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Introduction

The assessment of durability is vital in many branches of engineering, such as the automotive industry, aerospace applications, railway transportation, the design of windmills, and off-shore construction. A fundamental element of the discussion is the very meaning of *durability*. A rather general definition is the following:

> Durability is the capacity of an item to survive its intended use for a suitable long period of time.

In our context, durability may be defined as the ability of a vehicle, a system or a component to maintain its *intended function* for its *intended service life* with *intended levels of maintenance* in *intended conditions of use*.

The analysis of durability loads is discussed with truck engineering in mind, however, most of the contents are applicable also to other branches of industry, especially for applications in the automotive context. Properties of loads that cause fatigue damage are emphasized rather than the properties of extreme crash loads or acoustic loads. The fatigue damage mechanisms are assumed to be similar to those encountered in metal fatigue, but a few comments concerning rubber and composite material are given in Section 2.1.5.

In vehicle engineering the purpose of load analysis is:

- to evaluate and quantify the customer service loads;
- to derive design loads for vehicles, sub-systems, and components;
- to define verification loads and test procedures for verification of components, subsystems, and vehicles.

The *Guide* is divided into three parts, where the introductory part sets the scope. Part II, *Methods for Load Analysis*, presents different methods with the aim of providing an understanding of the underlying principles as well as their usage. It is important to know where and when each method is applicable and what merits and disadvantages it has. Part III, *Load Analysis in View of the Vehicle Design Process*, is organized according to the bullet list above, and describes what methods are useful in the different steps of the vehicle engineering process.

Guide to Load Analysis for Durability in Vehicle Engineering, First Edition. Edited by P. Johannesson and M. Speckert.

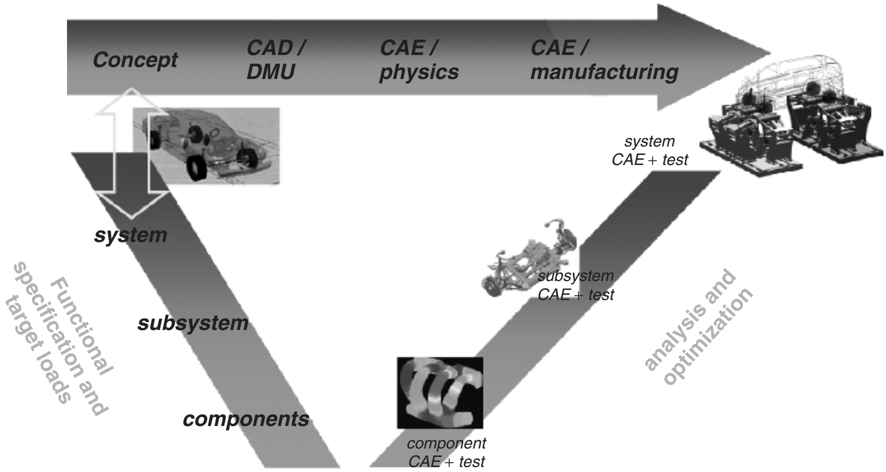


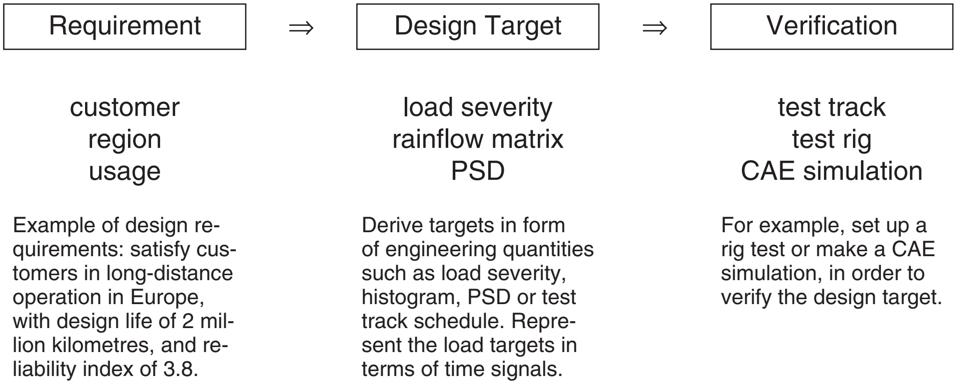
Figure 1.1 The vehicle engineering process

1.1 Durability in Vehicle Engineering

In vehicle engineering the aim is to design a vehicle with certain physical properties. Such properties can be specified in the form of ‘design targets’ for so-called ‘physical attributes’ such as durability, NVH (Noise Vibration Harshness), handling, and crash safety. Design variants are analysed, optimized, and verified by means of physical tests and numerical simulations for the various attributes. An often used view of the vehicle engineering process is illustrated in Figure 1.1, and can be summarized as follows:

1. Concept for the new vehicle (class of vehicles, market segment, target cost, size, weight, wheel base, etc.).
2. Overall targets and benchmarks are defined for the physical properties of the vehicle (performance, durability, safety (crash), acoustics, vibration comfort, etc.).
3. Target cascading: Design targets for the sub-systems and components are derived (chassis suspension, engine, transmission, frame, body, etc.); those targets are again related to different physical attributes (durability, NVH, handling, crash, etc.).
4. Design of components, sub-systems and the full vehicle.
5. Design verification and optimization by means of physical tests and numerical simulations on the various levels for the various attributes.
6. Verification on vehicle level.

Especially for trucks, durability is one of the most important physical attributes for the customer, and therefore durability needs to be highlighted in the development process. The vehicle engineering process in Figure 1.1 needs to be implemented with respect to load analysis for durability. The process illustrated in Figure 1.2 is frequently used in the automotive industry.



Example of design requirements: satisfy customers in long-distance operation in Europe, with design life of 2 million kilometres, and reliability index of 3.8.

Derive targets in form of engineering quantities such as load severity, histogram, PSD or test track schedule. Represent the load targets in terms of time signals.

For example, set up a rig test or make a CAE simulation, in order to verify the design target.

Figure 1.2 An implementation of the vehicle engineering process with respect to load analysis

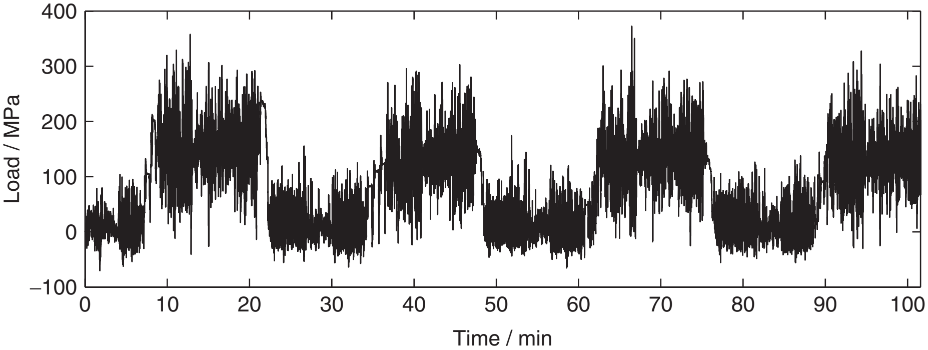


Figure 1.3 A measured service load of a truck transporting gravel

Metal fatigue and other durability phenomena are degradation processes in the sense that an effect builds up over time. A certain force applied to a structure once or a few times may cause no measurable effect, but if it is applied a million times, the structure may fail. Loads in durability engineering need to be studied with regard to the fatigue phenomenon as well as with regard to the vehicle dynamics and the variation in customer usage.

Loads may be displacements (linear or rotational), velocities, accelerations, forces, or moments. They may represent road profiles, wheel forces, relative displacements of components, frame accelerations, or local strains. When we talk about *load signals*, we mean one- or multi-dimensional functions of time as they appear in the vehicle, for example, during customer usage, on test tracks, in test benches, or in virtual environments. Figure 1.3 shows an example of a measured service load, where a stress signal has been recorded for about 100 minutes on a truck transporting gravel. There we can observe different mean levels as well as different standard deviations of different parts of the load. The changes in the mean level originate from a loaded and an unloaded truck while the changes in the standard deviation derive from different road qualities.

1.2 Reliability, Variation and Robustness

The overall goal of vehicle design is to make a robust and reliable product that meets the demands of the customers; see Bergman and Klefsjö [22], Bergman *et al.* [23], O'Connor [172], Davis [64] and Johannesson *et al.* [126] on the topic of reliability and robustness. In order to achieve this goal it is important not only to predict the life of a component, but also to investigate and take into account the sources of variability and their influence on life prediction. There are mainly two quantities influencing the life of the component, namely, the load the component is exposed to, and the structural strength of the component. Statistical methods provide useful tools to describe and quantify the variability in load and strength, see Figure 1.4. The variability in the structural strength depends on both the material scatter and geometrical variations. The customer load distribution may be influenced by the application of the vehicle, the driver behaviour, and the market. From a component designer's point of view, the varying vehicle configurations on which the component, for example, a bracket, is to be used are yet another variation source. For example, for trucks, the same design may well be used on semi-trailer tractors as well as on two- and three-axle platform trucks. This adds to the load variation, as these truck configurations have considerably different dynamic properties. Further, the verification is often performed using test track loads, which represent conditions that are more severe than those of a normal customer. Even though the test track conditions are well controlled, they also exhibit variation, which is illustrated by its distribution in Figure 1.4.

The conventional strategy for reliability improvement has been to utilize feedback from testing and field usage in order to understand important failure mechanisms and to find engineering solutions to avoid or reduce the impact of these mechanisms. Based on past experience it has also been the practice to perform predictions of future reliability performance in order to find weak spots and subsequently make improvements already in the early design stages. However, the conventional reliability improvement strategy has strong limitations, as it requires feedback from usage or from testing. Thus, it is fully applicable

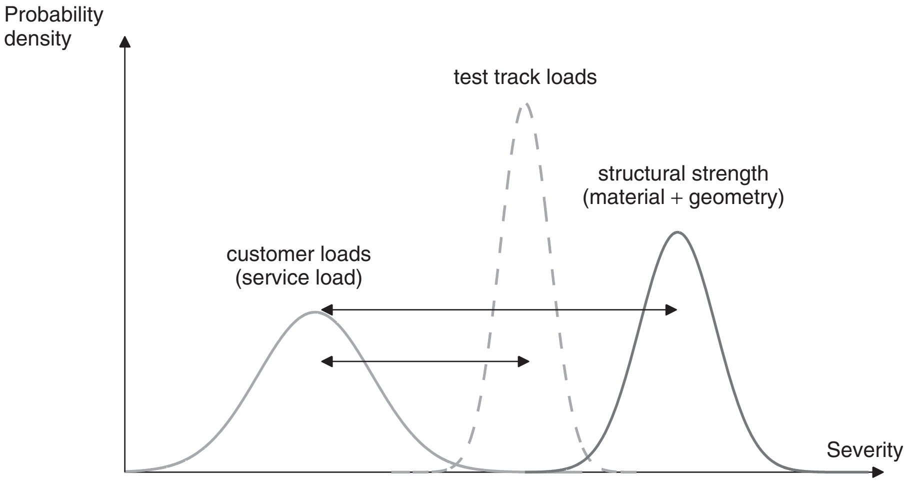


Figure 1.4 Distributions of customer loads, test track loads and structural strength

only in the later stages of product development when already much of the design is frozen and changes incur high costs. Therefore, we propose putting effort into load analysis also in the early design stage, and not primarily in the verification process. In this context, understanding load variation is an important aspect of engineering knowledge.

In industry, the method of *Failure Mode and Effect Analysis* (FMEA) is often used for reliability assessments. Studies of FMEA have indicated that the failure modes are in most cases triggered by unwanted variation. Therefore, the so-called *Variation Mode and Effect Analysis* (VMEA) has been developed, which takes the quantitative measures of failure causes into account; see Johannesson *et al.* [127], Chakhunashvili *et al.* [54] and Johannesson *et al.* [125]. The VMEA method is presented at three levels of complexity: basic, enhanced and probabilistic. The basic VMEA can be used when we only have vague knowledge about the variation. The sensitivity and variation size assessments are made by engineering judgements and are usually made on a 1–10 scale. When better judgements of the sources of variation are available, the enhanced VMEA can be used. The probabilistic VMEA can be used in the later design stages where more detailed information is available. It can, for example, be more detailed material data, finite element models for calculating local stresses, and physical experiments in terms of load and strength. The different sources of uncertainty can be measured in terms of statistical standard deviation. The load-strength model described in Section 7.6 is an implementation of the probabilistic VMEA for the application of fatigue and durability problems. Both FMEA and VMEA are methods well suited for use in the framework of *Design for Six Sigma* (DfSS). The above topics are further discussed in Bergman *et al.* [23] and Johannesson *et al.* [126].

1.3 Load Description for Trucks

Here we give a description of the typical features of loads for the truck application, and discuss the so-called load influentials. The particular durability loads which affect trucks are governed by their applications. The application decides where the truck will be used and how it may be used. The main factors governing the loads are

- *The vehicle utilization*, that is the particular use of the truck, given the utilization profile described by, for example, the transport mission and yearly usage.
- *The operational environment*, that is, the road conditions and other environmental conditions that the truck will experience.
- *The vehicle dynamics*, for example, the transfer of external road input to local loads will be affected by the particular tyres and the suspension of the truck.
- *The driver's behaviour*, that is, the driver's influence on the load such as speed changes, braking, and the ability to adapt to curves.
- *Legislation*, for example, the speed limits, and allowed weight and size of trucks, in different regions and countries.

Loads that will act on a truck can be described by using the above load influentials, that is, by making a description of the vehicle utilization, the operational environment, the vehicle dynamics, and so on. One such approach is given in Edlund and Fryk [87]. The different load influentials are preferably described as simply as possible, for example, by classifying the types of roads, or by describing each road by some few parameters. Such approaches have been developed especially for the vertical road input, see for example, Bogsjö [30], Bogsjö *et al.* [33], Öijer and Edlund [175, 176] and the references therein, but also for lateral loads, see for example, Karlsson [132].

It is desirable to separate the load description into a vehicle-independent load environment and a description of the vehicle-dependent load influentials. The *vehicle usage* and the *vehicle dynamics* can then be connected to the *vehicle independent load environment* description, in order to compute the *load distribution for the customer population of interest for a specific vehicle*, see the schematic view in Figure 1.5. Here, the vehicle usage is the vehicle utilization together with the driver's behaviour, both of which are dependent on the specific vehicle. The load environment is independent of the specific vehicle and includes the operational environment as well as legislation.

The vehicle utilization may be described and classified, by for example

- *Transport cycle* (Long distance – Distribution – Construction).
- *Transport mission* (Timber – Waste – Trailer – Distribution – and so on).
- *Yearly usage*.
- *Pay load or gross combination weight*.

The operational environment may be described by a number of influential variables, such as

- *Road surface quality* (Smooth – Rough – Cross-country).
- *Hilliness* (Flat – Hilly – Very Hilly).
- *Curve density* (Low – Moderate – High).
- *Altitude* (Sea level – High altitudes).
- *Climate* (Temperature, humidity, dust, etc.).

The driver's behaviour also causes variations in the load. The origin of the variation is the driver's influence on the way of driving the vehicle, such as speed changes, braking, and acceleration. A specific driver may be characterized by his or her load severity, while a population of drivers may be described by the distribution of their load severities.

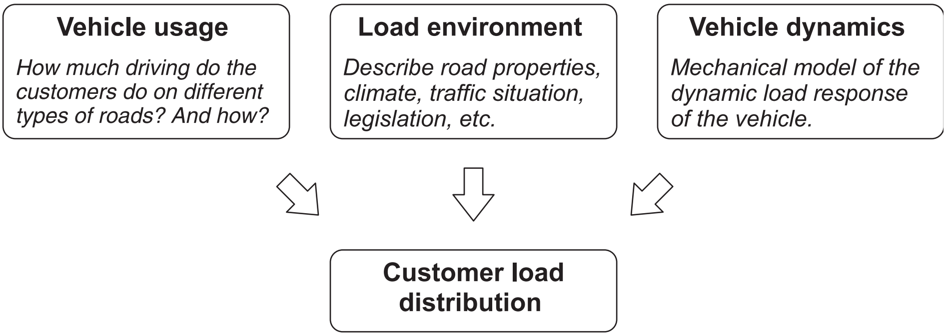


Figure 1.5 The customer load distribution can be described in terms of the vehicle-independent load environment together with the vehicle usage and the vehicle dynamics

Further, the loads can be classified according to their origin, namely *external excitations*, for example, coming from the road, and *internal excitations*, for example, coming from the engine and transmission.

1.4 Why Is Load Analysis Important?

Lack of durability is not only a problem for customers, also the producers suffer. Failures reduce company profitability through call-backs, warranty costs and bad will. In other words, good durability leads to good quality, company profitability and customer satisfaction; see Bergman and Klefsjö [22]. In order to make a good durability assessment there are many influences that need to be considered and most of those are not fully known beforehand. This is illustrated by Figure 1.6 showing a schematic view of engineering fatigue design.

The numerical procedures for calculating stresses and strains of mechanical systems are nowadays excellent and quite accurate, however, the calculations are surrounded by uncertainties. On the input side, loads are approximated by simplifications of the service environment; material strength is represented by empirical characteristics; geometry is given by specifications where defects like scratches, inclusions, pores and other discontinuities are neglected because of lack of information. On the output side, the stresses and strains are further processed using empirical fatigue models, such as the Wöhler curve, the Palmgren-Miner rule, and Paris' law. These rough models introduce model errors and their parameters are empirically determined, often from quite limited information, for example, data in the literature on similar materials, a number of fatigue tests, or previous experience. Thus, in order to evaluate the output of the fatigue assessment, it is necessary to reflect on the

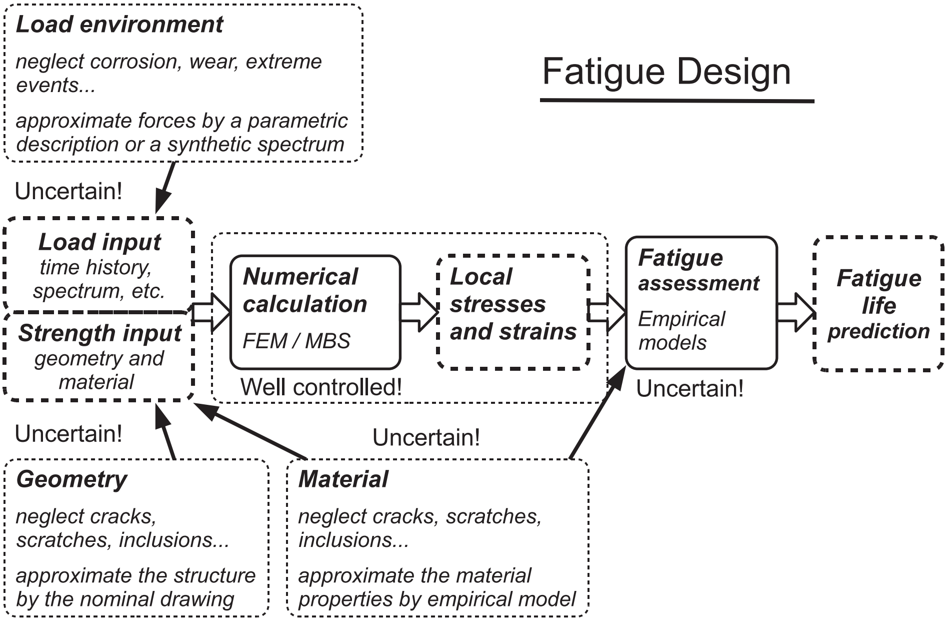


Figure 1.6 Schematic view of fatigue design

uncertainties in load as well as the uncertainties in strength defined by material and geometry input. However, it should be noted that also the numerical procedures may have significant model errors, especially for non-linear modelling of, for example, welded joints in FEM (Finite Element Models) and tyres in MBS (Multi-Body Simulation). Moreover, load analysis is not only important when analysing the load input, but also for the numerical simulation process, the evaluation of measurements, and the physical verification tests.

The *Guide* is mainly devoted to the load input problem; how should the service environment be evaluated and represented in the design process? However, in order to correctly understand and treat the load information some basic knowledge about the other pieces is necessary. Further, methods are developed which handle the overall uncertainty problem by using the load-strength model, which is presented in Chapter 7.

1.5 The Structure of the Book

The material is organized into three parts.

Part I Overview

Part I contains, apart from the introduction, Chapter 2 presenting some basic concepts of fatigue assessment and how to apply those to different kinds of loads. It is indicated how the type of system or component affects the choice of suitable load analysis methods to be applied. Finally, it is emphasized that fatigue prediction is affected by a number of sources of variation and uncertainty, which need to be treated and quantified in a reasonable way.

Part II Methods for Load Analysis

Part II gives an account of the different methods that are useful for load analysis. Apart from presenting how the methods work, we also aim to describe their assumptions, relevance, merits, disadvantages, and applicability.

Chapter 3 Basics on Load Analysis

Chapter 3 gives a broad background of load analysis. Section 3.1 treats amplitude-based methods, where the rate of the load signal is neglected in the analysis, thus focusing on the fatigue mechanism. Methods described are rainflow cycle counting, level crossing counting, and other counting methods. In Section 3.2 frequency-based methods are studied, focusing on the power spectral density (PSD). Section 3.3 introduces the case of multi-input loads.

Chapter 4 Load Editing and Generation of Time Signals

There are many situations where modifying load signals is necessary. Section 4.1 discusses which properties of loads are essential for durability, and how to define the criteria for the equivalence of loads. Frequently, measured data are incorrect in the sense that the data show some deviation from what was intended to measure. Besides measurement noise, there are essentially three types of disturbances, namely offsets, drifts and spikes. Methods for inspection and correction of load signals are treated in Section 4.2. Editing of load signals in the time domain is studied in Section 4.3, where amplitude-based methods such as hysteresis filtering are considered, as well as frequency-based methods such as low or high pass filtering. Load editing in the rainflow domain is the topic of Section 4.4, especially rescaling, superposition, and the extrapolation of rainflow matrices are discussed. In some cases the time signal is not available, but only, for example, the rainflow matrix. Section 4.5 presents methods for generating load signals from condensed load descriptions.

Chapter 5 Response of Mechanical Systems

When analysing loads it is necessary to consider the mechanical structure that the loads act on. The role in durability applications of multi-body simulations, ‘from system loads to component loads’, and finite element models, ‘from component loads to local stress-strain histories’, are reviewed in Section 5.2 and Section 5.3, respectively. The issue of invariant system loads is addressed in Section 5.4, that is, the question of getting realistic excitations before measurements on prototypes have been made.

Chapter 6 Models for Random Loads

Load signals in customer usage vary in a more or less unpredictable manner. The load variability can be modelled by using random processes, which are treated in Chapter 6. Statistical modelling of load signals and their durability impact, in terms of damage, are discussed in connection with range-pair counts and level crossing spectra. Two main classes of random loads are treated: Gaussian loads, which model the frequency content, and Markov loads, which model the turning points of a load. The main topic is to compute the expected damage of a random load. Furthermore, the uncertainty in a measured damage number is treated.

Chapter 7 Load Variation and Reliability

The reliability of a component depends on both the load it is subjected to and its structural strength. The sources of variability in load and strength are discussed, and different reliability approaches are reviewed. Our recommendation is to use a second-moment reliability method. Thus, a load-strength model, adopted to the fatigue application, is developed in Section 7.6. The safety factor can then be formulated in terms of a reliability index. In Section 7.6.9 a compromise between statistical modelling and engineering experience is proposed by combining a statistically determined safety factor with a deterministic safety factor based on engineering judgement.

Part III Load Analysis in View of the Vehicle Design Process

The idea of Part III is to present load analysis in view of the vehicle design process, and describe which methods are appropriate in the different stages of design. Recall the vehicle design process presented in Figure 1.2 on page 5, which also represents the structure of Part III.

A brief description of the tasks to be solved may start at the end of the process, namely the verification of the final design. A question that arises is: 'How many specimens should be tested with which loads, such that a given reliability target can be verified?' First, the reliability target needs to be formulated in terms of engineering quantities. It may be given as a safety factor based on engineering experience, for example, by using in-house standards at the company. However, we promote the use of safety factors derived by using the load-strength interference, see Figure 1.4, thus including statistical modelling in order to take care of the uncertainties in load and strength.

It is important to follow the reliability requirements throughout the design process. The design and verification loads should thus be determined with respect to the customer population that the vehicle is aimed for. Customer loads may, for example, be obtained from measurement campaigns on public roads, either with professional test drivers along a planned route, or by selecting suitable that of customers. It is often practical to define a design load that is more severe than a typical customer, and the concept of a severe target customer, say, the 95%-customer, is widely used. The design load is often represented as driving schedules on the proving ground.

Finally, the task is to derive verification loads for testing, and relate the corresponding test results to the reliability target. As has been illustrated above, a statistical point of view should be taken in the design process, which is especially the case when performing and evaluating the verification tests. However, it is also important to use previous experience and engineering judgement, for example, in matters of how to accelerate testing without changing the failure modes.

Chapter 8 Evaluation of Customer Loads

The main task of Chapter 8 is to assess the customer load distribution. Apart from defining the load of interest (e.g. the load on the steering arm), it is important to define which population it represents, e.g. all potential customers, a specific application (e.g. timber trucks), or a specific market (e.g. the European market). In this context, principles of survey sampling are discussed. Further, the uncertainty in the calculated load severity is evaluated. In Chapter 8 we discuss three strategies for estimating the customer load distribution:

- *Random sampling*: Choose customers randomly, however, not necessarily with equal probabilities, and measure their loads.
- *Customer usage and load environment*: Estimate the proportion driven on different road types, and combine this with measurements from the different road types.
- *Vehicle-independent load description*: Define models for customer usage, road types, driver influence, and legislation, which can then be combined with a model for the vehicle dynamics.

Chapter 9 Derivation of Design Load Specifications

The topic of Chapter 9 is to derive loads for design and verification purposes. The basic specification is the severity of the load, which needs to be related to the design approach taken. Load time signals can be derived using simple synthetic loads, random load models, modification of measured signals, standardized load sequences, test track measurements, or can be defined through an optimized mixture of test track events.

Chapter 10 Verification of Systems and Components

Chapter 10 is devoted to the verification process; principles of verification, generation and acceleration of loads, and planning and evaluation verification of tests. Three verification approaches are discussed:

- *Highly Accelerated Life Testing*, HALT, based on the idea that failures give more information than non-failures and give rise to improvements regardless of severities that exceed what is expected.
- *Load-Strength analysis based on characterizing tests*. Strength and load properties are investigated by characterizing experiments. Uncertainties are evaluated within a statistical framework to verify the design against reliability targets by means of established safety factors.
- *Probability-based formal procedures*, with test plans based on formal consistent rules that, by experience, give safe designs. Typically, a low quantile in the strength distribution is verified by testing.