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Specific Durability Testing with FEV Master Program

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ABSTRACT

During the past years, there has been an increasing tendency to seriously question and break up old and ingrained structures in combustion engine testing. The reason for this is the continuously increasing number of engine and vehicle variants and a variety of applications resulting from it, which significantly push up development costs and times when carrying out the classical testing patterns.

The following article by FEV Motorentechnik GmbH introduces a comprehensive test methodology for purposeful endurance testing of modern drive units (in particular from the fields of passenger cars and commercial vehicles). The procedure and the testing philosophy are explained in detail, illustrated by a concrete development example. The result is the FEV MASTER Programme as an advanced testing methodology which is purposefully geared to deal with all aspects of the many application variants while keeping the testing duration short and the number of test subjects small in order to avoid increasing total development costs and periods.

INTRODUCTION

Due to the emergence of new markets and vehicle applications, there is a growing diversity of engine variants and applications. Therefore, the development of a combustion engine and its variants up to readiness for start of production becomes increasingly complex. Each variant requires adequately extensive testing in order to prove its reliability, taking the targeted useful life into account. Despite these increased requirements, it is still the goal to reduce development costs and periods. It is for this purpose that the FEV MASTER Program has been developed. The name MASTER here stands for “Map for Synchronized Testing, Engineering and Engine Reliability”.

VEHICLE-SPECIFIC DRIVES

The requirements placed on combustion engines vary significantly, depending on the type of load. Different vehicle segments require different drive concepts. So for instance, a Formula 1 engine is expected to provide maximum performance with the lowest possible weight, while a long useful life is deliberately disregarded. If it runs well for a weekend, it has fulfilled its purpose. Engine development for vehicles intended for general road traffic and normal use by customers, however, is completely different. Essentially, three areas are distinguished with regard to general road traffic: motor cycles, passenger cars, and commercial vehicles. For these three areas, the main requirement is high reliability. In this regard, the area of commercial vehicles makes the highest demands in application; usable life requirements of 15,000 running hours or > 1 million running kilometres are normal target values. Differences in requirements on motorcycle and passenger car engines are to be found not only with regard to the usable life, but even more so with regard to the design for torque, speed, and performance. Even with a similar layout of combustion engines, there are many fundamental differences in design. These differences in design become apparent when designing engines for so-called off-highway applications. Here, reliabilities of e. g. 30,000 running hours for locomotive engines and 60,000-80,000 running hours for marine engines are demanded.

APPLICATION-SPECIFIC VARIANTS

Different applications require appropriately adjusted engine variants (Figure 1). The diversity of variants of a passenger car engine is clearly determined by the regional markets. So usually, different emission standards apply for the markets. For instance, noise reduction plays an important role in Japan, much more important than in many other Asian markets. For reasons of taxation, fuel consumption has been more important for the European market than for the US market, so far. Furthermore, there are differences due to individual engine components, such as turbochargers, charge air coolers, exhaust gas aftertreatment systems, etc. The transmission types can vary as well; they, too, are strongly determined by the local markets. In Europe, the diversity of the overall aggregates has clearly increased due to new types of transmissions, such as dual clutch transmissions (DCT), automated manual transmissions (AMT), and hybrid applications. Different vehicles, as e. g. limousines and transporters with the same basic aggregate, are another factor.

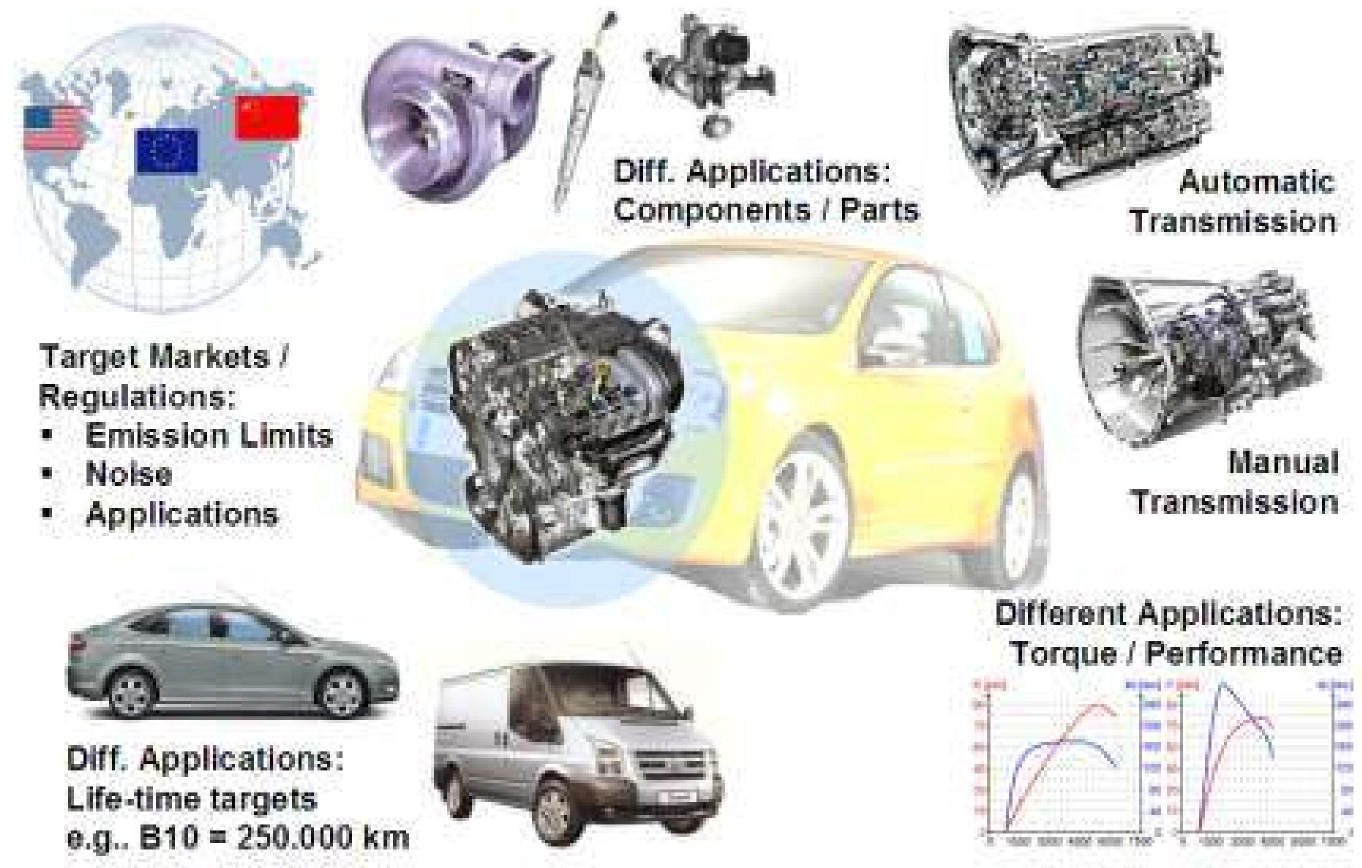


Figure 1: Different applications require different engine variants. Endurance testing according to the requirements.

Each of these possible variants requires an appropriate adjustment of the powertrain, and afterwards an assessment of all components used. Consequently, the development of a combustion engine is becoming increasingly complex, since all this must be considered in engine development in order to be able to predict the useful life. Therefore, it is becoming increasingly difficult to take the resulting target conflict, namely: reduction of the development period and costs, into account.

The FEV MASTER Program is applied predominantly in the field of passenger cars and commercial vehicles, since this is where the largest number of test subjects is used for validation, and the diversity of variants and applications requires a programme in order to recognise and utilise synergies with regard to these, and therefore to save costs and time in the overall development process. But this methodology can basically also be applied with any other engine designs, e. g. in the off-highway field.

V-CYCLE FOR MECHANICAL DEVELOPMENT

In order to illustrate the processes and connections in the development of the engine with regard to engine mechanics, FEV is showing them in the form of V-cycle diagrams (Figures 2/3).

VIRTUAL AND PHYSICAL DEVELOPMENT PHASES IN THE OVERALL PROCESS

First of all, a distinction is made between virtual and physical development. The left V-leg in Figure 2 shows the virtual development and design of mechanical testing. This includes, among other things, the early use of databases and benchmarks. The use of CAE (CFD, MBS, FEA, etc.) plays an increasingly important role.

The arithmetical predictions are becoming increasingly accurate, and thereby also more reliable.

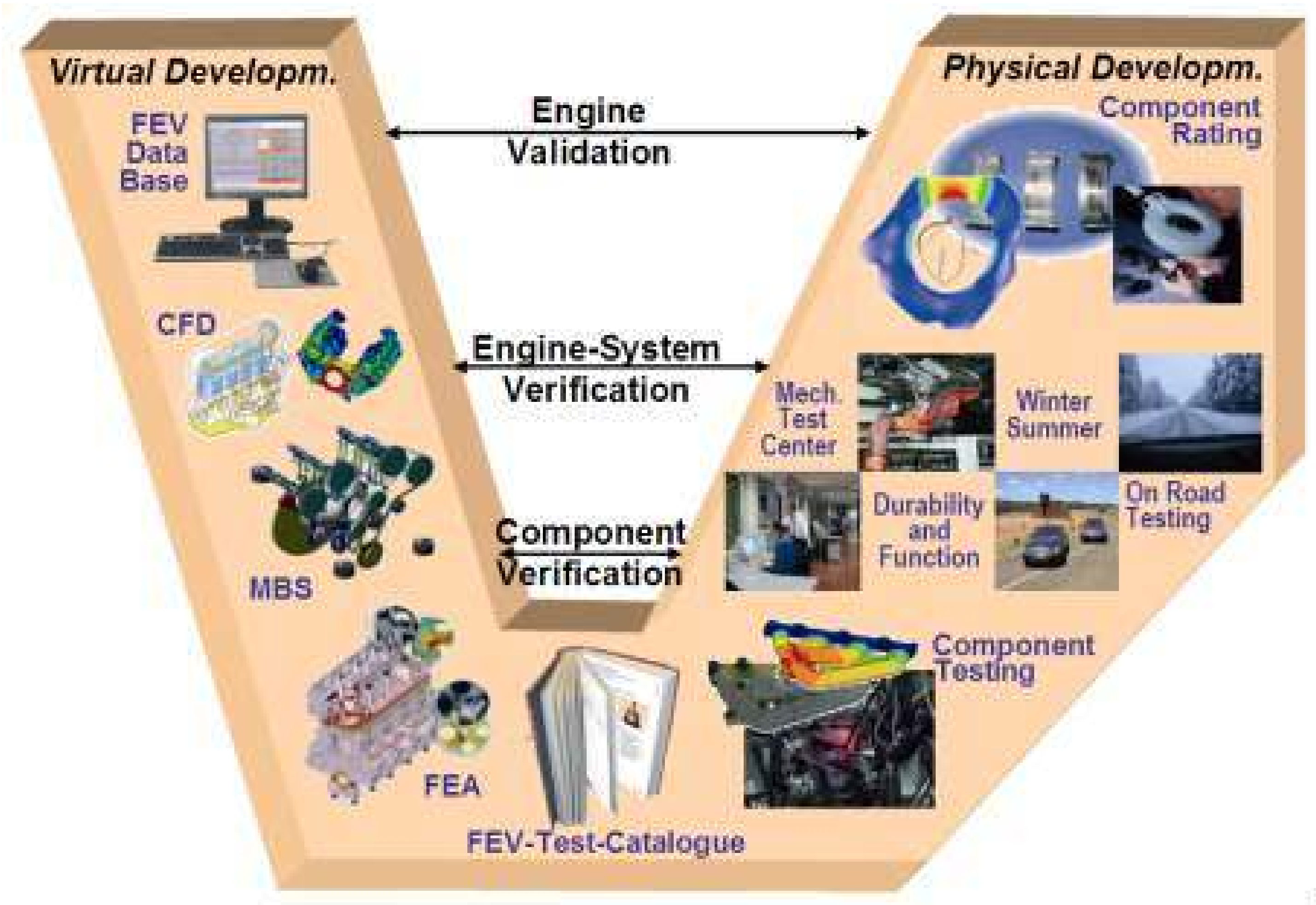


Figure 2: FEV V-Cycle for Engine Mechanical Development (virtual development – physical development).

The right V-leg describes the physical part of development, i. e. hardware testing. After testing individual components, the engine is run both on the test rig and in the vehicle on the road under the most diverse conditions. Examination and assessment of the components after the tests are an absolutely necessary part of testing.

The root point between the two V-legs is the FEV test catalogue. It constitutes the interface between CAE and hardware testing and is a comprehensive collection of predefined test programmes developed from longstanding practical experience. A close link and permanent exchange between the two branches of development is absolutely required in order to effectively reduce development time and thereby also costs. Depending on the stage of development, we are talking about component testing, engine system testing and, finally, engine validation.

ANALYSIS, SYNTHESIS, AND VALIDATION AS BASIC COMPONENTS OF THE TESTING PHASE

Physical testing can be divided into a definition and an execution phase for the test programme; Figure 3 illustrates the connections in the form of a V-cycle diagram.

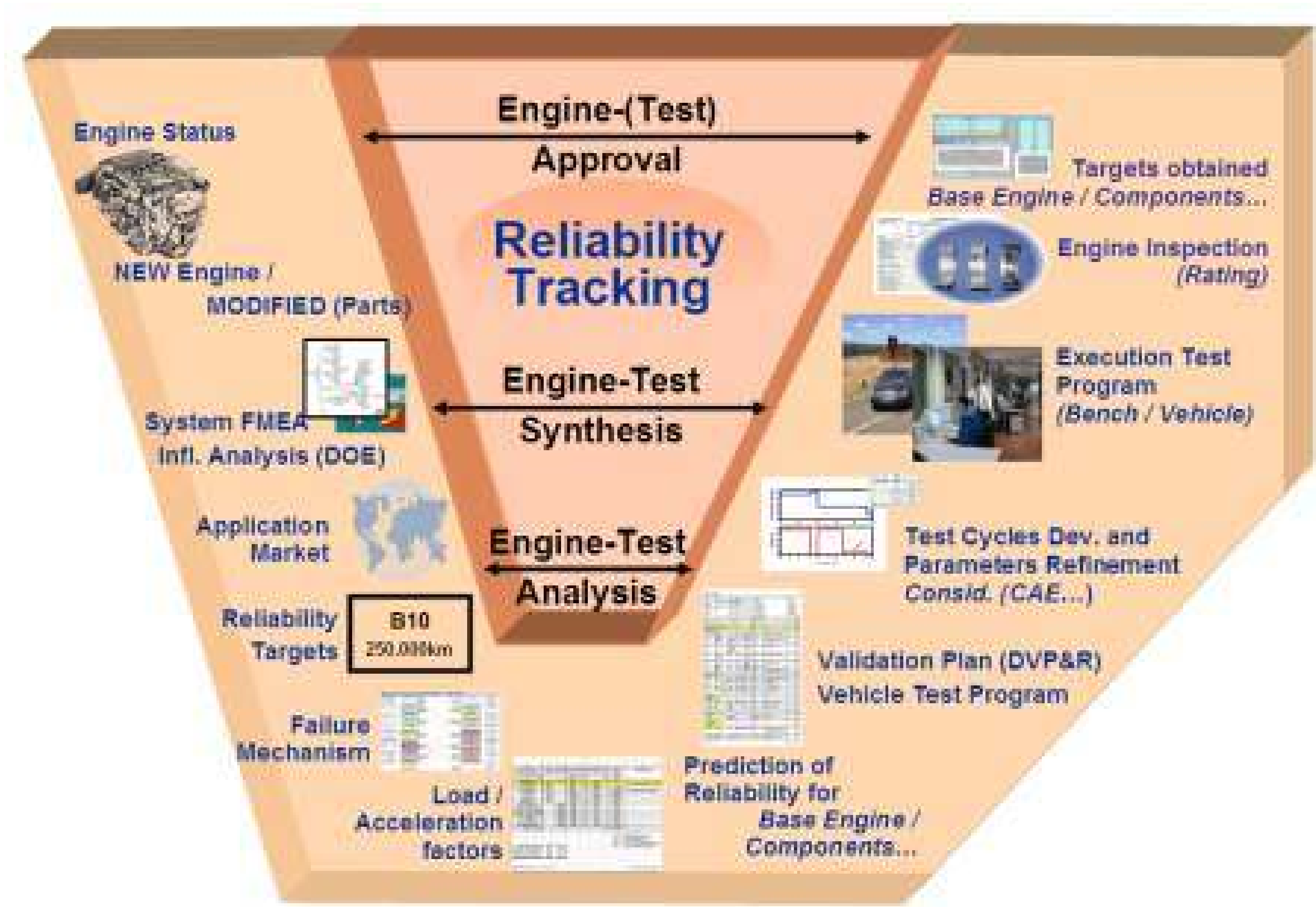


Figure 3: FEV V-Cycle for Engine Mechanical Testing (Testing Definition – Testing Execution – Tracking).

What is the aim of development, what is the stage of development? In the beginning of testing, the development status must be recorded. Subsequently, it is checked whether helpful data from FMEA (system) and DOE are available which could be used. The market must be analysed and determined in order to be able to place the product in the correct chronological order on the target markets. Furthermore, the target value for reliability must be defined which may very well vary from market to market. With regard to engine specifics, the question of which failure mechanisms must be taken into account is examined. Typical failure mechanisms are the fatigue strength of steel, the fatigue strength of aluminium, the resistance to cyclic temperature stress of aluminium, contamination, sooting, and wear. Important input data, such as parameters of engine and transmission design (driving profile, with fuel consumption, with corresponding shares in load and speed, gear ratio, etc.) have additional influence on the contents of the testing plan.

The root point of the V-cycle for the testing phase is the determination of a concrete test matrix with test-specific acceleration factors (from a comparison between the average statistical loads from customer-related operation and the test run). This first test matrix can then be used to prepare a detailed validation plan for predicting and substantiating the required reliability. After the individual tests have been carried out on the test rig or in the vehicle, respectively, the critical components are submitted to a rating and measured in order to determine the wear rates found. Also the observed oil consumption and blow-by behaviour are included in the assessment of the test results. Based on a rating catalogue and/or the component wear, the equivalent kilometres are calculated, i. e. the prospective running time to failure.

Permanent tracking is required in order to keep the test matrix as small as possible, which is the ultimate way to minimise time and costs. This means that the matrix and also the reliability analyses must be examined time and time again during the entire process and corrected, if required. This develops into an intensive interaction between test definition and test execution. The analysis of the tests starts with the selection of known, or the definition of new test patterns, is then continued in the synthesis by constantly merging the analysis data, and is completed only with the release of the unit. Therefore, the test matrix is nurtured by the variable adjustment of the test runs, the running hours, and the evaluation and incorporation of the rating results.

TYPICAL TESTS

Figure 4 shows the principal failure disciplines and the usual test conditions. Typical endurance runs on the test rig are multi-point endurance run, hot/cold endurance run, city endurance run, resonance tests, hot idle test, sooting tests, and also standard endurance runs with various execution times and patterns (Figure 5). The test on the test rig is complemented by customer-relevant tests in vehicle testing. In commercial vehicle testing, additional examinations specific to commercial vehicles, such as engine brake tests, or e. g. tests for examining the complex systems for exhaust gas after treatment, are carried out, among others.

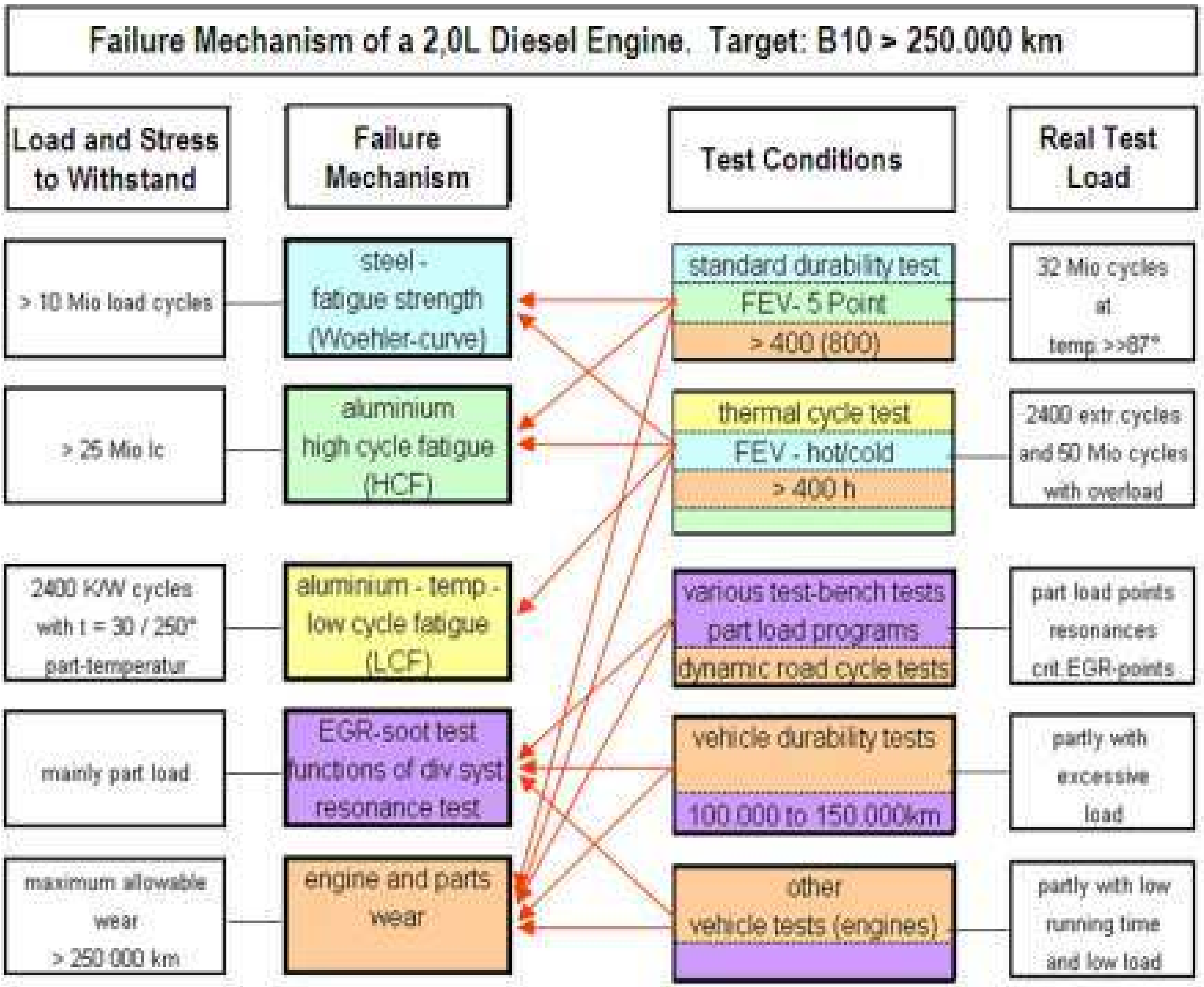


Figure 4: Assessment of tests to failure mechanisms.

	Typical Durability Tests Bench and Vehicle *Basis: Passanger Vehicle*	bench (h)	vehicle (km)
Bench	standard durability	~ 200	-
	standard durability	≥ 600	-
	hot/cold	≥ 400	-
	dynamic road	≥ 600	-
	resonance	≥ 300	-
	hot idle	≥ 800	-
	soot test	≥ 1.000	-
	⋮	⋮	⋮
Vehicle	extreme city cycle	-	≥ 50.000
	hot/city/cold	-	≥ 50.000
	extreme vehicle durability	-	~ 150.000
	Basis: low/medium/heavy duty	bench	vehicle
Bench	⋮	⋮	⋮
	engine break test	≥ 400	-
	filter killer test	~ 1000	-
	crystallization test	~ 1000	-
	⋮	⋮	-
	⋮	-	⋮

Figure 5: Typical bench and vehicle durability tests.

CYCLE DEVELOPMENT

It is particularly difficult to assess components which are not durable, but which are only of limited durability. Typical examples in this context are e. g. the highly loaded aluminium components. Due to the high loads, cracks increasingly tend to appear in the structure which, at an advanced stage, often lead to failure of the component. In most cases, such cracks can be attributed to classical low- or high-cycle failure mechanisms. Nowadays, it is possible to accurately simulate these failure mechanisms. While formerly, such components were validated in a complex manner by means of endurance runs based on experiences, today the simulation results from the virtual development phase are used for the cycle development of tailor-made acceptance tests.

Figure 6 shows the scattering range of different hot/cold tests (FEV test catalogue, database). Plotted is the maximum temperature amplitude occurring in the respective cycle in the cooling agent over the number of cycles mandatory for the tests. On the right axis, the maximum material temperature in the flame deck of the cylinder head occurring during the test is plotted as a damage parameter by way of example – it correlates to the greatest possible extent with the temperature amplitude in the cooling agent plotted on the left side.

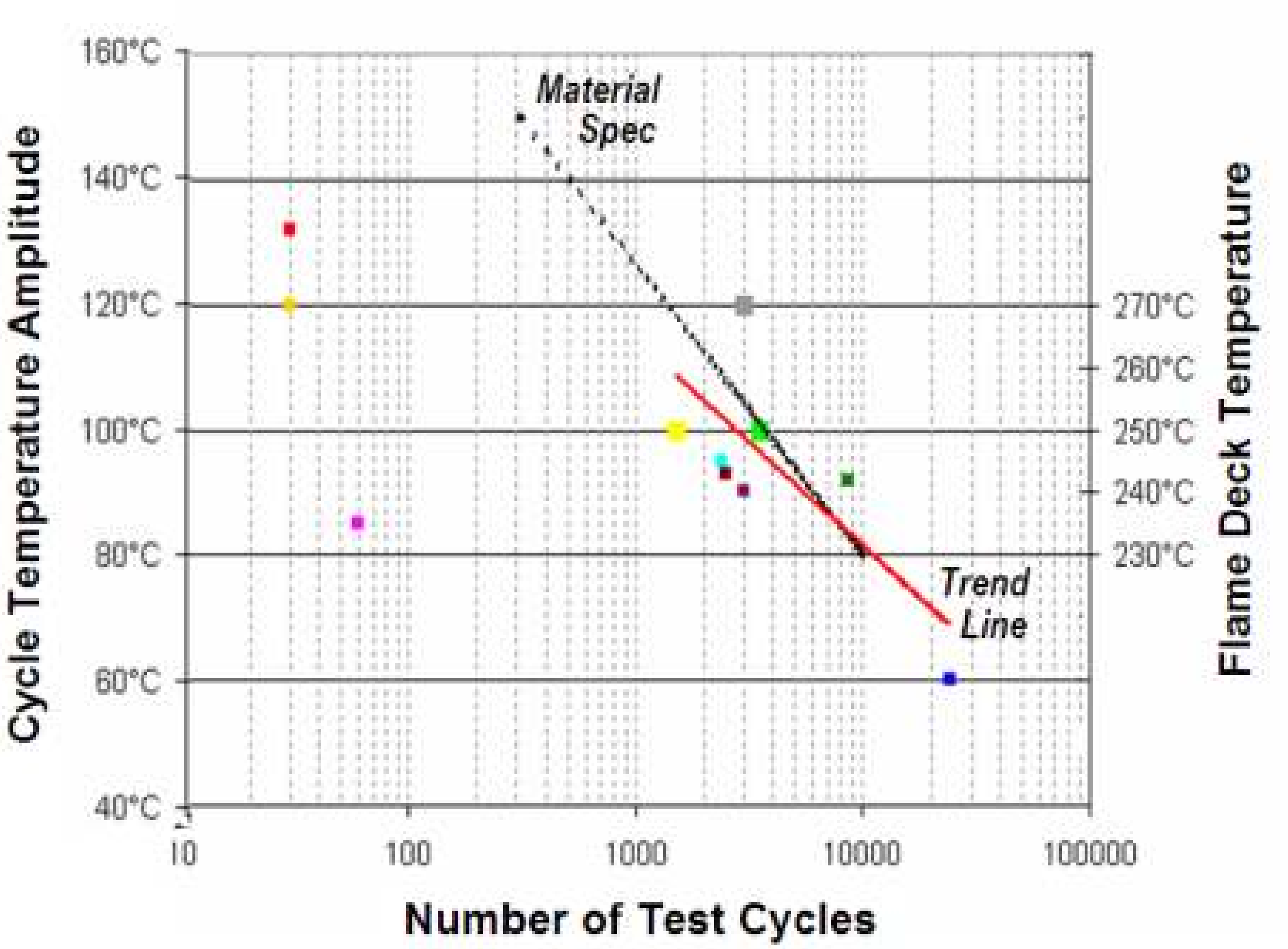


Figure 6: Test cycle development, e.g. hot/cold test.

The single points on the very left side of the diagram (few test cycles) are from hot/cold tests, in particular for the acceptance of the cylinder head gasket. The cluster of points on the right side (many test cycles) mainly represents tests for the validation of the above-mentioned low-cycle mechanism. The broad scattering range suggests different test philosophies: Low-load tests require longer running times than tests with a harder load spectrum – each OEM has gathered its own experiences with this. The trend line of the real tests (solid line in the diagram) is compared with the temperature-dependent number of cycles to failure for a common aluminium alloy from the simulation (broken line). The comparison illustrates that a very good approximation of the experience-based tests can be covered in the simulation. In this manner, load spectra which achieve the same component damage in significantly less test rig time than in the long-running, experience-based acceptance tests can be purposefully determined by means of CAE. As a result, component validation can nevertheless be carried out safely with clearly reduced time and cost requirements.

COMPONENT RATING AND MEASUREMENT

After a successful test, all important components are measured with regard to wear and undergo a rating. The results are assessed based on a 5-stage grading system; Figure 7 illustrates the assessments by way of three concrete examples.

- Grade = 1 (excellent), there are no or only minimum wear patterns.
- Grade = 2 (acceptable), there are only little traces of wear, scratches, or changes.
- Grade = 3 (critical), detailed analysis required for insight into further function.
- Grade = 4 (unacceptable), leakages, breaks, or distinct material loss.
- Grade = 5 (loss of function), component must be exchanged for further operation.

Figure 7: Engine component rating after dura-testing.

Another factor is determined from wear, rating, and oil consumption and blow-by behaviour, which is used to predict the running time to failure. The fictitious running time to failure of the respective test engine is then defined from the most unfavourable factor.

TESTING SCHEDULE

Figure 8 shows the typical testing schedule for an engine. The upper area marks the basic stages of development. The four testing stages are shown underneath.

- test rig function testing with parallel working out of the calibration,
- test rig endurance testing taking the subdivision into further programme stages into account,
- vehicle testing for function and for refinement of ECU data.
- vehicle endurance testing for the pilot production run. The time schedule has relevant milestones for release from prototype engines up to SOP.

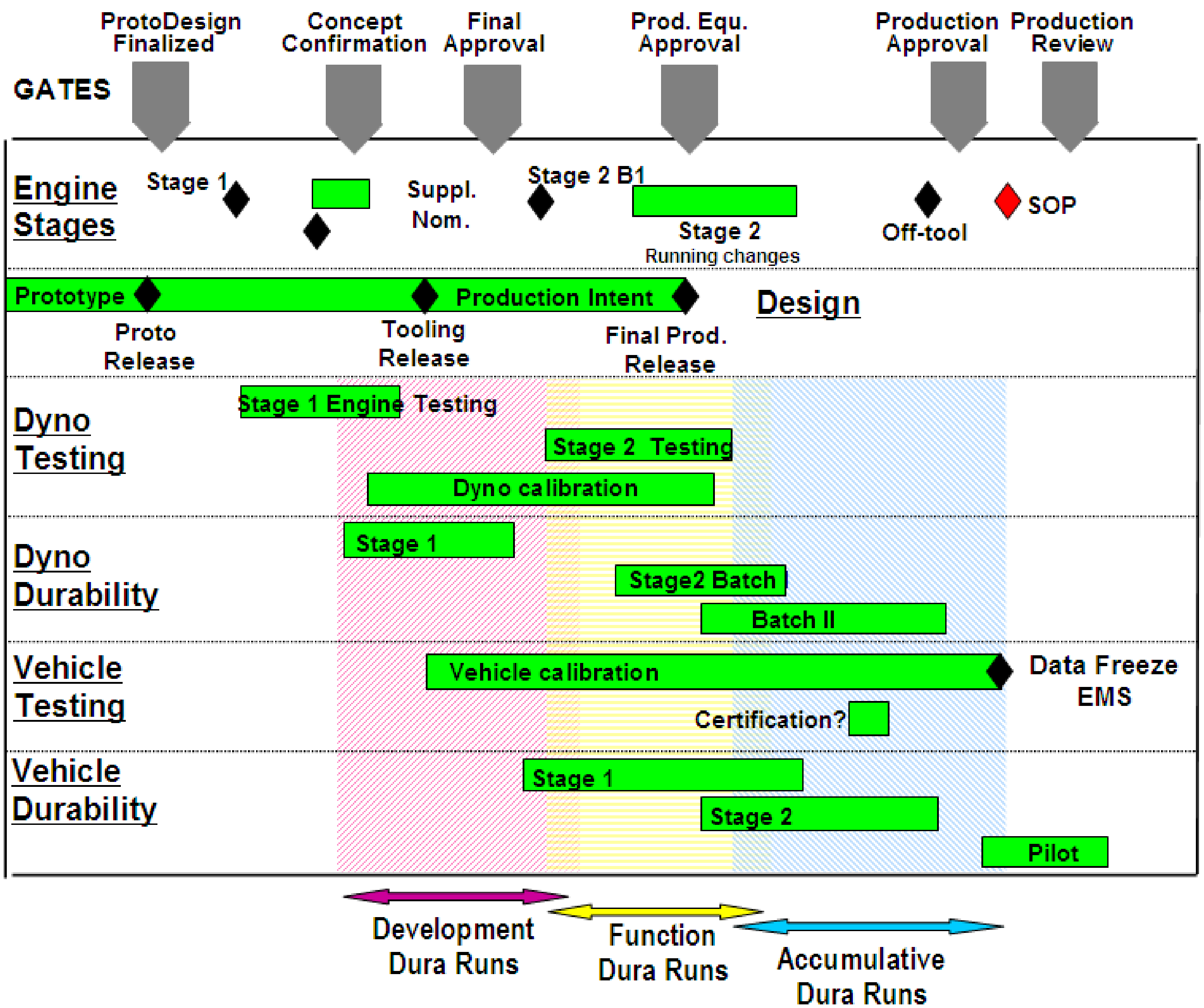


Figure 8: Typical time schedule for engine testing.

According to definition by FEV, three different types of endurance testing are distinguished, graded by the level of maturity. Depending on the development stage, a distinction is made between development endurance runs, which is the typical prototype development where daily running times of 18-20 hours are rather rare, and which is therefore cost- and time-intensive. The next stage are function durability runs which need less attendance than a development endurance run, but which must be monitored, and therefore still permit less running hours than the last stage, the accumulative durability runs. This endurance run which is carried out in the last phase of development is usually applied to pre-production engines and engines from series running or series production itself. The FEV Master Program takes all engines and their components with the different levels of maturity into account.

DEVELOPMENT EXAMPLE WITH DIFFERENT APPLICATION VARIANTS

The following example serves to explain the FEV MASTER Program based on a 1.7 litre natural aspired engine with 83 kW at 6000 rpm and a maximum torque of 142 Nm at 3500 to 4500 rpm. The introduced engine will for instance be used in a saloon car and fulfil a target of 250,000 km (B10 value).

LEAD APPLICATION AND MARKET-SPECIFIC DERIVATIVES

Figure 9 shows an extract from a test programme which has been compiled and successfully carried out and assessed by FEV. The customer-related operation for 250,000 km shaded in grey in the table constitutes the basis for the assessment of the corresponding test runs. Furthermore, various test rig runs and vehicle test runs with the corresponding number of testing hours or kilometres are listed. The testing hours are converted in accordance with the rotational speed and speed parameters and are represented in kilometres. The kilometre equivalent of each test run is now calculated by means of different acceleration factors which are determined from the comparison between the average statistical loads of customer-related operation and test run. The total kilometre equivalents are finally calculated by multiplying this by the number of test runs and, in this example, come to approx. 5 million kilometres in total as development target resulting from 45 test runs.

complete endurance test program; gasoline turbo	**duration test bench**	**duration vehicle**	**speed parameter**	**acceleration factor**	**equivalent kilometer**	**number of test runs**	**total equivalent kilometer**
testprogram	(h)	(km)	(km)	(-)	(km)	(-)	(km)
customer usage (Basis)		250.000	250.000	1,00	250.000	-	-
FEV 4-point	200	-	43.243	2,18	94.118	1	94.118
FEV 4-point	800	-	172.973	2,18	376.471	4	1.508.882
FEV hot/cold	600	-	97.297	2,60	252.972	3	758.917
FEV dynamic road	800	-	129.730	2,54	329.412	4	1.317.647
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
hot/city/cold	-	50.000	50.000	1,76	88.235	1	88.235
extreme vehicle endurance test	-	50.000	50.000	1,76	88.235	2	176.471
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
total :						**45**	**4.983.521**

Figure 9: Test matrix of acceleration factors.

Now, in the subsequent component assessment, all of the components – in our example, engine number 7 – are assessed (Figure 10). Parts which had to be repaired during the tests because of minor defects are dropped from the assessment, since the aim is to achieve or simulate a total failure of the engine. All other components which have reached the equivalent kilometres are now assessed based on the rating catalogue mentioned above. The grading system is based on specific factors for calculating the expected equivalent kilometres of each component. In doing so, a distinction is made between a factor from visual inspection and the factor from wear. The smaller of the two, i. e. the one which is first to lead to loss of function of the component, is used to calculate the kilometre performance at total failure. Consequently, this is a fictitious running time to failure.

Rating Engine	**Nr.: 7**							
Part/Function	Test Type	eff. duration (h)	eff. equivalent kilometer (km)	Factor F1 according visual inspection	Factor F2 according wear	min. Factor	predicted equivalent km. **(="Engine break"!)** (km)	Remarks
hose clip	FEV hot/cold	100	42.162	**1**	-	1,00	***42.162***	repaired
spark plug		300	126.486	**1**	-	1,00	***126.486***	rapaired
conrod bearing		600	252.972	**1,5**	4,00	1,50	379.458	
main bearing		600	252.972	2	**1,82**	1,82	460.409	
cylinder-head gasket		600	252.972	**1,5**	-	1,50	379.458	
first piston ring		600	252.972	1,85	**1,25**	1,25	**316.215**	**smallest value**
piston		600	252.972	**1,675**	-	1,68	423.728	
timing chain		600	252.972	**-**	**1,33**	1,33	336.453	
cylinder liner wear		600	252.972	**-**	**2,50**	2,50	632.430	
camshaft		600	252.972	**1,85**	2,22	1,85	467.998	
TVD		600	252.972	**2**	-	2,00	505.944	
⋮		600	252.972	⋮	⋮	⋮	⋮	

Figure 10: Test matrix of engine part rating factors.

Now the smallest total kilometre value is selected from each component rating. In our example, endurance test engine no. 7 has a predicted running time to failure of 316,215 km, determined by the failure of the first piston ring. All other endurance runs were evaluated according to the same pattern, each of them resulting in a fictitious running time to failure. These figures are now statistically evaluated according to Weibull (Figure 11). In order to achieve the default value B10, maximally 10 percent of the later customer engines may fall below a running performance of 250,000 km. In our example, 90.47 % of the engines have achieved the required 250,000 kilometres; therefore, the target has been reached.

Engine #	Smallest predicted engine values: (km)
1	221.000
3	277.852
5	299.752
7	**316.215**
2	323.009
6	352.777
4	376.549
12	376.767
10	432.210
9	456.798
13	478.960
8	479.960
14	511.111
15	567.890
11	634.000
⋮	⋮

	reliability in %	Km
	1,00%	662.555
	10,00%	555.371
	30,00%	470.859
Char.Lebensd.63,2%	36,80%	449.087
	50,00%	409.113
	70,00%	345.447
B10	90,00%	253.252
	99,00%	139.234
Tester		
Input of KM?	250.000 km	
% of engines-target reached	90,47 %	

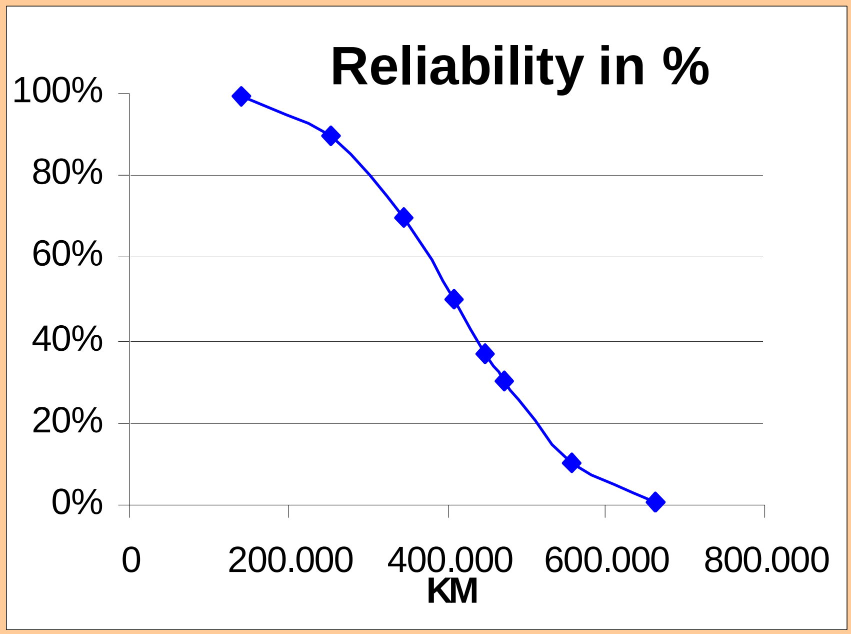
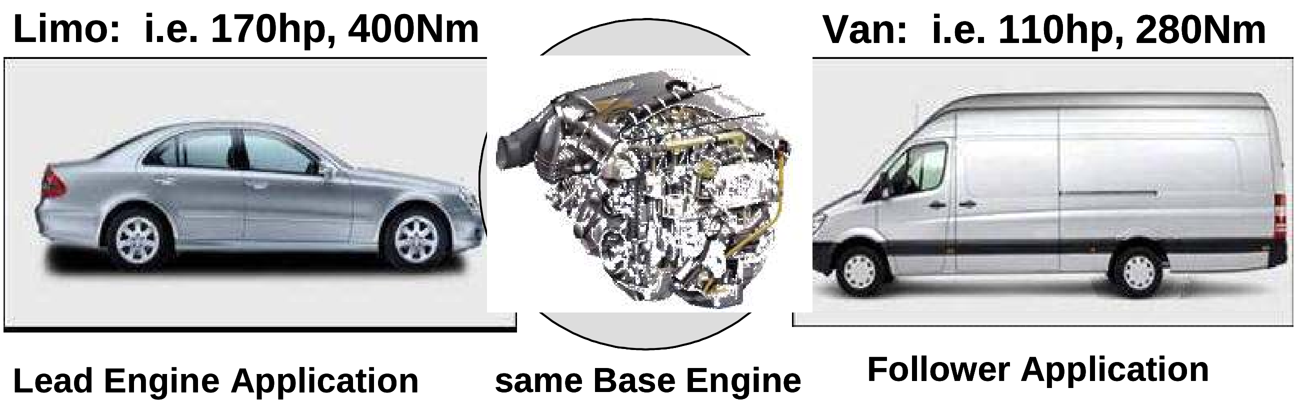


Figure 11: Result to reach the reliability targets.

APPLICATION-SPECIFIC VARIANTS

If the same engine is used in a commercial vehicle, the higher load in the commercial vehicle will cause a reduction of the acceleration factors, and the 5 million “passenger car kilometres” will be reduced to only 3 million total equivalent kilometres in the commercial vehicle (Figure 12). In this case, further tests or an extension of the test running times are required in order to achieve the 5 million kilometres.



complete endurance test program diesel utility vehicle	duration test bench	duration vehicle	speed parameter	acceleration factor	equivalent kilometer	number of test runs	complete equivalent kilometer
testprogram	(h)	(km)	(km)	(-)	(km)	(-)	(km)
customer usage (Basis)		300.000	300.000	1,00	300.000	-	-
FEV 5-point	450	-	69.811	1,92	134.037	5	670.186
FEV hot/cold	600	-	98.919	2,03	200.806	3	602.417
⋮	⋮		⋮	⋮	⋮	⋮	⋮
vehicle with trailer	-	25.000	25.000	0,86	21.500	1	21.500
extreme vehicle durability	-	150.000	150.000	1,09	163.500	4	654.000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
total :						**45**	**3.000.000**

Figure 12: Test matrix definition of the follower application.

Conversely, this system can be used to estimate how the testing programme, and possibly also the number of test engines, can be reduced, if e. g. a large engine is installed in a very small and light-weight vehicle. With a systematic evaluation of the present results of the endurance runs in relation to the single components, it is possible to assess whether these are possibly overdimensioned.

SUMMARY

The FEV MASTER Program comprises three levels of testing: analysis, synthesis, and validation. The focus is on a profound consolidation of all test-relevant findings about the engine. Based on these findings from the thorough analysis, the test matrix, the test cycles, and the validation plan will be drawn up. During the test phase, the test plans are permanently reviewed with regard to target achievement in relation to useful life, costs, and time. This is done both for the basic engine and for the individual components and component variants of the engine.

The assessment of the corresponding test runs from the test matrix is based on the expected customer-related operation. Appropriate runs on the test rig and vehicle test runs with the corresponding number of testing hours or kilometres are compiled. The testing hours are then converted to “real” equivalent kilometres. After successful testing, “predicted” kilometres are derived from the real equivalent kilometres by means of the rating results and the wear data. This is determined both for the basic engine and for the components. These predicted data are processed according to Weibull with the support from other software, and used for determining the target useful life, e. g. according to B10.

By making use of synergies during the tests of the various engine variants, the FEV MASTER Program is able to design the total development programme in such a streamlined manner that the corresponding target useful lifetimes are reached and proved, and at the same time, a reduction of costs and development time is achieved.

LITERATUR

[1] S. Pischinger, et. al: Das neue FEV Dauerlaufprüfzentrum in Brehna bei Leipzig. MTZ extra, Sonderheft 58922, März 2009.

[2] F. Maassen: Hybride Analyseverfahren für die moderne Mechanikentwicklung. MTZ Motortechnische Zeitschrift, 68(2007)6

[3] A. Küsters; F. Maassen; T. Rinkens; H. Brüggemann: Mechanical testing – still necessary! SAE World Congress, 16.-19.04.2007, Detroit/MI, Paper 2007-01-1768

[4] http://www.fev.com/data/documents/TTM_Mechanical-Testing_1_05.pdf

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

MASTER	MAp for Synchronized Testing, Engineering and Reliability
CAE	Computer-Aided-Engineering
CFD	Computational-Fluid-Dynamics
MBS	Multi-Body-Simulation
FEA	Finite-Element-Analysis
B10	Reliability target per definition in km or h - % of engines not reached reliability target
Weibull	Statistical calculation method for B10 calculation