M	N	O	P
Cylinder Head - HCF								Customer Reference Duty Cycle		
Class of Damage Model										
Test	Number	Click to select Duration / Planned	Unit	Defects during tests	Category	Activated	Relevance	Acceleration Factor	Equivalent-km (one repetition)	Equivalent-km (all repetitions)
Component Test 1	1	200	h		2		1	0	0	0
Component Test 2	1	500	h		2		1	0	0	0
Engine Cyclic Load Test	3	750	h		3		1	2	67500	202500
Engine Thermal Cycle Test	2	300	h		3		1	0,5	6750	13500
Reliability Vehicle - City Cycle	5	100000	km		4		1	1	100000	500000
Reliability Vehicle - Highway Track	10	200000	km		4		1	1,5	300000	3000000
Customer Vehicles	20	150000	km		4		1	1	150000	3000000

tests

number and duration

acceleration factors

equivalent mileage

Example. Load Matrix Summary Sheet

Unit (km, mi)	**km**
confidence level	0,9
Show: planned duration	

B10-target (km)	**250.000**
Demonstrable reliability at (km)	**60.000**

Component Information					**Customer Reference Duty Cycle**		
Sheet	**Crit. Component / Failure Mode**	**Weibull Parameter Gamma**	**Weibull Parameter Beta**	**Reliability Target**	**Maximum of Equivalent km in one single test**	**Sum of Equivalent km**	**Demonstrable Reliability (Weibull Distribution)**
1	Cylinder Head - HCF	0	1,00	0,999	300.000	6.716.000	**0,980**
2	Cylinder Head - LCF valve bridge	0	2,50	0,998	240.000	5.957.125	**0,996**
3	Piston Ring - Wear	0	2,00	0,995	280.000	6.534.750	**0,994**
4	DPF - Substrate Crack (thermal cycling)	0	2,50	0,990	300.000	6.250.000	**0,997**
5	Injector joint - wear (engine vibration)	0	1,50	0,999	300.000	6.611.000	**0,989**

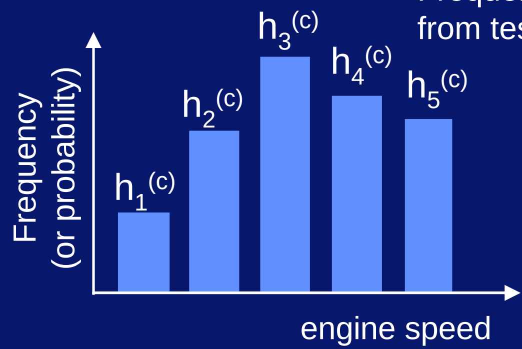
- Highlights existing durability risks of the validation program
- Indicates to what extent the test program is adequate to demonstrate the target reliabilities

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

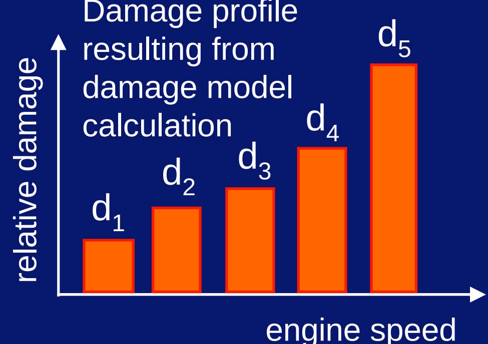
Calculation of Acceleration Factor (simplified)

Test: Cyclic Load Test

Frequency Plot resulting from test procedure

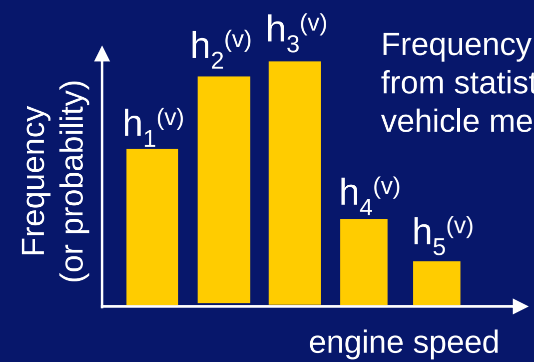


Damage profile resulting from damage model calculation

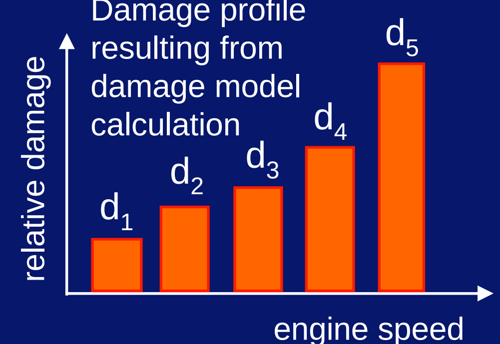


Vehicle (duty cycle)

Frequency Plot resulting from statistics and in-vehicle measurements



Damage profile resulting from damage model calculation



Relative damage per hour in Cyclic Load Test: $D_R^{(c)} = \sum h_i^{(c)} d_i$

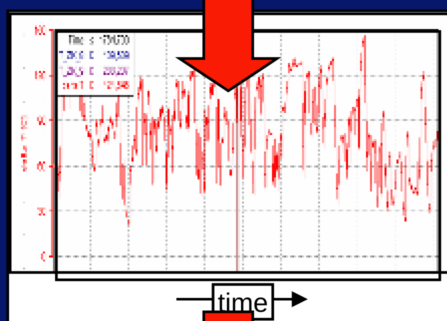
Relative damage per hour in vehicle (duty cycle): $D_R^{(v)} = \sum h_i^{(v)} d_i$

Acceleration Factor $= D_R^{(c)} / D_R^{(v)}$

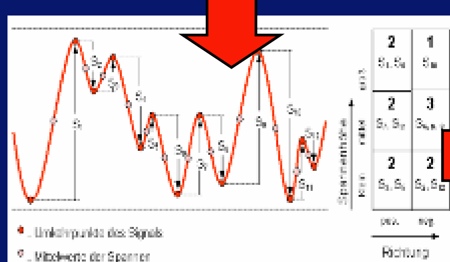
Data Processing w.r.t. to Damage

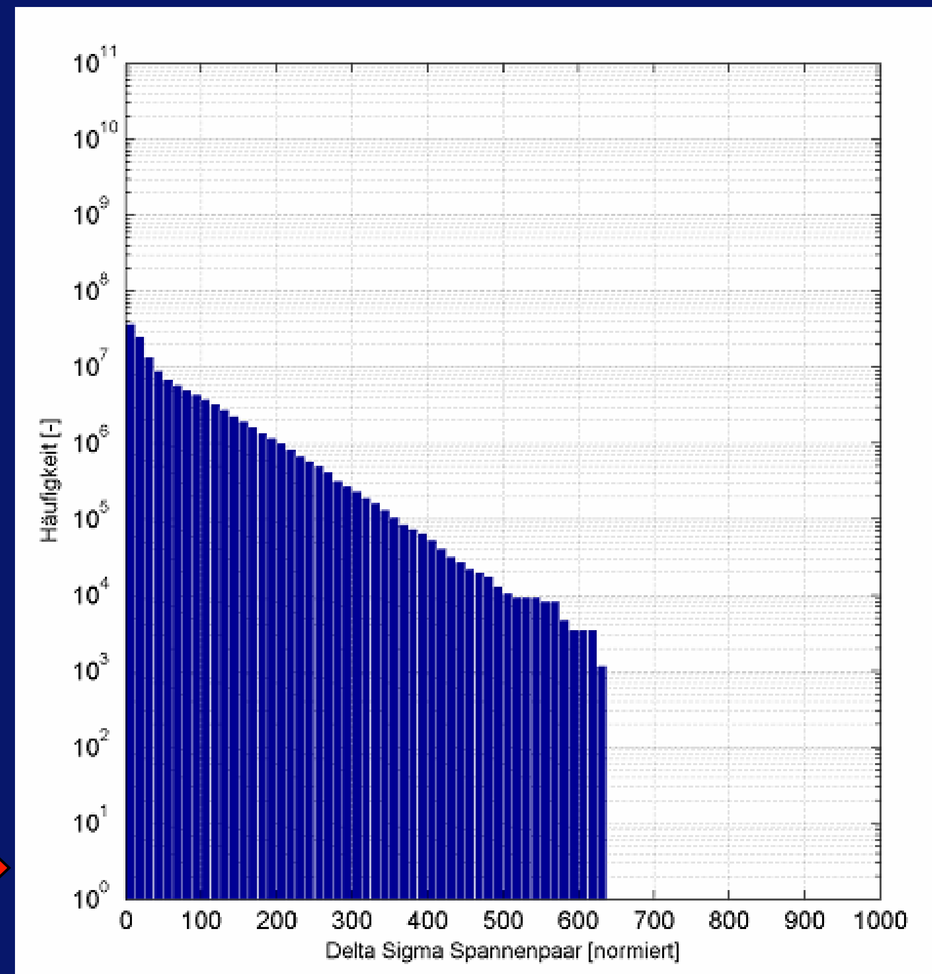
vehicle operation

acquisition of damage related parameters

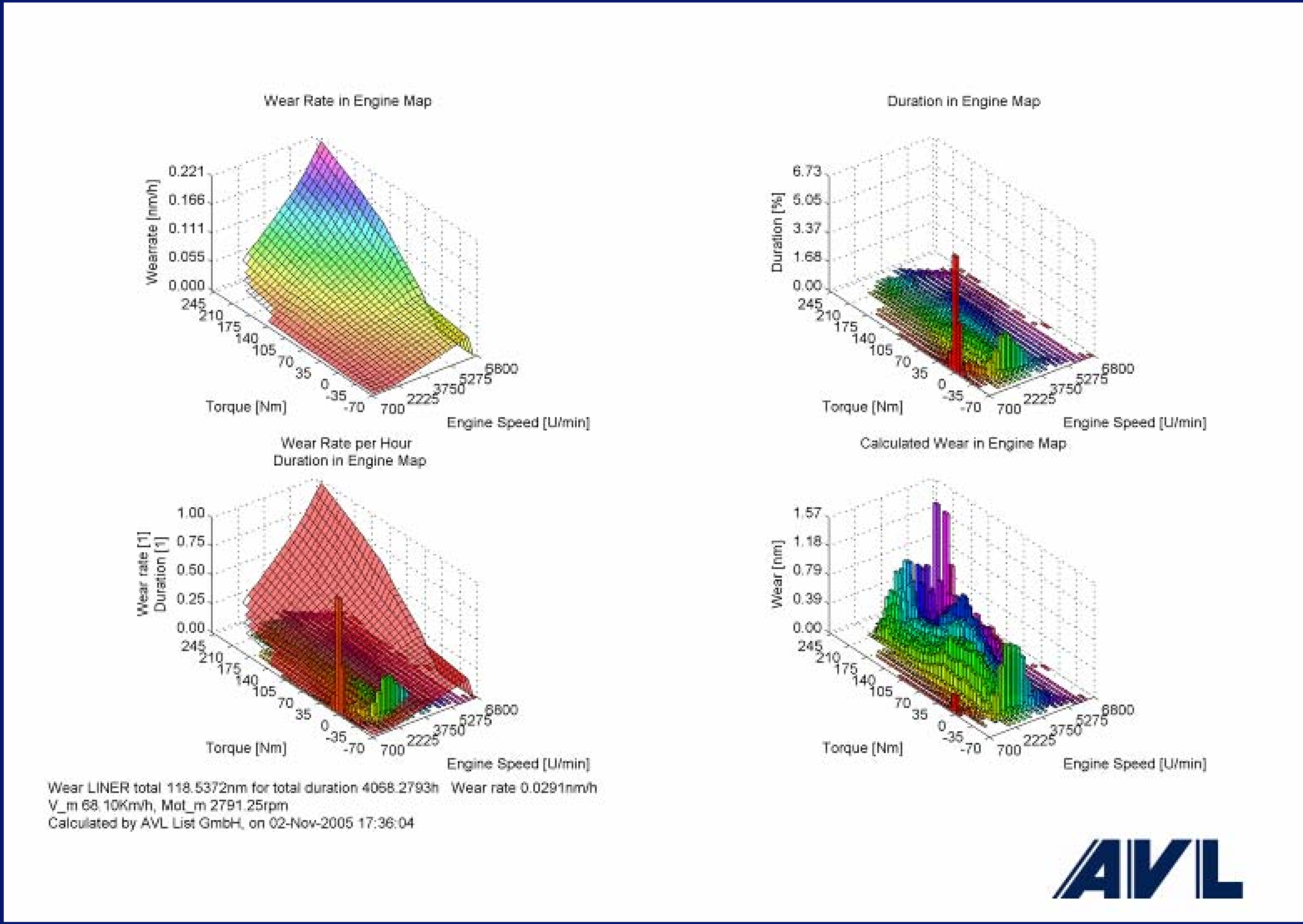


data processing





Example of Damage Calculation (Matlab-based)



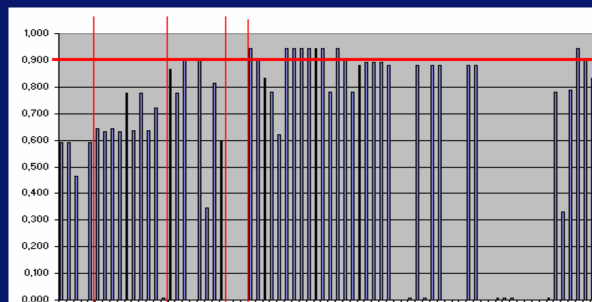
Classes of Damage Models

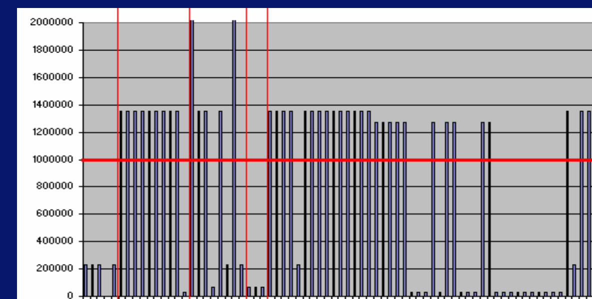
Class	Method	Example
A	empirical model based on general experience	damage is proportional to the number of actuations
B	simplified physical model	$L = (C/P)^m$ for the lifetime of a ball bearing
C	full physical model Modell	FE-Analysis + Damage Accumulation Hypothesis + Actual material data

Example. Optimization of an Exhaust Aftertreatment System Validation Plan

Reliability | **Durability**

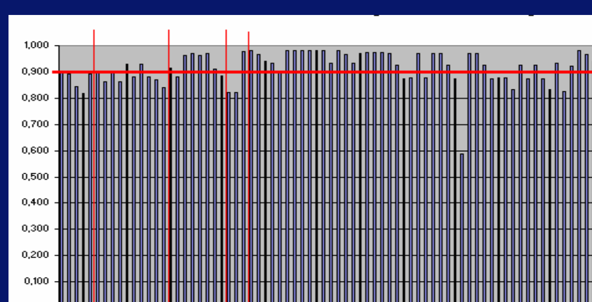
Ori-ginal Plan

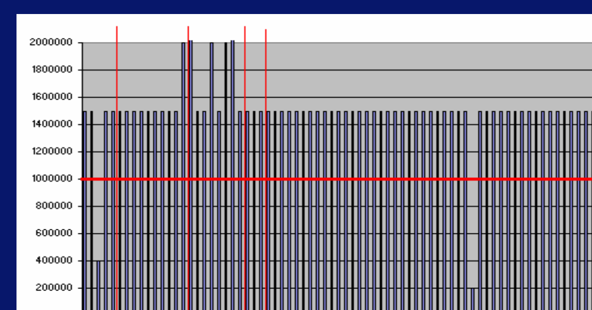




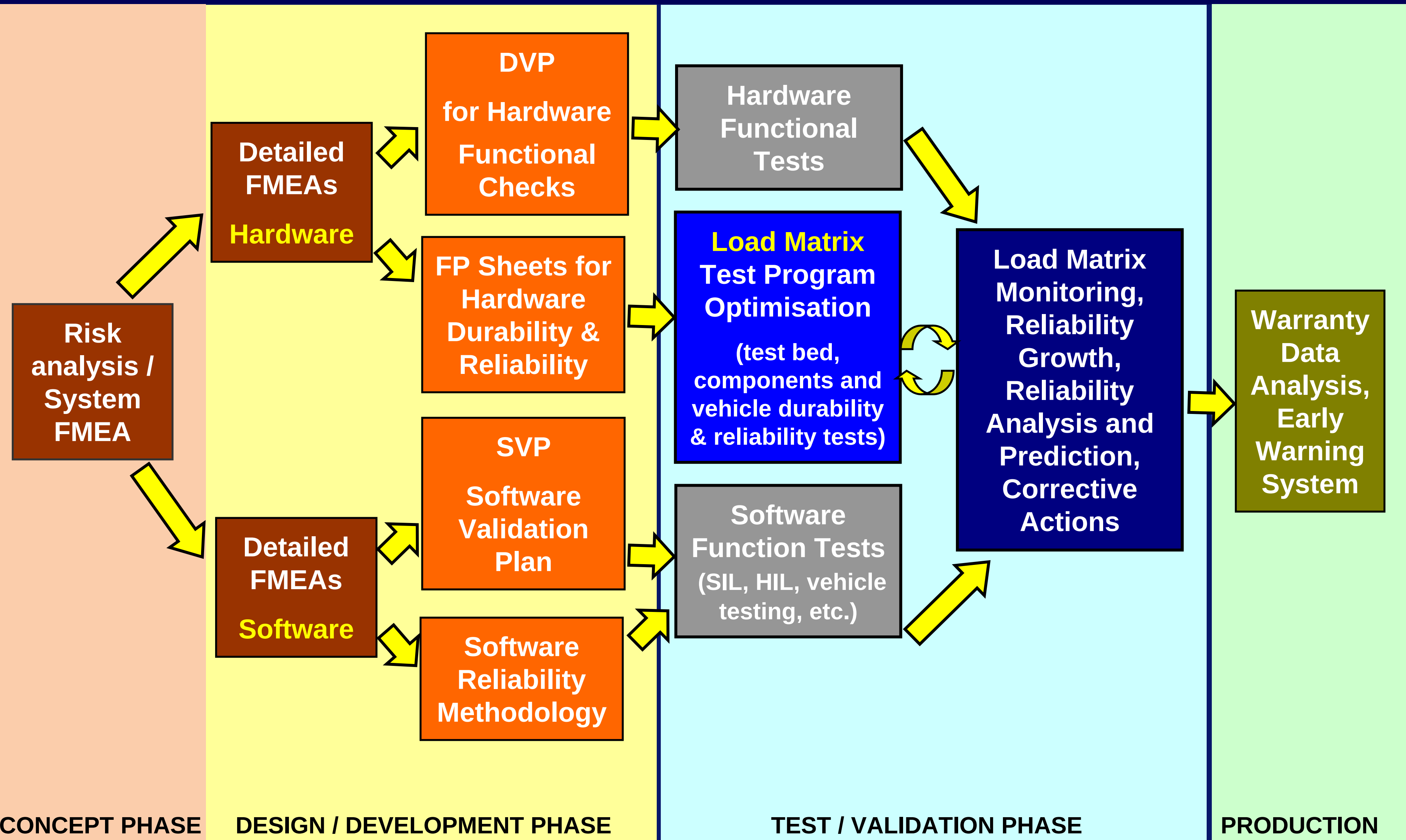
Optimization

Plan after Optimi-zation





Load Matrix as Key Element of an Overall Risk Mimimisation Process



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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

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

Thank you for your attention!