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Standard Load Spectra for Commercial Vehicle Brakes

Working Group Standard Load Spectra for Commercial Vehicle Brakes

This not binding technical recommendation was developed by the working group “Standard Load Spectra for Commercial Vehicle Brakes” and contains:

- Customer relevant operating load spectra for the commercial vehicle brake in Europe
- Standardized reliability requirements
- Standardized reliability demonstration concept

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1 Basics

This technical recommendation was developed by the working group "Standard Load Spectra for Commercial Vehicle Brakes" to achieve common understanding in the brake industry about customer relevant operating load spectra for commercial vehicle brakes in Europe and their reliability demonstration. The following companies participated in the working group: BPW Bergische Achsen KG, DAF Trucks NV, Daimler AG, Haldex Brake Products AB, IVECO S.p.A., Knorr-Bremse SfN GmbH, MAN Truck & Bus AG, Meritor HVBS (UK) Ltd., SAF-HOLLAND GmbH, WABCO Radbremsen GmbH.

1.1 Scope

Area of validity:

- The scope of this recommendation are commercial vehicle wheel brakes, designed for 22,5" inch rims operating in Europe.
- This document describes operating load spectra for clamping force and braking torque. Other load types (e.g. vibration) are not taken into consideration.
- The operating load spectra described in this document are covering 99%-customer's usage, for a given vehicle mission and a distance of 100 000 km.
- Suitable extrapolation methods have to be chosen for an extrapolation to the brake's service life.
- The load spectra in this document do not cover any type of special vehicle missions like for example motorsport or military applications.
- The described reliability tests are recommendations. However, other reliability demonstration tests are valid as long as the test load spectrum correlates with the operating load spectra described in this document.

1.2 Nomenclature

Generally, the vocabulary of the ISO 611 "Road vehicles – Braking of automotive vehicles and their trailers – Vocabulary" is used. However, some of the used terms are not part of the ISO 611. These terms are described in Table 1-1. The formula symbols used in this document are listed in Table 1-2.

Table 1-1: Nomenclature in addition to ISO 611

Term	Definition
ALT	Accelerated Life Test
BTLS	Braking Torque Load Spectra
CFLS	Clamping Force Load Spectra
EoL	End of Life Test
PBA	Parking Brake Actuator
SBA	Service Brake Actuator
SRT	Success Run Test

Table 1-2: Formula symbols

Symbol	Definition	Unit
μ	Mean value	[km, h, a]
b	Weibull shape parameter	-
CL	Confidence level	[%]
L_V	Lifetime-ratio	-
n	Sample size	-
R	Reliability	[%]
R_{req}	Required reliability	[%]
R_{test}	Demonstrated reliability	[%]
t	Required lifetime	[km, h, a]
T	Characteristic lifetime	[km, h, a]
t_0	Failure free time	[km, h, a]
t_p	Accelerated test time	[km, h, a]
σ	Standard deviation	[km, h, a]

2 Operating Load Spectra

The load spectra described in this chapter are representative for 99%-customer's usage over 100 000 km and the assigned mission. This recommendation describes load spectrum modules for specific load cases, to deal with the complexity of different brake system architectures for trucks and trailers. By combining these modules, the load spectra for clamping force and braking torque can be determined suitable to the used brake system architecture. For the same reason each truck module is defined for a brake mounted at the front and the rear axle. The guidelines for the determination of clamping force and braking torque load spectra are described in 2.3.1 and 2.4.1. The modules and their description are defined in 2.1.

The load spectrum modules are 99% envelopes, determined using real field data with approximately 10 000 truck, tractor and bus vehicles. The trailer load spectra are derived from these measurements. The modules, described in this document, are a result of different brake types (drum and disc), actuator sizes, vehicle configurations, loading conditions, traffic situations, road types and drivers. Additionally, influences of the electronic braking system (e.g. braking ratio, wear harmonization, etc.), the secondary braking systems and the bus stop function are covered. Of course, a field data analysis is subject to uncertainties, but these have been reduced to a minimum and the results were validated with measurement vehicles.

2.1 Load Spectrum Modules

The load levels of the following modules have to be calculated individually based on the pressure level or the number of brake actuations. For the clamping force following parameters have to be considered: actuator diameter or spring force, actuator efficiency, the lever ratio of the brake and the brake's efficiency. In addition to that the parameters: wheel brake characteristic C* and the effective friction radius have to be considered for the braking torque load level calculation.

Service Brake Module

The Service Brake Module contains all clamping force loads induced by the service brake actuator (SBA) while driving forward, reversing and stationary without parking brake actuation. The load is defined using the applied pressure at the SBA. The resulting clamping force has to be determined individually dependent on the actuator and the brake.

Parking Brake Module

The Parking Brake Module contains all clamping loads induced by applying the parking brake. For this module only the frequency of parking brake actuations is defined. The load level has to be defined individually, dependent on the brake and the parking brake actuator (PBA).

For trailers connected to a truck it has to be considered that the parking brake actuation is induced by the SBA, which is applied with system pressure. While parking a trailer without the truck, the parking brake actuation is induced by the PBA.

Overload Module

The Overload Module describes the usage of the service brake while the parking brake is applied. Therefore, it contains all service brake actuations while the parking brake at the vehicle is applied. It's defined using the applied pressure at the SBA, without the share of the parking brake actuator (PBA). The resulting overload force has to be determined individually. The load frequency of this module is already part of the Parking Brake Module.

If no PBA is mounted at the brake, the service brake pressure of this module will still be induced to the SBA. In this case the SBA-Share of the Overload Module has to be considered in the clamping force load spectrum determination.

Service Brake – Forward Driving Module

This module contains all clamping loads induced by the service brake actuator while the vehicle is driving forward. That includes braking manoeuvres because of speed reduction and to standstill. The braking torque has to be determined individually based on the pressure applied for a minimum application time.

Service Brake – Reversing Module

This module contains all clamping loads induced by the service brake actuator while the vehicle is reversing. That includes braking manoeuvres because of speed reduction and to standstill. The braking torque has to be determined individually based on the pressure applied for a minimum application time.

Roll Back (Knock Back) Module

Roll back torque occurs especially during emergency braking. During emergency braking, the vehicle body first pitches in the driving direction before the pitching movement reverses after the vehicle has come to a standstill. This leads to an opposite braking torque when the brake is applied. In Figure 2-1 this is qualitatively shown at the rear axle for an emergency brake while forward driving. In this case the same torque, required for deceleration, can be induced into the opposite direction. After this the braking torque is oscillating as long as the vehicle is pitching. Due to the higher load cycle, the roll back torque has to be considered separately from the load cases forward driving and reversing.

The amount of roll back torque is dependent on the vehicle configuration, it's weight and centre of gravity. The frequency of this load case is mainly depending on the drivers braking behaviour and emergency braking systems. As a result of this complexity, it cannot be standardized with the current database. An example will be given in this document how the "Roll Back Module" could be considered based on the current load spectrum modules.

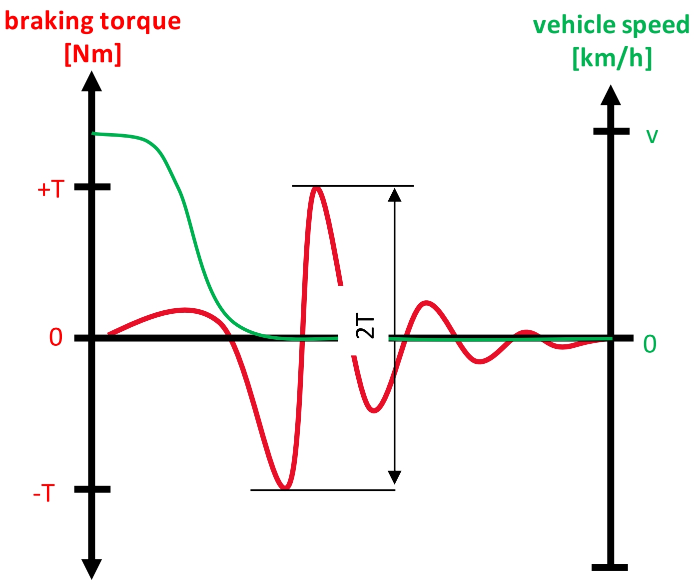


Figure 2-1: Qualitative description of torque measurement at rear axle while emergency braking

2.2 Vehicle Missions

To account for the differences in customer usage for truck, bus and truck-trailer combinations a differentiation for the mission is necessary. The suitable choice of the vehicle's mission is an important task applying this recommendation. For every mission the median distance per year is indicated in Tables 2-1 and 2-2. Tables 5-1 and 5-2, in the appendix, show statistical descriptions of annual distances, based upon a total of more than 100 000 vehicles, taking all the categories into account.

2.2.1 Truck and Bus Missions

The relevant truck and bus missions can be divided into five groups: long haulage, regional delivery, construction/off-road, municipal utility and city bus. The load spectra are based on measurements according the criteria of the vehicle type (tractor or chassis), the axle configuration and the maximum average speed, as listed in Table 2-1. In the last column the median distance per year for the vehicle missions is indicated.

Table 2-1: Description of truck and bus missions

mission	**axle configuration**	**average speed**	**median annual distance**
long haulage	tractor: 4x2, 6x2	no limitation	110 000 km
regional delivery	chassis: 4x2, 6x2	< 40 km/h	27 500 km
construction\ off-road	chassis: 4x4, 6x4, 6x6, 8x4, 8x6, 8x8	no limitation	27 500 km
municipal utility	chassis: 4x2, 6x2, 6x4, 8x2	no limitation	22 500 km
city bus	chassis: 4x2	< 40 km/h	55 000 km

2.2.2 Trailer Missions

The trailer missions described in this document can be divided into long haulage and long haulage off-road mission. The load spectra are based on measurements according the criteria of the truck-trailer combination, as listed in Table 2-2.

Table 2-2: Description of trailer missions

mission	**truck-trailer combination**	**average speed**	**median annual distance**
long haulage	tractors (4x2, 6x2) and semitrailer	no limitation	110 000 km
long haulage off-road	tractors (4x4, 6x4, 6x6, 8x4) and semitrailer	no limitation	60 000 km

2.3 Clamping Force Load Spectra

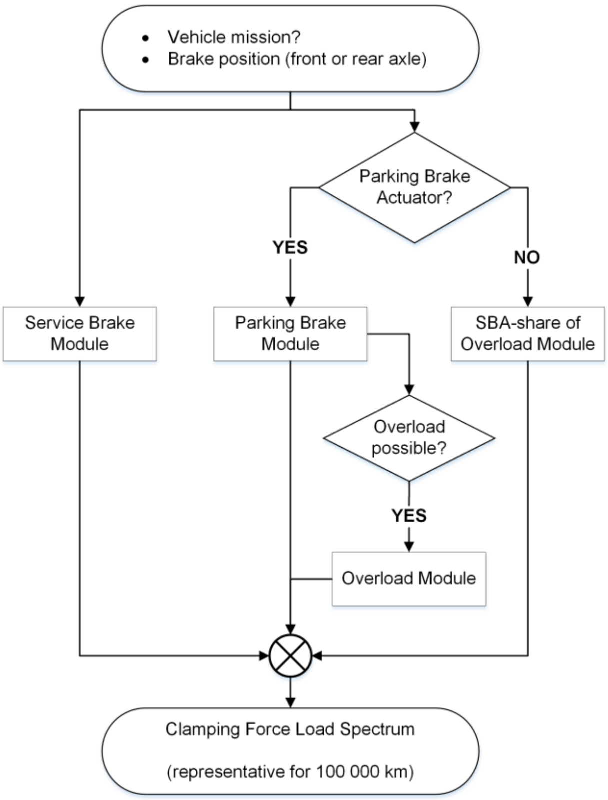
2.3.1 Guideline for Clamping Force Load Spectrum Determination

The load spectra in this subchapter describe the clamping force using the modules:

- Service Brake Module
- Parking Brake Module
- Overload Module

Dependent on the architecture of the braking system and the mounting axle not every module is necessary to describe the mission sufficiently. For the determination of a representative load spectrum, the guideline, shown in Figure 2-2, has to be used. Purpose of this guideline is the selection and combination of appropriate load spectrum modules for the generation of a 99% clamping force operating load spectrum for a given vehicle mission, system architecture and axle position. The load spectrum modules are described in 2.3.2 for trucks and buses and in 2.3.3 for trailers.

Flow Chart



Stepwise Instructions

1. Selection of vehicle mission
2. Selection of brake position (front or rear axle)
3. Select Service Brake Module
4. Parking brake actuator mounted at brake?
   a. Yes: Select Parking Brake Module
   b. No: Select SBA share of Overload Module and go on with 6
5. Is overload possible? (SBA and PBA at same time)
   a. Yes: Select Overload Module
   b. No: Overload module not necessary
6. Combination of selected modules

Figure 2-2: Guideline for clamping force load spectrum determination

2.3.2 Truck and Bus Clamping Force Modules

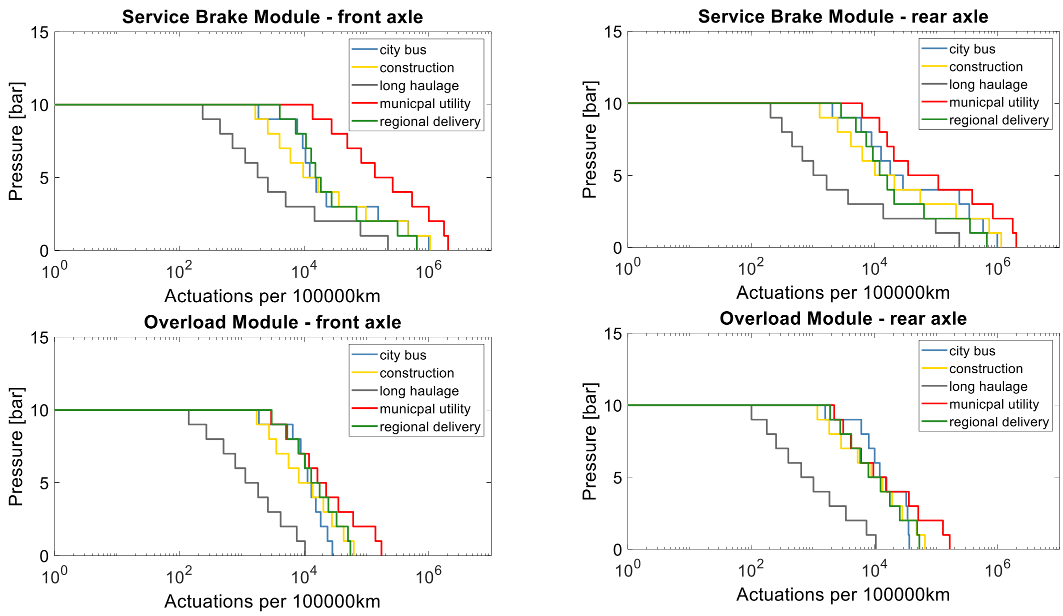


Figure 2-3: Service brake and overload modules for truck and bus missions

Service Brake Module

Table 2-3: Truck and Bus: Service Brake Module for front axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction/ off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	141345	327773	532974	589071	285033
1-2	65526	246914	314294	362996	754196
2-3	9681	41691	131605	61881	463492
3-4	2447	9067	7149	19407	275231
4-5	833	3400	3317	7056	127236
5-6	663	2197	1796	3625	54246
6-7	427	2287	1036	2011	33219
7-8	265	3404	1723	1433	21724
8-9	213	3265	5942	968	13953
9-10	237	4085	1860	1655	13742
Cumulative frequency	221637	644083	1001696	1050103	2042072

Table 2-4: Truck and Bus: Service Brake Module for rear axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction/ off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	138854	311304	403980	411766	248736
1-2	84487	290228	232319	515058	916858
2-3	10154	42685	107113	155181	445383
3-4	2053	4711	208552	34132	275828
4-5	654	3995	10985	10876	73385
5-6	344	2688	5207	3837	14538
6-7	217	2078	3825	2195	4521
7-8	147	2353	2871	1630	4027
8-9	109	2128	4018	1229	5728
9-10	206	2869	2079	1289	6304
Cumulative frequency	237225	665039	980949	1137193	1995308

Overload Module

Table 2-5: Truck and Bus: Overload Module for front axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction/ off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	2725	4733	4666	19624	34838
1-2	3436	17387	5318	15116	78262
2-3	1578	8695	3042	7617	25854
3-4	803	6788	2378	6674	12909
4-5	693	4755	1696	5519	6219
5-6	356	2781	983	2574	4381
6-7	278	2012	1544	2066	3897
7-8	241	2863	2267	843	2979
8-9	131	2363	4706	1002	2189
9-10	141	3031	1893	1745	2968
Cumulative frequency	10382	55408	28493	62780	174496

Table 2-6: Truck and Bus: Overload Module for rear axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction/ off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	3093	4115	1060	17792	36997
1-2	3984	23593	1224	19762	77804
2-3	1580	7961	1683	9058	15124
3-4	838	5219	17056	5698	20817
4-5	377	4572	3504	4663	5761
5-6	248	2090	2110	3550	3522
6-7	147	1668	1980	2462	1942
7-8	75	1431	1980	1030	1016
8-9	79	882	4524	660	892
9-10	101	1904	1587	1185	2222
Cumulative frequency	10522	53435	36708	65860	166097

Parking Brake Module

Table 2-7: Truck and Bus: Parking Brake Module (100 000 km)

	long haulage	regional delivery	city buses	construction/ off-road	municipal utility
parking brake actuations	28350	191710	39115	170061	260110

2.3.3 Trailer Clamping Force Modules

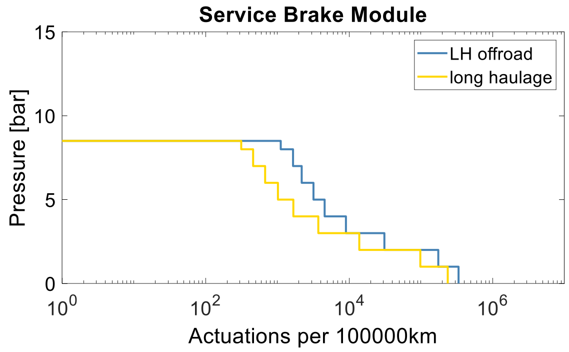


Figure 2-4: Service brake module for trailer missions

Service Brake Module

Table 2-8: Trailer: Service Brake Module (100 000 km)

SBA pressure [bar]	long haulage	long haulage off-road
	frequency	frequency
0-1	138854	160467
1-2	84487	144044
2-3	10154	22025
3-4	2053	4480
4-5	654	1374
5-6	344	1005
6-7	217	531
7-8	147	540
8-8.5	314	1116
Cumulative frequency	237224	335582

Parking Brake Module

Table 2-9: Trailer: Parking Brake Module (100 000 km)

	long haulage	long haulage off-road
parking brake actuations	28350	58100

2.4 Braking Torque Load Spectra

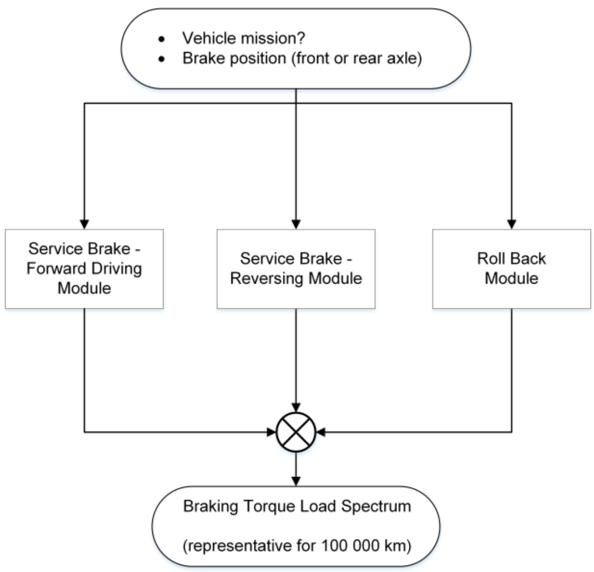
2.4.1 Guideline for Braking Torque Load Spectrum Determination

The load spectra in this subchapter describe the braking torque using the modules:

- Service Brake – Forward Driving Module
- Service Brake – Reversing Module
- Roll Back Module

Dependent on the architecture of the braking system and the mounting axle not every of these modules is necessary to describe the individual mission sufficiently. For the determination of a representative load spectrum the guideline, shown in Figure 2-5, has to be used. Purpose of this guideline is the selection and combination of appropriate load spectrum modules for the generation of a 99% operating load spectrum for a given vehicle mission, system architecture and axle position. The load spectrum modules are described in 2.4.2 for trucks and buses and in 2.4.3 for trailers.

Flow Chart



Stepwise Instructions

1. Selection of vehicle mission
2. Selection of brake position (front or rear axle)
3. Select Service Brake – Forward Driving Module
4. Select Service Brake – Reversing Module
5. Assume and select Roll Back Module
6. Combination of selected modules

Figure 2-5: Guideline for braking torque load spectrum determination

2.4.2 Truck and Bus Braking Torque Modules

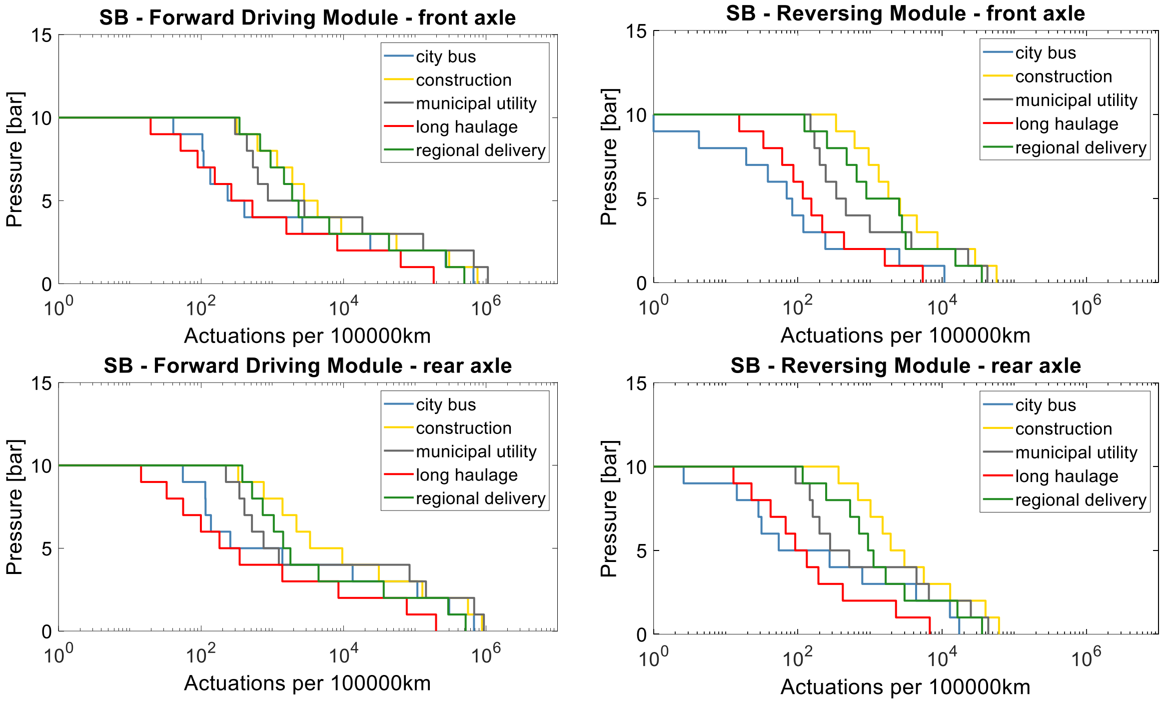


Figure 2-6: Service brake - Forward Driving and Reversing Modules

Service Brake - Forward Driving Module

Table 2-10: Truck and Bus: Service Brake - Forward Driving Module for front axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction /off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	120324	219376	394000	453256	387300
1-2	55086	231254	246160	247311	538966
2-3	6567	37037	21034	45930	112295
3-4	1050	3945	2228	4924	15508
4-5	260	440	169	1531	1952
5-6	111	438	102	878	240
6-7	67	513	27	741	93
7-8	38	272	4	549	95
8-9	33	328	64	303	139
9-10	19	346	40	316	300
Cumulative frequency	183555	493949	663828	755739	1056888

Table 2-11: Truck and Bus: Service Brake - Forward Driving Module for rear axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction /off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	121238	221555	371560	316866	250472
1-2	68403	257008	194577	428614	535460
2-3	7083	32060	94913	96161	58832
3-4	1032	2656	12002	21604	82947
4-5	167	376	1126	6205	480
5-6	82	370	120	1201	236
6-7	44	316	23	791	112
7-8	24	213	1	632	61
8-9	19	141	60	426	122
9-10	14	379	55	331	223
Cumulative frequency	198106	515074	674437	872831	928945

Service Brake - Reversing Module

Table 2-12: Truck and Bus: Service Brake - Reversing Module for front axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction /off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	3787	20193	8196	28188	19465
1-2	1167	12151	2310	20030	19205
2-3	219	343	122	4154	2746
3-4	64	240	36	1851	531
4-5	37	1647	14	812	123
5-6	31	237	32	476	98
6-7	27	178	20	363	43
7-8	28	222	15	348	32
8-9	18	130	4	273	21
9-10	15	123	0	338	149
Cumulative frequency	5393	35464	10749	56833	42413

Table 2-13: Truck and Bus: Service Brake - Reversing Module for rear axle (100 000 km)

SBA pressure [bar]	long haulage	regional delivery	city buses	construction /off-road	municipal utility
	frequency	frequency	frequency	frequency	frequency
0-1	4446	19441	4418	21484	18605
1-2	1873	13272	8462	27015	18420
2-3	227	1362	3572	7341	2138
3-4	60	531	506	2575	3893
4-5	42	180	221	1063	236
5-6	25	234	23	438	81
6-7	26	176	3	480	39
7-8	20	284	15	335	15
8-9	10	131	12	316	54
9-10	12	116	2	366	92
Cumulative frequency	6741	35727	17234	61413	43573

Roll Back Module – Example for Assumption

In the following an example for this module is described. Every user of this recommendation is responsible by their own for a sufficient consideration of the roll back torque. In general, sufficient assumptions for the load levels and the frequencies have to be made.

Example:

- Load level: It will be assumed that it is sufficient to consider only emergency brake applications, which cause a roll back torque as high as the deceleration torque on front and rear axle.

- Frequency: For the number of emergency brakes the assumption will be made that load cycles bigger than 8 bar of the Service Brake Forward Driving and Reversing Modules are emergency brake application.

2.4.3 Trailer Braking Torque Modules

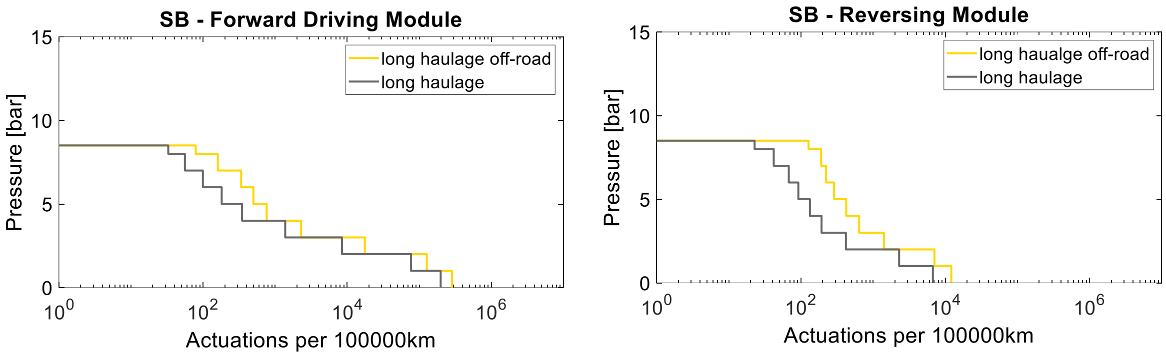


Figure 2-7: Service Brake Forward Driving and Reversing Modules

Service Brake Forward Driving Module

Table 2-14: Trailer: Service Brake – Forward Driving Module (100 000 km)

SBA pressure [bar]	long haulage	long haulage off-road
	frequency	frequency
0-1	121238	157425
1-2	68403	109485
2-3	7083	15271
3-4	1032	1530
4-5	167	264
5-6	82	162
6-7	44	178
7-8	24	82
8-8.5	32	79
Cumulative frequency	198105	284476

Service Brake Reversing Module

Table 2-15: Trailer: Service Brake - Reversing Module (100 000 km)

SBA pressure [bar]	long haulage	long haulage off-road
	frequency	frequency
0-1	4446	5051
1-2	1873	5668
2-3	227	772
3-4	60	216
4-5	42	137
5-6	25	65
6-7	26	33
7-8	20	63
8-8.5	22	127
Cumulative frequency	6741	12132

Roll Back Module

Has to be assumed. An example for this assumption is described in 2.4.2 for trucks and buses.

3 Reliability Requirements

A lifetime requirement for a demonstration test has to be defined statistically. Therefore, it is state of the art to use reliability requirements. To define an appropriate reliability requirement, two specifications have to be made. Firstly, the required reliability *R* for a required lifetime *t* or load spectrum and secondly, a certain confidence level *CL* to specify the necessary confidence for the reliability demonstration. For more detailed information, please see:

Bernd, Bertsche: Reliability in Automotive and Mechanical Engineering. Springer-Verlag Berlin Heidelberg, 2008.

The exact definition of the reliability requirement is in the responsibility of the individual customer or manufacturer. Therefore, a quantitative definition of lifetime, reliability and confidence level is not indicated, but it is necessary to define the reliability requirement for the wheel brake containing:

Reliability *R* [%]

The reliability *R* is the probability that a product does not fail during a defined period of time *t* under defined conditions. It is specified in percentage for a lifetime *t* or for a specific load spectrum.

Lifetime *t* [km, hours, years]

The lifetime *t* is a necessary definition for the reliability. In commercial vehicle industry typical values for the lifetime are distance and time requirements like: kilometres, operating hours and years. Alternatively, a specification of a load spectrum representative for service life can be made.

Confidence Level *CL* [%]

The confidence level specifies the confidence for the demonstration of the reliability requirement. It is specified in percentage.

4 Reliability Demonstration

The reliability demonstration methods described in 4.2, 4.3, 4.4 and 4.5 can be applied generally for all load types and failure modes. However, this recommendation only describes the operating load spectra for clamping force and braking torque. Hence it follows that the recommendation covers fatigue strength only with regard to clamping force and braking torque.

4.1 Test Load Spectra Definition

4.1.1 Lifetime Extrapolation

The load spectra defined in this document are only valid for 100 000 km. To represent the service life of the brake, an extrapolation of the load spectra is necessary. The user of the recommendation is responsible for the selection of an appropriate extrapolation method and the definition of the service life according the vehicle's mission.

4.1.2 Definition of Load Sequence

In order to take sequential influences into account, one of the following adjustments has to be made for test load spectra:

a) Definition of a fixed load cycle with alternating load levels
b) Random order of load levels
c) A one or two level test load spectrum is also possible if its damage is equivalent to the operating load spectrum. The calculation can be made for example using damage accumulation.

For the braking torque load spectra, the change of the braking torque direction has to be considered in the same way:

a) Definition of a fixed load cycle with alternating load levels and their direction
b) Random order of load levels and their direction
c) A one or two level test load spectrum is also possible if its damage is equivalent to the operating load spectrum. The calculation can be made for example using damage accumulation.

4.1.3 Accelerated Test Load Spectra

The test load spectra might be accelerated in accordance with the customer, but the correlation between the accelerated and the operating load spectra has to be proven.

4.2 Reliability Demonstration Concept

The concept consists of three optional paths for the reliability demonstration of the wheel brake, as shown in Figure 4-1. It describes only the fundamental demonstration tests. The usage of other demonstration tests has to be done in accordance with the customer. In addition, the correlation of accelerated load spectra to the operating load spectra has to be proven. The three optional paths are the test methods: Success Run Test (SRT), End of Life Test (EoL) and Accelerated Life Test (ALT). Reliability demonstration can be achieved using one of these test methods. Reliability is demonstrated, when the demonstrated reliability for the required confidence level is higher than the required reliability.

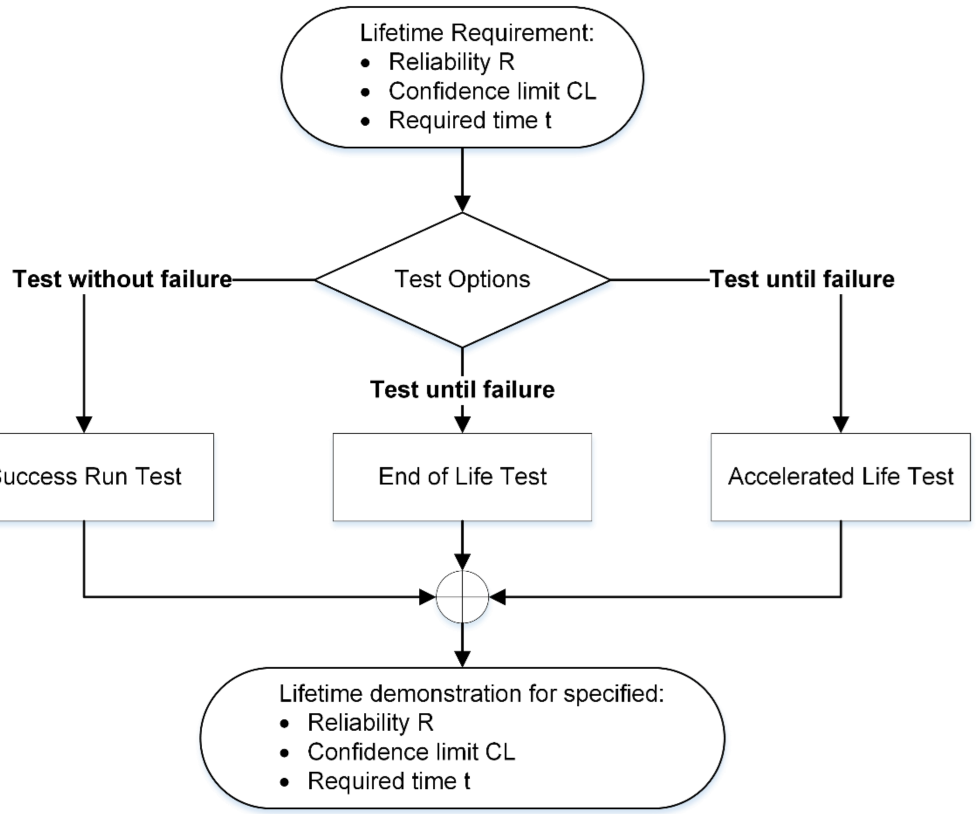


Figure 4-1: Reliability demonstration concept

4.3 Success Run Test

A SRT can be used to demonstrate a minimum reliability for a specified time *t* and a confidence level CL. The success run is based on the binomial distribution and is typically applied for the two and three parameter Weibull distribution. Crucial for the SRT is that no failure occurs during test, but because of this a SRT gives no information about the failure behaviour of the brake. On the other side the sample size for the test can be planned easily using the following equation (4.1):

$$n = \frac{ln(1-CL)}{ln\big(R(t)\big)} \tag{4.1}$$

For a known Weibull shape parameter *b*, the necessary sample size can be reduced by extending the test time t_p. In this case the sample size can be estimated using the following equations (4.2) and (4.3):

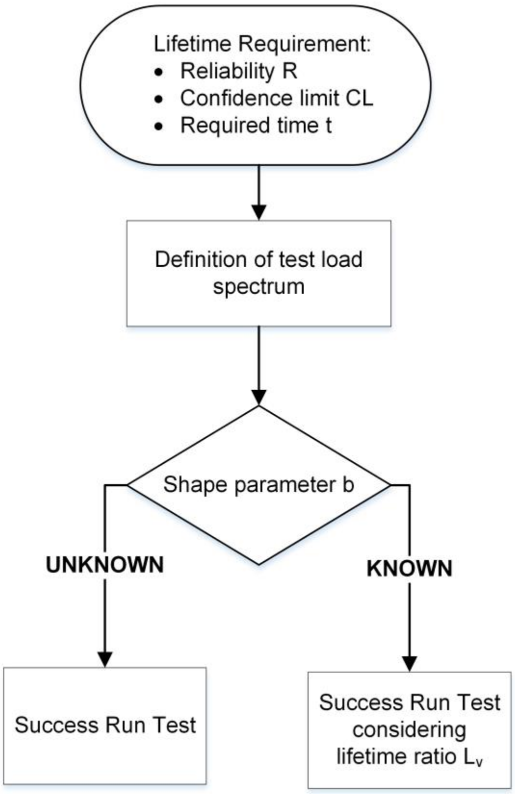
$$L_V = \frac{t_p - t_0}{t - t_0} \tag{4.2}$$

$$n = \frac{1}{L_V^b} \cdot \frac{ln(1-CL)}{ln\big(R(t)\big)} \tag{4.3}$$

For the planning and execution of SRT the guideline in Figure 4-2 can be used for orientation. The result of this tests might be:

a) The reliability for a required lifetime t and a confidence level CL is demonstrated if all specimens pass the test time t_p without failures.
b) If failures occur during the SRT then it may still be possible to demonstrate the required reliability and confidence by changing the test strategy to End of Life (EOL).

Flow Chart



Stepwise Instructions

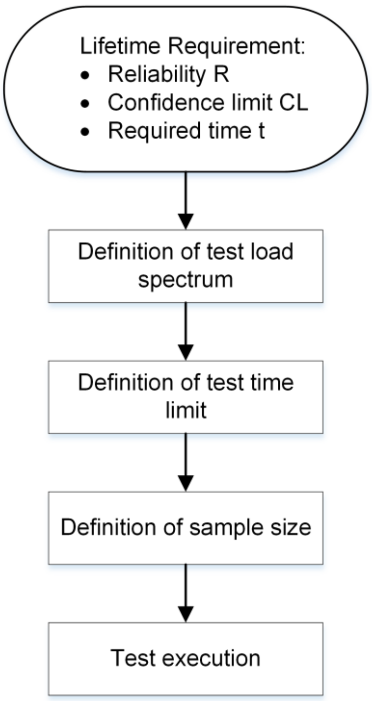
1. Clarification of lifetime requirements
2. Definition of operating test load spectrum
   a. Clamping force: 2.3, 4.1.1, 4.1.2
   b. Braking torque: 2.4, 4.1.1, 4.1.2
3. Shape parameter known?
   a. No: SRT
   b. Yes: SRT considering L_V
4. Definition of test time t_p
5. Determination of sample size:
   a) Equation (4.1)
   b) Equation (4.3)
6. Test execution
7. Test results
   a. No failures: Reliability demonstration successful
   b. Failures: Go on with EoL

Figure 4-2: Guideline for Success Run Test

4.4 End of Life Test

End of life tests (EoL) are performed until every specimen has failed during test. Optional a maximum test time can be defined when a test run will be stopped, even if the specimen is still intact. Then the specimen and their test time can be considered as censored data. But even in this case failures within the sample are necessary. Advantage of testing until failure is gaining knowledge about the brake's failure behaviour. The guideline for EoL is described in Figure 4-3.

Flow Chart



Stepwise Instructions

1. Clarification of lifetime requirements
2. Definition of operating test load spectrum
   a. Clamping force: 2.2, 4.1.1, 4.1.2
   b. Braking torque: 2.3, 4.1.1, 4.1.2
3. Definition of maximum test time
4. Definition of sample size
5. Test execution
6. Test results
   a. Current reliability ≥ Target reliability: Successful demonstration
   b. Current reliability < Target reliability: Tighten confidence interval with additional tests

Figure 4-3: Guideline for EoL Test

The test result of the EoL might be:

a) The reliability demonstration with the EoL is successful if the required reliability $R_{req}(t)$ is less than or equal to the demonstrated $R_{test}(t)$ for the required confidence level CL.
b) If $R_{req}(t)$ is greater than $R_{test}(t)$ then the confidence interval should be tightened. Therefore, additional specimens need to be tested until either the requirement is fulfilled or it becomes apparent that the reliability and confidence target cannot be achieved.

4.5 Accelerated Life Test

An Accelerated Life Test (ALT) is used to reduce the test time t_p. An ALT is performed at least on two test levels as displayed in Figure 4-4. The test levels are defined according a suitable damage value. The test levels have to be defined with a higher damage value than the field level. It is recommended to define test level 1 close to the technical maximum. Test level 2 has to be defined in an optimal way to be on one hand close to the field level but on the other hand with a sufficient reduction of test time. The operating load spectra described in this document are representative for the field level of the ALT. The tests on each level have to be executed until failure or until a defined maximum test time. After test execution, it has to be proven that the failure mode is the same for all test levels. For the field prognosis a lifetime model is necessary. The choice of the suitable lifetime model and the number of test specimens and the damage value for the tests levels lies in the user's responsibility. The whole process for an ALT is described in Figure 4-5. More information about ALT and lifetime models can be find in:

Nelson, Wayne: Accelerated Testing: Statistical Models, Test Plans, and Data Analysis. Wiley Hoboken, 2009.

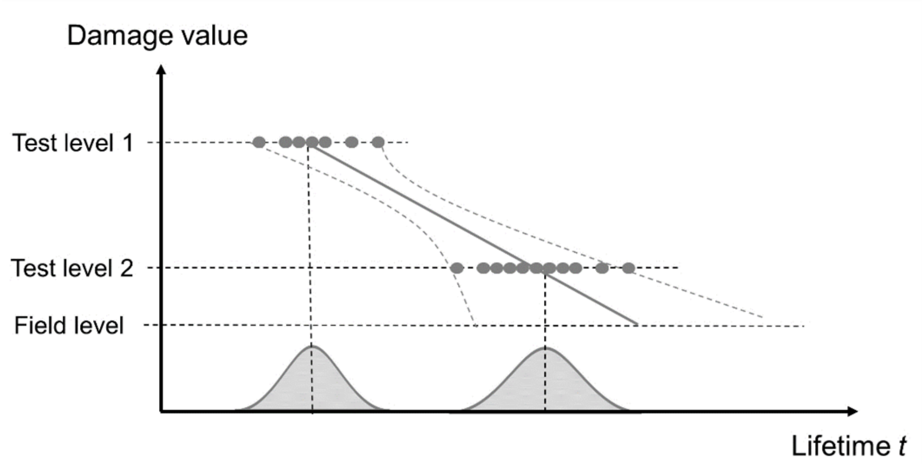
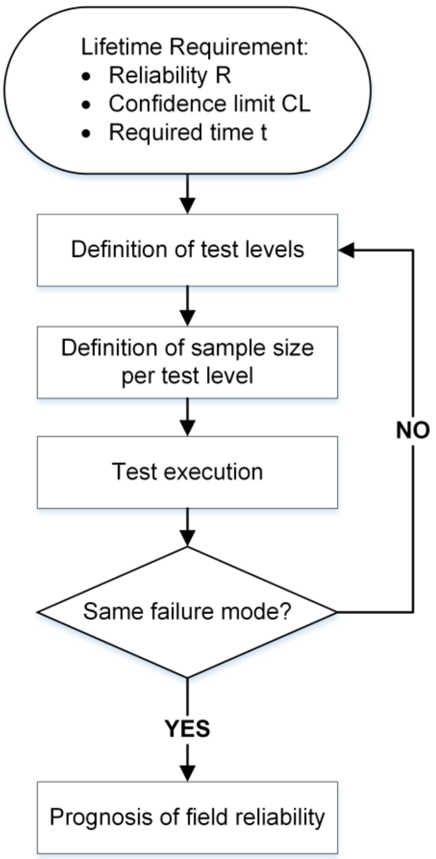


Figure 4-4: Accelerated Life Test

The test result of the ALT might be:

a) The reliability demonstration with the ALT is successful if the required reliability $R_{req}(t)$ is less than or equal to the prognosis of $R_{test}(t)$ on field level for the required confidence level CL.
b) If $R_{req}(t)$ is greater than $R_{test}(t)$ then the confidence interval should be tightened. Therefore, additional specimens need to be tested on the lowest test level until either the requirement is fulfilled or it becomes apparent that the reliability and confidence target cannot be achieved.

Flow Chart



Stepwise Instructions

1. Clarification of lifetime requirements
2. Definition of operating load spectrum
    a. Clamping force: 2.2, 4.1.1, 4.1.2
    b. Braking torque: 2.3, 4.1.1, 4.1.2
3. Definition of test levels
    a. Acceleration of 2.a for the test levels
    b. Acceleration of 2.b for the test levels
4. Definition of maximum test time
5. Definition of sample size per level
6. Test execution
7. Same failure mode?
    a. No: Adjustment of test levels
    b. Yes: Prognosis of field reliability
8. Prognosis of field reliability
9. Test results
    a. Current reliability ≥ Target reliability: Successful demonstration
    b. Current reliability < Target reliability: Tighten confidence interval with additional tests on lowest test level

Figure 4-5: Guideline for ALT

5 Appendix

A Statistical Description Annual Distance

Table 5-1: Statistical description of annual distance for truck and bus missions

mission	**distribution**
long haulage	Normal: µ=107 084 km, σ=37 088 km
regional delivery	Weibull: T=38 131 km, b=1,39
construction\ off-road	Weibull: T=37 442 km, b=1,27
municipal utility	Weibull: T=26 891 km, b=2,15
city bus	Normal: µ=56 139 km, σ=18 733 km

Table 5-2: Statistical description of annual distance for trailer missions

mission	**distribution**
long haulage	Normal: µ=107 084 km, σ=37 088 km
long haulage off-road	Weibull: T=63 811 km, b=1,75

B Example Load Spectra Determination

Example for Trucks:

Vehicle: Chassis 4x2; PBA only at rear axle; Overload is possible

Applying guideline in Figure 2-2, the following load spectrum modules have to be chosen according the vehicle's mission for clamping force:

clamping force	
load spectrum modules front axle	**load spectrum modules rear axle**
- Service Brake Module - SBA share of Overload Module	- Service Brake Module - Parking Brake Module - Overload Module

Applying guideline in Figure 2-5, the following load spectrum modules have to be chosen according the vehicle's mission for braking torque:

braking torque	
load spectrum modules front axle	**load spectrum modules rear axle**
- Service Brake - Forward Driving Module - Service Brake - Reversing Module - Roll Back Module	- Service Brake - Forward Driving Module - Service Brake - Reversing Module - Roll Back Module

Example for Trailers:

Truck-trailer combination: tractor-semitrailer; PBA on all axles; Overload is impossible

Applying the guidelines described in Figure 2-2 and Figure 2-5 the following load spectrum modules have to be chosen according the vehicles mission:

clamping torque	**braking torque**
load spectrum modules	**load spectrum modules**
- Service Brake Module - Parking Brake Module	- Service Brake - Forward Driving Module - Service Brake - Reversing Module - Roll Back Module

C Example Reliability Demonstration

Annotation: The following example is only valid for one failure mode. Of course every relevant failure mode has to be considered for reliability demonstration. The load levels, requirements and failure times of this example are purely fictional.

Requirement: For a lifetime of 2 000 000 km, a reliability of 90% has to be proven for a confidence level of 95%.

R(t)=90%, t = 2 000 000 km; CL = 95 %

According the reliability demonstration concept (Figure 4-1), 3 different tests can be used to demonstrate this requirement. For all of these tests an example is described in the following.

SRT for R(t)=90%, t = 2 000 000 km; CL = 95 %

Using equation (4.1) for a Success Run with a test time t_p equivalent to 2 000 000 km a sample size of 29 is necessary according following calculation:

$$n = \frac{ln(1-CL)}{ln\big(R(t)\big)} = \frac{ln(1-0.95)}{ln(0.9)} = 28.43$$

Considering a Weibull shape parameter of 1.7 and a test time t_p equivalent to 5 000 000 km a sample size of 6 is necessary according following calculation using equations (4.2) (4.3):

$$L_V = \frac{t_p}{t} = \frac{5\ 000\ 000\ km}{2\ 000\ 000\ km} = 2.5$$

$$n = \frac{1}{L_V^b} \cdot \frac{ln(1-CL)}{ln\big(R(t)\big)} = \frac{1}{2.5^{1.7}} \cdot \frac{ln(1-0.95)}{ln(0.9)} = 5.99$$

Both test strategies succeed if no specimen fails until t_p.

EoL for R(t)=95%, t = 2 000 000 km; CL = 95 %

In this example an EoL is planned for the reliability demonstration with following boundary conditions:

- Sample size: 10
- Maximum test time: 10 000 000 km

Test results:

Failure times: 8 244 333 km, 3 819 438 km, 9 749 903 km, 9 935 591 km, 5 039 263 km, 5 417 486 km, 4 901 848 km

Suspension times: 10 000 000 km, 10 000 000 km, 10 000 000 km

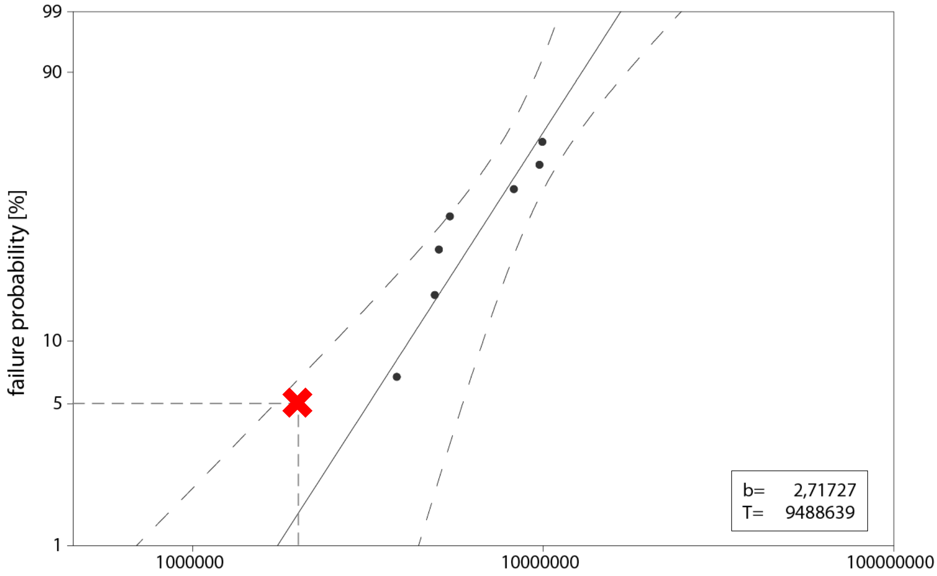


Figure 5-1: Life Data Analysis with 10 samples

- ***R_{test}(2 000 000 km, CL=95%) < 95%***
- ***Additional tests necessary!***
- ***10 additional specimens are tested***

Test results with 10 additional specimens:

Failure times: 8 244 333 km, 3 819 438 km, 9 749 903 km, 9 935 591 km, 5 039 263 km, 5 417 486 km, 4 901 848 km, 9 279 945 km, 9 926 113 km, 3 352 136 km

Suspension times: 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km, 10 000 000 km

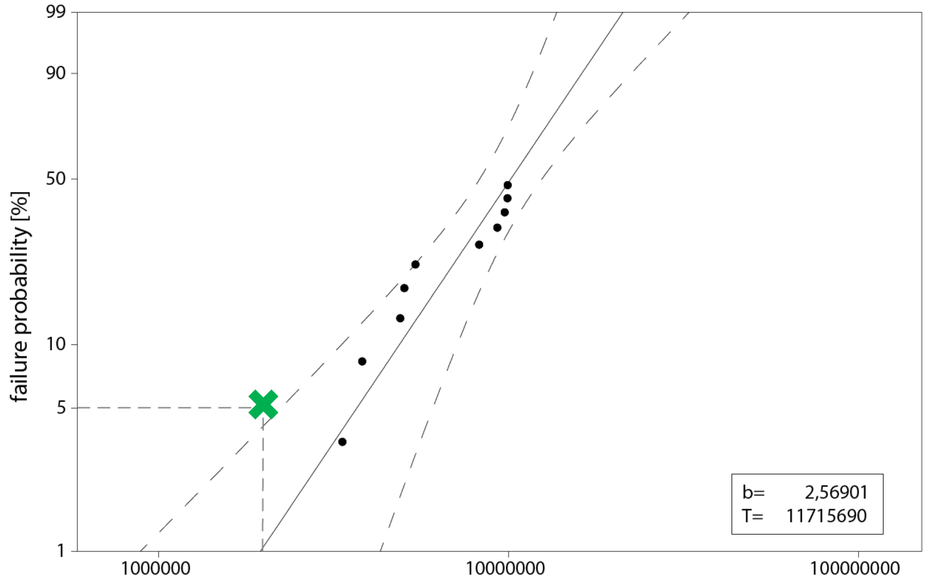


Figure 5-2: Life Data Analysis with 10 additional samples

- ***R_{test}(2 000 000 km, CL=95%) > 95%***
- ***Reliability demonstrated for the CL of 95%***

<u>Accelerated Life Test</u>

For this example it is assumed that 1 million load cycles (LC) with the load level of 6 bar correspond to a service life of 2 million kilometres. Boundary conditions for the ALT are:

- Test level 1: 16 bar
- Test level 2: 9 bar
- Field level: 6 bar
- Lifetime model: inverse power (logarithmic relationship)
- R_{req}(1 000 000 LC at 6 bar) = 90%
- CL = 95%

In total 20 specimens are available for the test and have to be assigned to the test levels. At test level 1 6 specimens and at test level 2 14 specimens are assigned. All samples are tested until failure and reach the following LC:

Test Level 1: 11 513 LC, 10 896 LC, 14 600 LC, 10 468 LC, 6 830 LC, 4 598 LC

Test Level 2: 126 090 LC, 109 984 LC, 238 635 LC, 206 936 LC, 263 078 LC, 241 182 LC, 287 634 LC, 402 671 LC, 363 360 LC, 301 023 LC, 387 756 LC, 208 534 LC, 214 942 LC, 420 163 LC

First step in the analysis is now to check if the Weibull shape parameter is the same on both load levels. The Weibull parameters are separately estimated for both test levels. The estimated shape parameters have the values: b_1=3.2 and b_2=3.5, as can be seen in Figure

5-3. Therefore, it can be stated that the failure mode should be the same on both load levels. Next step is the prognosis of the reliability for field level of 6 bar.

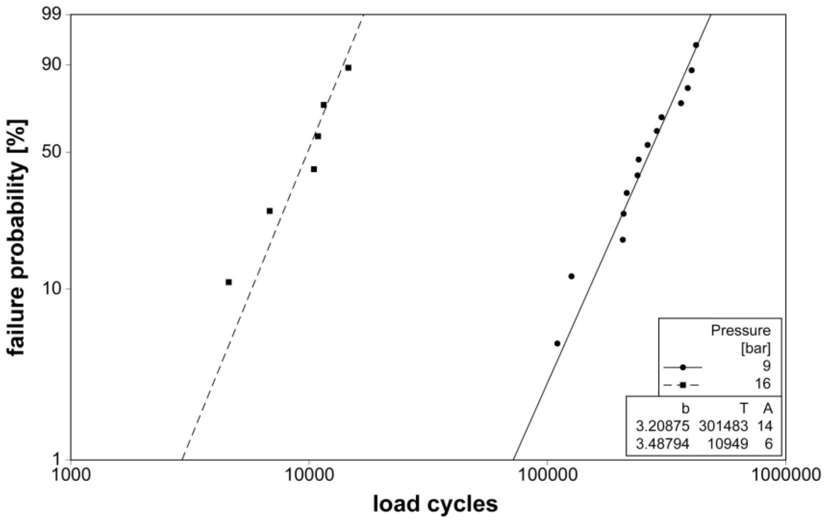


Figure 5-3: Failure mode comparison for load levels

The prognosis for the field reliability is made for the required Reliability of 90%, which is equal to a failure probability of 10%. The graphical solution is shown in Figure 5-4, where can be seen that for R=90% and a CL of 95% the number of load cycles is bigger than 1 million. Because of this the reliability requirement is demonstrated.

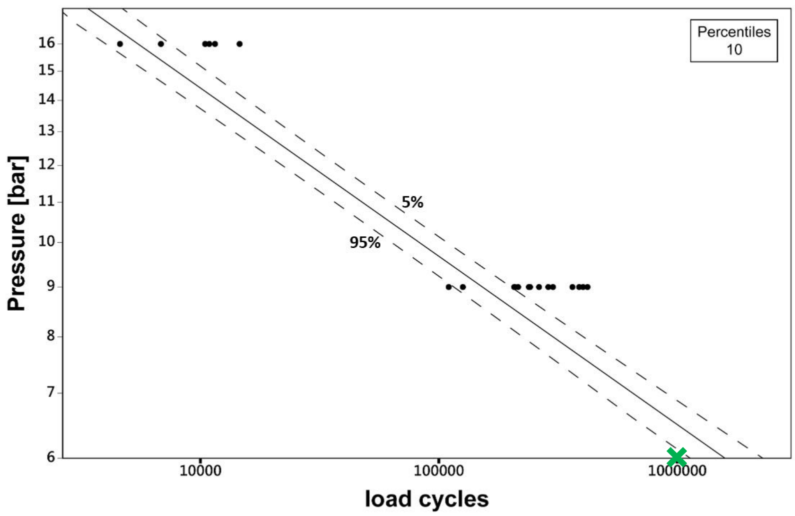


Figure 5-4: Prognosis of field reliability