AVL List GmbH (Headquarters)

Development methods for reliable piston-bore-interface layouts
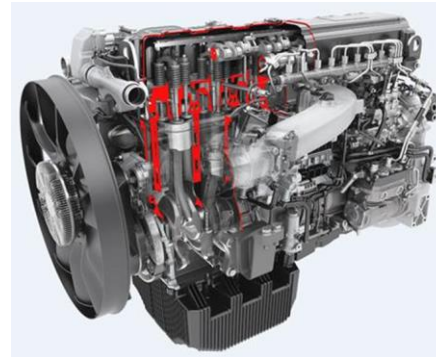# 可靠的活塞-缸孔-接口布置的开发方法

Dr.-Ing. Mirko Plettenberg

Main goals of PBI development: high durability, high efficiency, low emissions
PBI开发的主要目的：高可靠性、高效率、低排放

Friction Losses 摩擦损失

- Significant **CO_2 reduction** targets defined for HD vehicles worldwide
- Up to **50% of engine friction losses** due to Piston Bore Interface (PBI)

Lube Oil Consumption (LOC) 机油消耗

- Low burned and unburned **particle and HC emissions**
- Risk of **component damage** due to pre-ignition of oil particles
- Poisoning of exhaust aftertreatment systems due to oil particles

Component Wear 部件摩擦

- Heavy wear **affects component function**
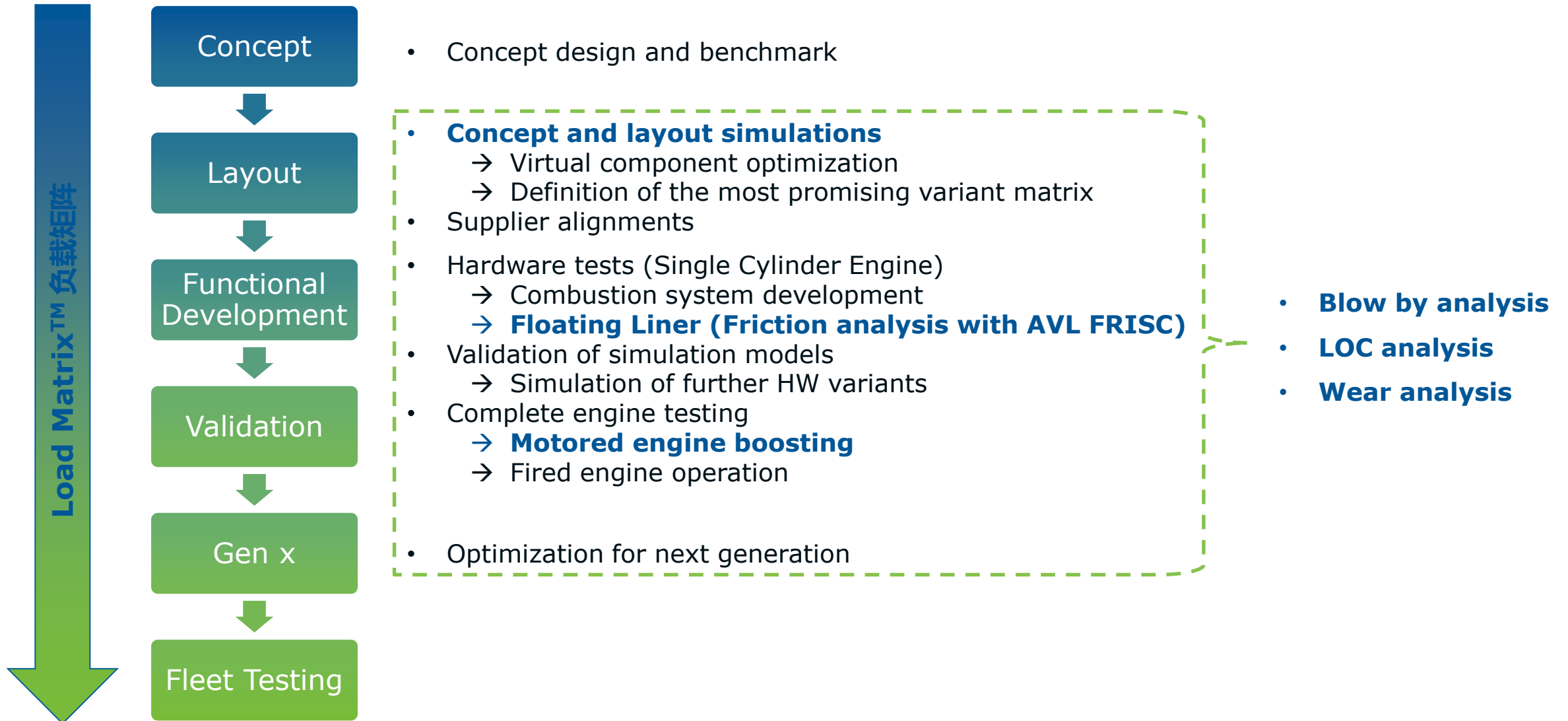- Metallic contamination of the oil can lead to **component damage**

Blow by 漏气

- Increased **engine efficiency** due to low compression losses
- Hot gases may lead to high part temperatures and **damages**

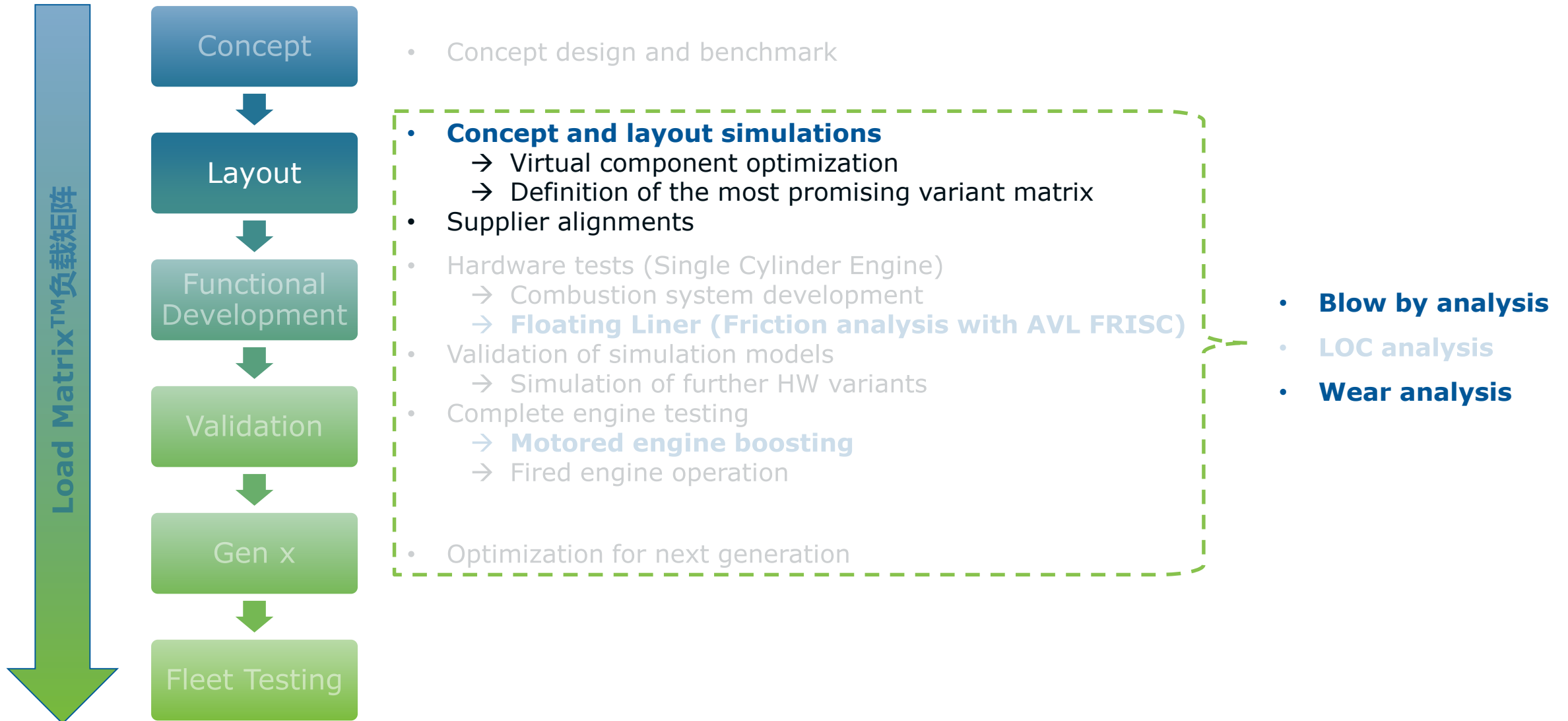**Detailed monitoring of all parameters during PBI development**
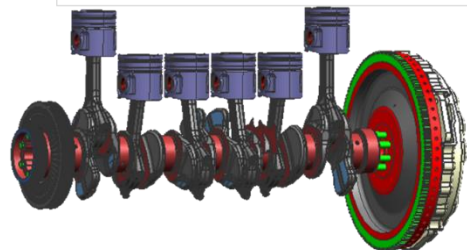
PBI development process 开发流程

Load Matrix™ 负载矩阵

Concept

Layout

Functional Development

Validation

Gen x

Fleet Testing

- Concept design and benchmark

- **Concept and layout simulations**
  - → Virtual component optimization
  - → Definition of the most promising variant matrix
- Supplier alignments

- Hardware tests (Single Cylinder Engine)
  - → Combustion system development
  - → **Floating Liner (Friction analysis with AVL FRISC)**
- Validation of simulation models
  - → Simulation of further HW variants
- Complete engine testing
  - → **Motored engine boosting**
  - → Fired engine operation

- Optimization for next generation

- **Blow by analysis**
- **LOC analysis**
- **Wear analysis**

PBI development process 开发流程

Load Matrix™负载矩阵

Process Steps
Concept
Layout
Functional Development
Validation
Gen x
Fleet Testing

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Concept and layout simulations
概念和布置仿真

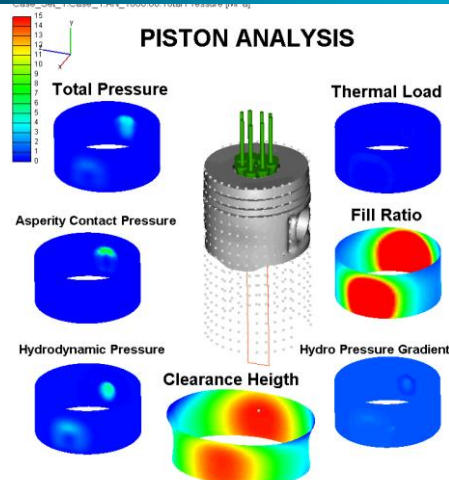## Initial design proposal 初始设计

Wall thickness oil gallery - bowl
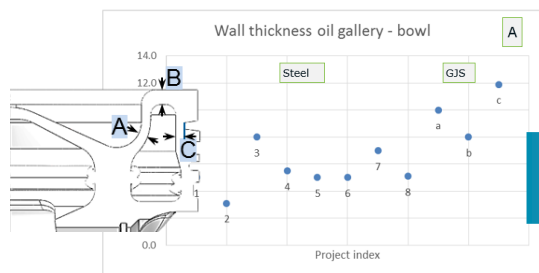
Initial design proposal:
- Geometry benchmarking
- Performance benchmarking

Initial simulations

EXCITE Power Unit 功率单元+ FEA

PISTON ANALYSIS

Total Pressure   Thermal Load

Asperity Contact Pressure   Fill Ratio

Hydrodynamic Pressure   Hydro Pressure Gradient
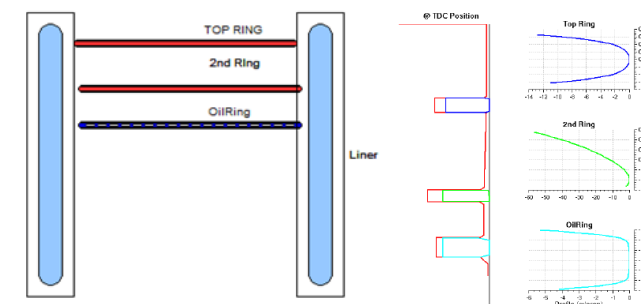
Clearance Heigth

Initial piston analysis for ideal geometry in view of:
- Performance
- Impact Forces
- Wear
- Friction
- NVH
- Liner cavitation
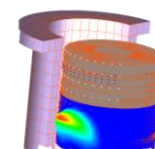
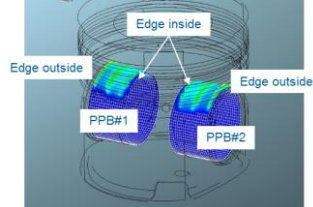## EXCITE Piston & Rings 活塞和活塞环

TOP RING

2nd RIng

OilRing

Liner

Initial piston ring analysis for a ring pack proposal or assessment of an available ring pack:
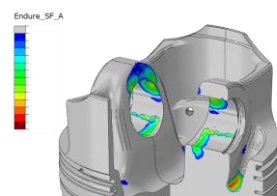- Sealing performance
- Ring motion
- Interring pressure
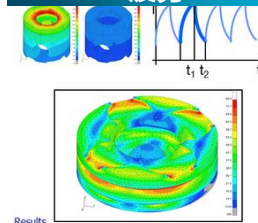- Friction
- Asperity contact / wear
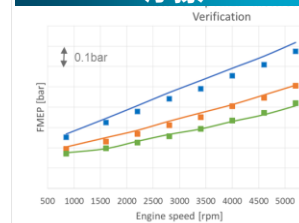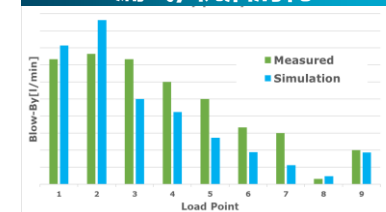- LOC
- Blow-By

Wear Load 摩擦负荷

Stress 应力

Fatigue 疲劳

Friction 摩擦

Blow-By / LOC 漏气/机油消耗

PBI development process 开发流程

Load Matrix™负载矩阵

```
Concept
   ↓
Layout
   ↓
Functional
Development
   ↓
Validation
   ↓
Gen x
   ↓
Fleet Testing
```

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- **LOC analysis**
- **Wear analysis**

Hardware tests 硬件测试
AVL FRISC combined with friction simulation

- Structure analysis
- Simulation of thermal liner deformation

Scaling

p_{Cyl}

F_{Fr} F_{Fr}

- Crank angle based friction forces
- Cycle averaged friction power
- → Detailed analysis of piston friction behavior and potentials

Validation

- Measurement results are transferred to the simulation model
- Virtual split of piston and piston ring friction

Scaling
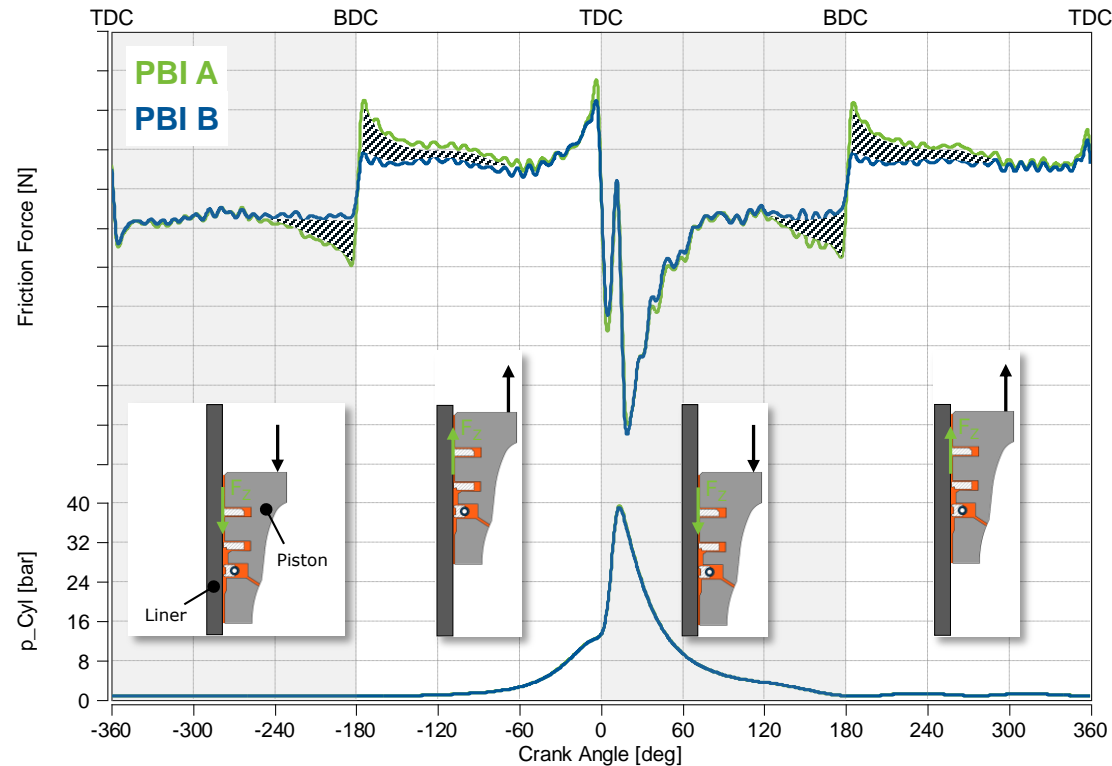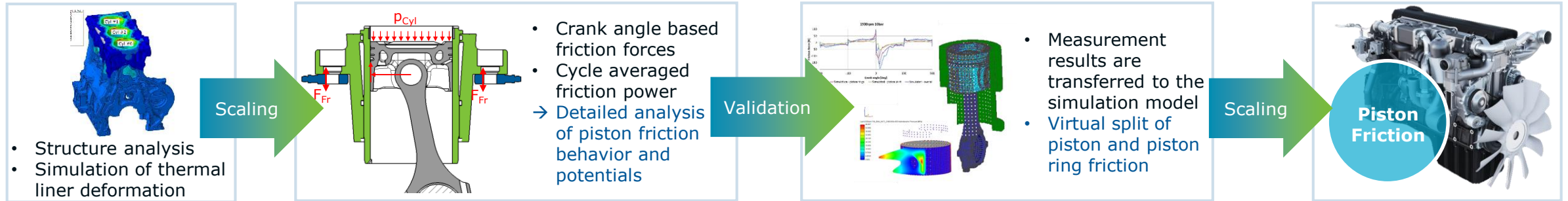
Piston Friction

Friction force 摩擦力 **PBI B** < Friction force 摩擦力 **PBI A**

→ Measures to reduce mixed friction at piston reversal:
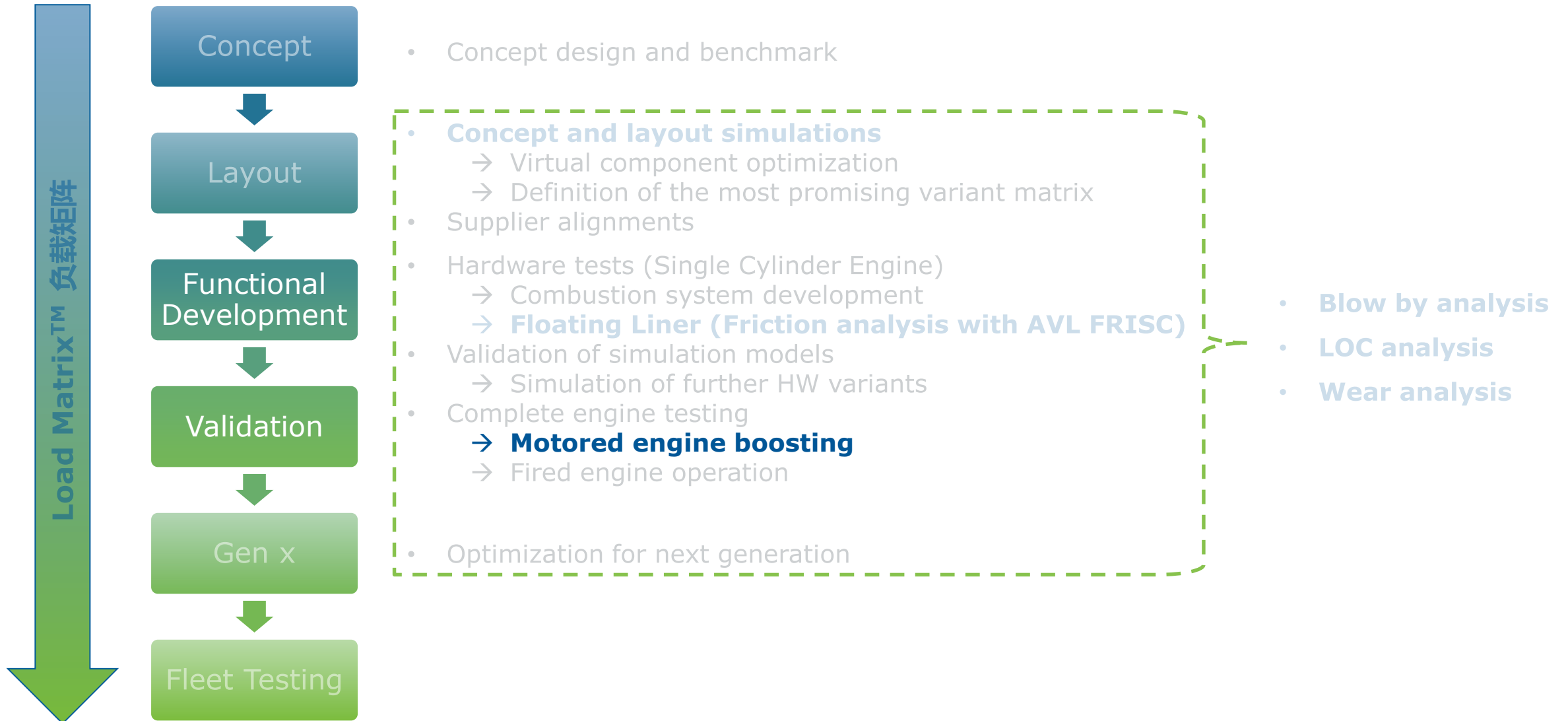 降低活塞反转时的混合摩擦的方法
  - Liner and piston shape
  - Liner and piston material
  - Liner surface structure
  - Optimized liner, piston and piston ring coatings
  - Piston ring tension
  - Friction modifier

→ Similar measures are used to reduce hydrodynamic friction at high piston speed
  类似方法也用于降低高活塞速度下的液力动力学摩擦

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Fleet Testing

Hardware tests 硬件测试
Motored engine boosting including cold friction

USE CASE 应用用例	SETUP 搭建

USE CASE 应用用例

- Friction measurement over complete speed and load map for very accurate relative comparison between load dependent sub-system variations
- **Used in early development phase to analyze friction improvement potentials**
- No combustion deviations (compared to fired measurements) & much smaller total IMEP & torque leads to results in better accuracy
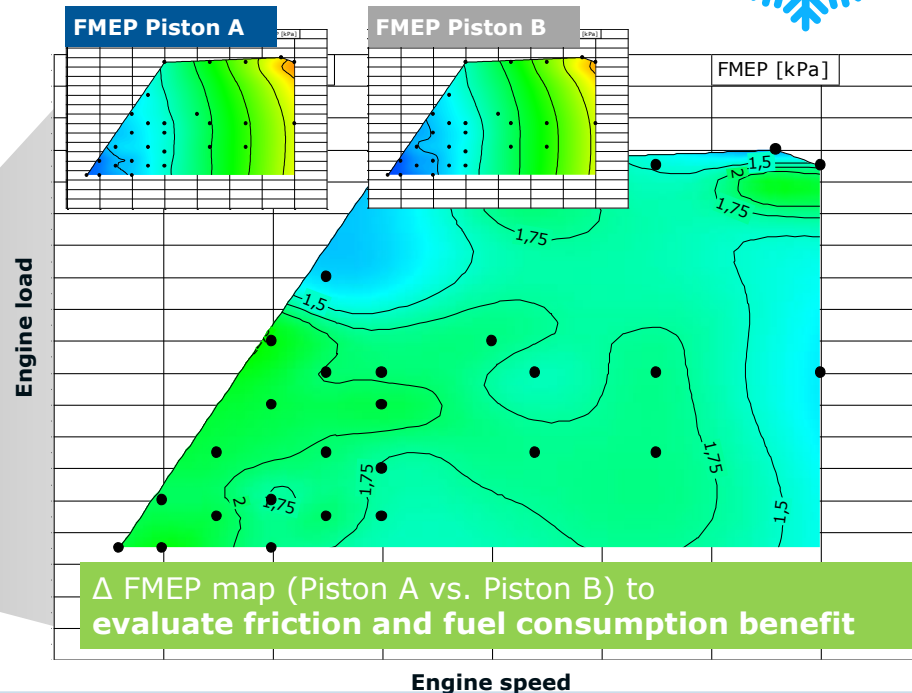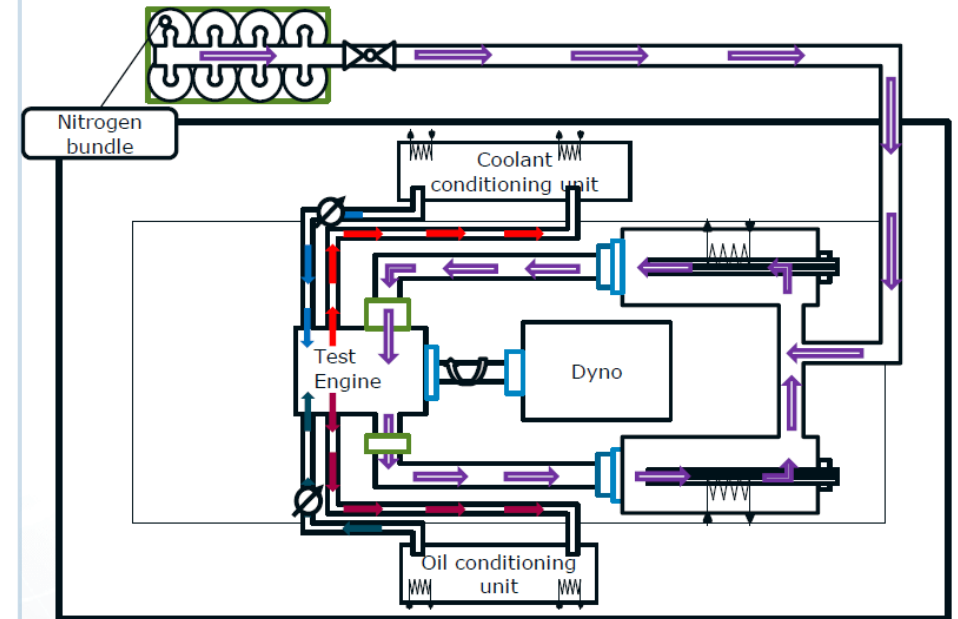- Measurements at low temperatures also possible (cold start)

Comp. A
- **Piston**
- *Rings*
- *Liner*
- *Oil*
- *...*

Comp. B
- **Piston**
- *Rings*
- *Liner*
- *Oil*
- *...*

FMEP Piston A

FMEP Piston B

FMEP [kPa]

Engine load

Engine speed

Δ FMEP map (Piston A vs. Piston B) to **evaluate friction and fuel consumption benefit**

SETUP 搭建

Nitrogen bundle

Coolant conditioning unit

Test Engine

Dyno

Oil conditioning unit

- Application of external boosting circuit to simulate thermal and mechanical conditions comparable to fired engine operation.
- Engine oil & coolant conditioning
- Exhaust gas is returned to intake resulting in a closed system
- Pressure and temperature of the gas can be adjusted achieve desired PMAX and mean piston temperature values
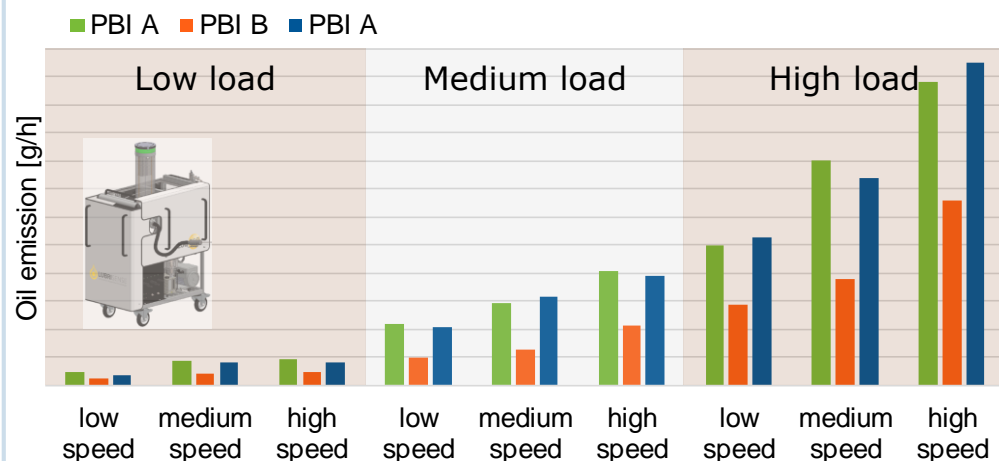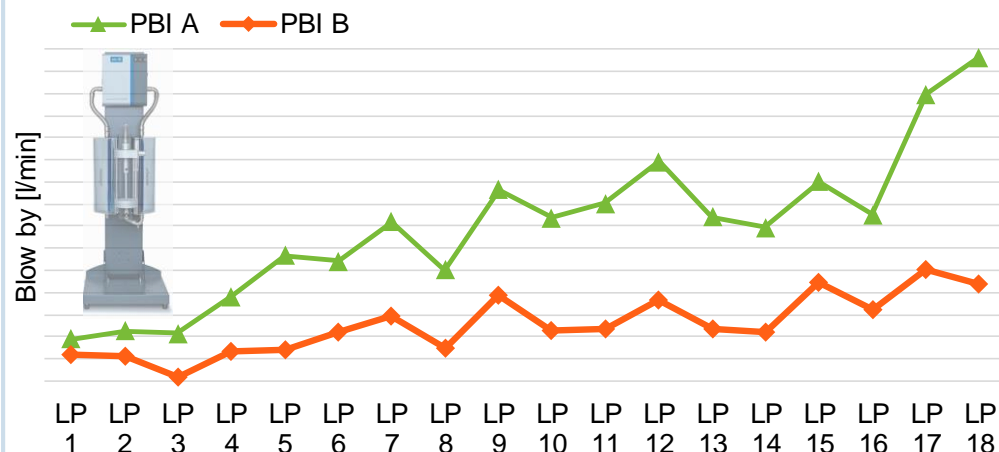
PBI development process 开发流程

Load Matrix™负载矩阵

Concept

Layout

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LOC and Blow By analysis
机油消耗和漏气分析

Time of flight (TOF) mass spectrometer TOF质谱仪

Legend: PBI A, PBI B, PBI A

Low load | Medium load | High load

Oil emission [g/h]

low speed, medium speed, high speed (×3 for each load)

AVL BLOW BY METER™漏气测量议

Legend: PBI A, PBI B

Blow by [l/min]

LP 1, LP 2, LP 3, LP 4, LP 5, LP 6, LP 7, LP 8, LP 9, LP 10, LP 11, LP 12, LP 13, LP 14, LP 15, LP 16, LP 17, LP 18

Validation

Results:
- Lube oil consumption
- Blow by gas flow
- Oil consumption mechanisms
  - Evaporation
  - Transport with reverse gas flow
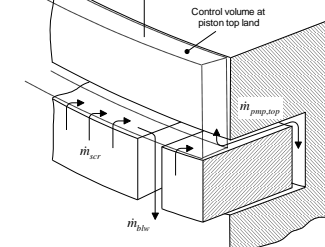 - Entrainment in blow by flow
  - Throw-off

Validation

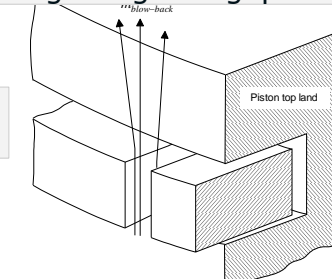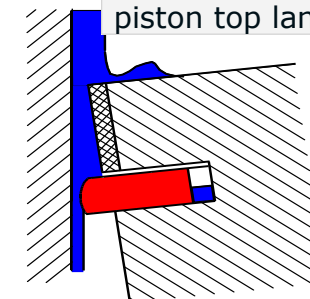## Mechanisms of LOC covered in Simulation
机油消耗机理仿真

Evaporation
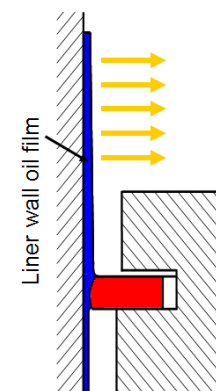
Throw off
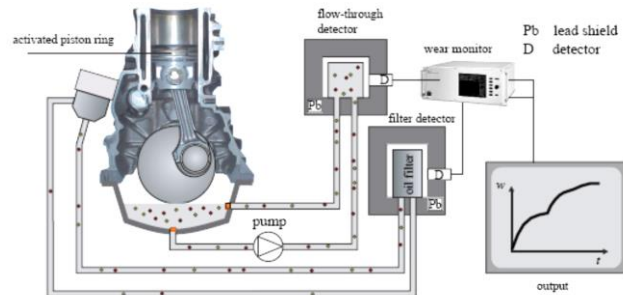
Reverse Blow-By oil blow through ring end gap

Scraping of piston top land
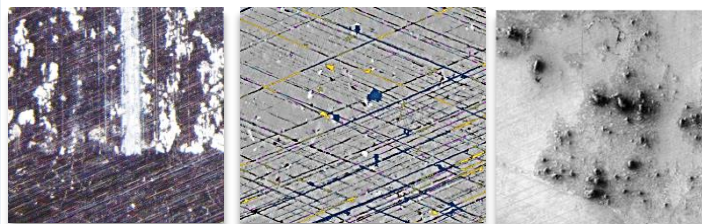
Wear analysis 摩擦分析

RNT wear measurement 摩擦测量
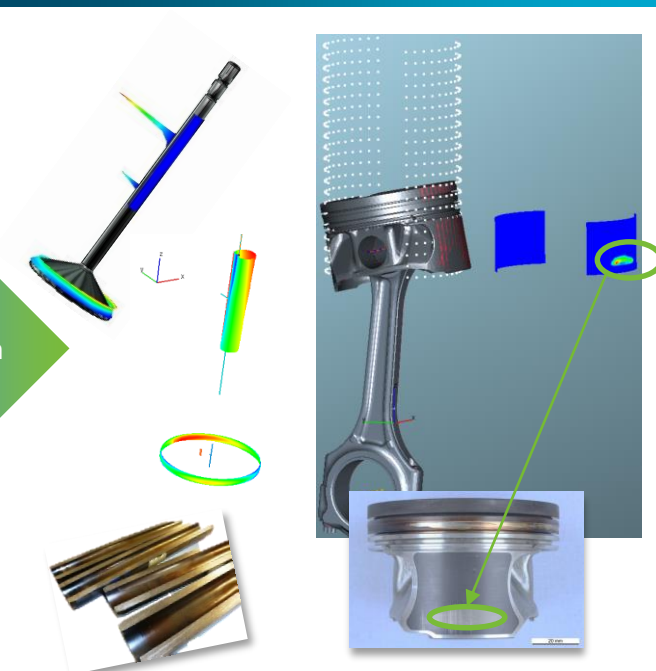

Wear detection

Surface analysis tools 表面分析工具

Optical Microscope, 3D-Surface Profiler, SEM

validation

Wear model in AVL EXCITE 摩擦模型

Online wear measurement with tracer isotopes
应用同位素追踪的在线摩擦测量

- Determination of critical operating conditions
- Wear maps
- Short term wear evaluation

Wear mechanism analysis
摩擦机理分析

- Abrasive wear
- Fretting (local friction based micro welding)
- Material adhesion
- Pitting (sub surface fatigue crack generation)

Wear simulation
摩擦仿真

- Wear accumulation
- Wear location
- Evaluation of wear progression
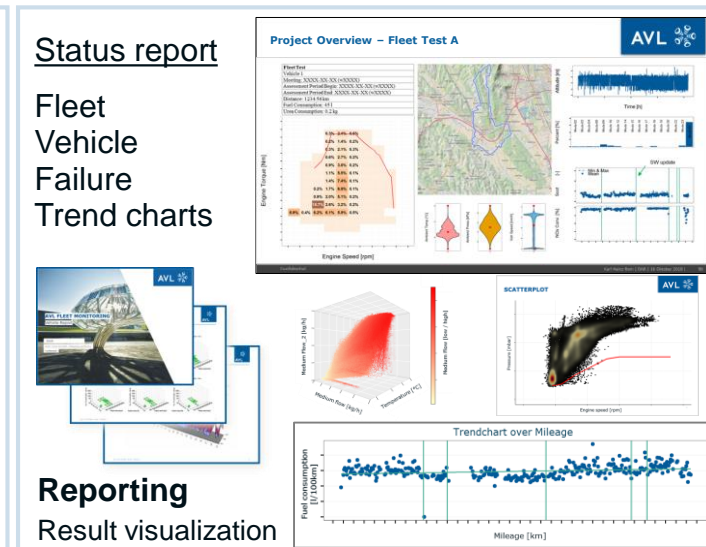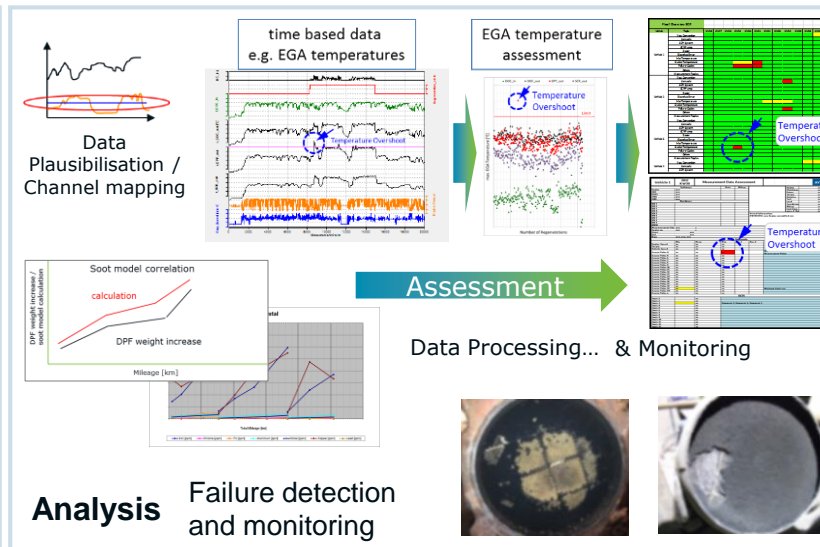- Lifetime estimation

PBI development process 开发流程

Load MatrixTM 负载矩阵

- Concept
- Layout
- Functional Development
- Validation
- Gen x
- Fleet Testing

- Concept design and benchmark

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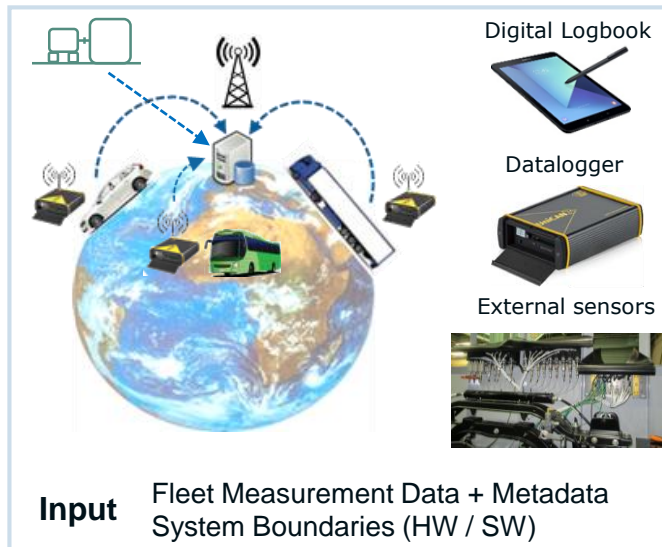- **LOC analysis**
- **Wear analysis**

AVL Fleet Data Monitoring & Analytics Service 车队数据监控和分析服务

Planning & Acquisition 计划及获取 ▸ **Assessment & Monitoring 评估及监控** ▸ **Reporting & Visualization 报告可视化**

Digital Logbook

Datalogger

External sensors

Input Fleet Measurement Data + Metadata System Boundaries (HW / SW)

Data Plausibilisation / Channel mapping

time based data e.g. EGA temperatures

EGA temperature assessment

Temperature Overshoot

Soot model correlation

calculation

DPF weight increase

Mileage [km]

Assessment

Data Processing... & Monitoring

Analysis Failure detection and monitoring

Status report

Fleet
Vehicle
Failure
Trend charts

Project Overview – Fleet Test A

SCATTERPLOT

Trendchart over Mileage

Reporting Result visualization

- Planning of testing, Usage Space Analysis
- Data driven route definition
- Definition of parameters
- Measurement installation and maintenance
- Execution of tests
- Data handling, transfer and systematic storage
- Securing data quality

- Continuous Fleet monitoring
- Operation parameter overview
- Trend chart analysis over testing time
- Failure detection and monitoring of system errors
- Anomaly detection
- Documentation of test fleet status and history
- Data mining approach
- Post calculation of acquired testing data

- Automated evaluation
- Web based reporting platform
  - Fleet status report
  - Vehicle status report
  - Failure occurrence overview
  - Customized evaluation
- Root cause analysis
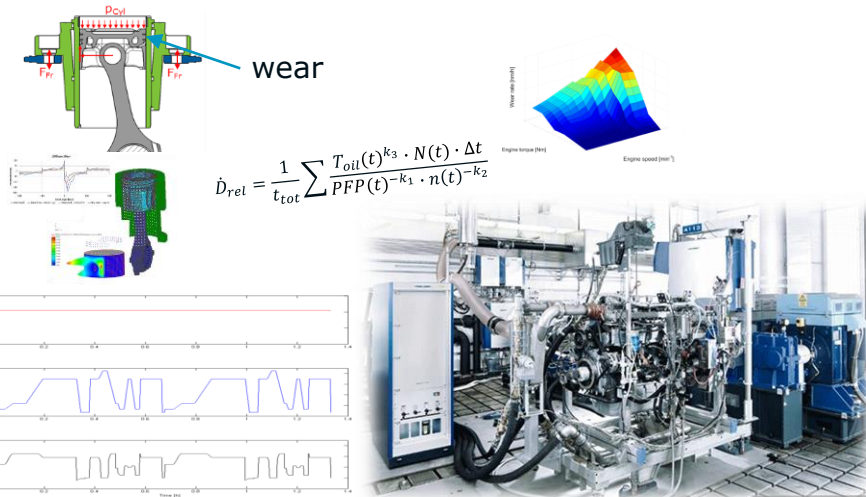- Reliability growth

PBI development process 开发流程

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Fleet Testing

Load Matrix™ 负载矩阵
Test Program Evaluation 测试项目评估

Verification and Validation/system sign off
验证、认证/系统签收

$$\dot{D}_{rel} = \frac{1}{t_{tot}} \sum \frac{T_{oil}(t)^{k_3} \cdot N(t) \cdot \Delta t}{PFP(t)^{-k_1} \cdot n(t)^{-k_2}}$$

wear

Vehicle operation/ usage
车辆运行/应用

- What needs to be tested?
- How can it fail?
- How do we model failure?
- How is it being tested?
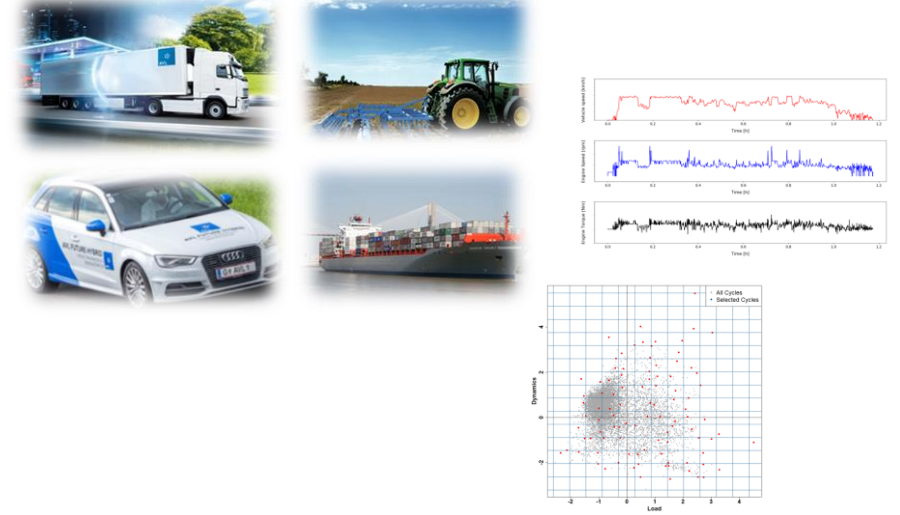
- How are the systems used?
- How reliable and durable do they need to be?

AVL Load Matrix™ combines customer usage and durability testing for high efficient testing
AVL负载矩阵结合客户应用及耐久测试

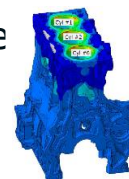# Load Matrix™ 负载矩阵
Test Program Evaluation 测试项目评估

Customer Usage 客户应用
Vehicle operation/ usage 整车运行
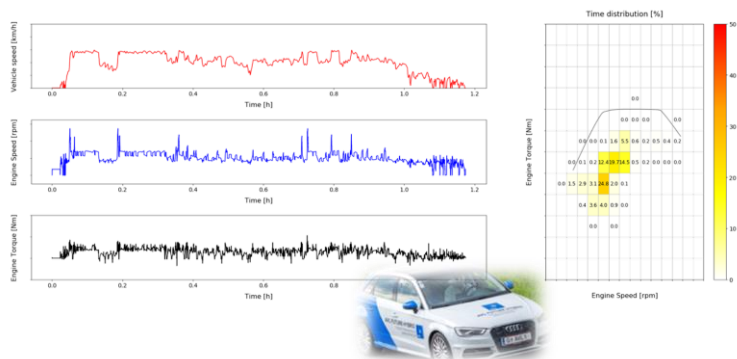
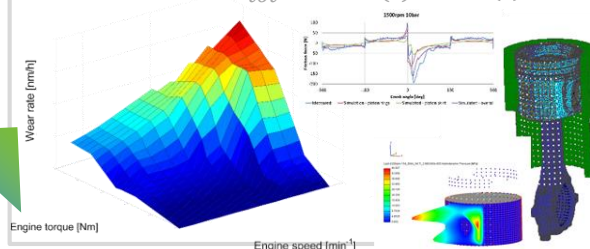## Damage model 损伤模型

Model calibration

- "Real world" damage measurement
- Simulations
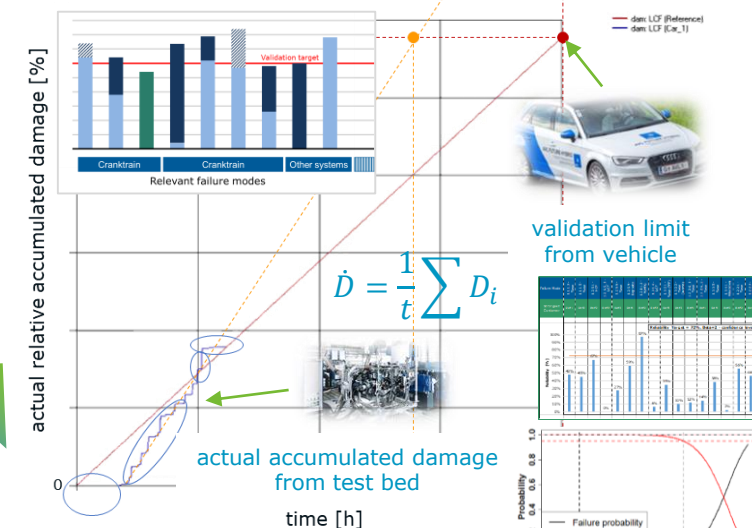
Mathematical formulation

$$D_i = f(n_i, M_i, T_{exh_i}, \dots)$$

$$\dot{D}_{rel} = \frac{1}{t_{tot}} \sum \frac{T_{oil}(t)^{k_3} \cdot N(t) \cdot \Delta t}{PFP(t)^{-k_1} \cdot n(t)^{-k_2}}$$

Test Program 测试项目
Validation test cycle 验证测试循环

Evaluation/ Output 评估/输出

Evaluation of test

validation limit from vehicle

$$\dot{D} = \frac{1}{t} \sum D_i$$

actual accumulated damage from test bed

Component Failure Mode based evaluation of test cycle or test program quality

- comparing customer component damage to
- validation test cycle damage using Physics of Failure

$$AF = \frac{\dot{D}_{Test}}{\dot{D}_{Ref}} \longrightarrow RAD = \frac{\dot{D}_{Test}}{\dot{D}_{Ref}} \frac{t_{Test}}{t_{Ref}}$$

Summary 总结

- High efficiency, zero impact emissions and maximum durability are the goals in current PBI development

  高效率、零排放及最佳耐久性是当前PBI开发的首要目的

- AVL offers multiple development solutions in simulation, testing and validation throughout the whole development process

  AVL提供贯穿整个开发过程的基于仿真、测试、验证的多种开发解决方案。

- Providing detailed information from the initial concept phase till SOP

  提供从初始概念阶段到SOP的详尽信息

- Development process is accompanied and driven by the AVL Load Matrix linking all information and leading to a reliable piston-bore-interface layout

  开发流程由AVL负载矩阵构成并驱动，连接所有信息并确保得到可靠的PBI布置。