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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

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CUSTOMER LOADS CORRELATION IN TRUCK ENGINEERING

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ABSTRACT
Safety and reliability requirements on the one side and short development cycles, low costs and lightweight design on the other side are two competing aspects of truck engineering. For safety critical components essentially no failures can be tolerated within the target mileage of a truck. For other components the goals are to stay below certain predefined failure rates. Reducing weight or cost of structures often also reduces strength and reliability. The requirements on the strength, however, strongly depend on the loads in actual customer usage. Without sufficient knowledge of these loads one needs large safety factors, limiting possible weight or cost reduction potentials.

There are a lot of different quantities influencing the loads acting on the vehicle in actual usage. These 'influencing quantities' are, for example, the road quality, the driver, traffic conditions, the mission (long haulage, distribution or construction site), and the geographic region. Thus there is a need for statistical methods to model the load distribution with all its variability, which in turn can be used for the derivation of testing specifications.

This paper describes new methods for the derivation of customer-correlated loads from field measurements. Simply taking the worst case ever measured as target load for testing is not sufficient. Instead assumptions on the distribution of the most important influence quantities are applied to derive the distribution of the loads acting on various spots on the truck (wheel forces, cabin accelerations etc.). Depending on the data, this process might involve parametric distribution estimation as well as Monte-Carlo methods for the simulation of customer loading. The result of this step is a certain percentile (e.g. a 95% customer) for the load acting on each component. In a second step this percentile is mapped to proving ground test scenarios corresponding to the derived customer loading profile. Based on this schedule testing is both customer-correlated (because of the derivation process) and accelerated (because of the special design of the test tracks). Component loads for further testing on servo-hydraulic rigs can also be derived from these test track schedules.

1 INTRODUCTION TO THE LOAD DERIVATION PROCESS

At the beginning of a durability developing process of heavy duty trucks, a target loading level has to be defined, by which the development objectives can be evaluated at any time. This defined target loading level usually accompanies the whole developing process from the first definition of the component load over the dimensioning of the component within the CAE-process to the final release of a component within a test. It is especially important that a consistent load spectrum is available for all development partners (e.g. designers, computation department, testing department) so that the target achievement is comparable during all development steps.

In the case of vehicle testing, the load spectrum is typically defined by Rough-Road-Testing. In the past, the characteristics and the damage intensity of Rough-Road-Testing have often been derived from correlations between executed tests and observed events in the field. Due to various disadvantages of this method new processes are executed to try to adapt the loading level more directly to the loads in the field already before starting the development process of a new vehicle generation. A means for this is the execution of load measurements of preceding generations in the field. On the basis of these measurements, a so-called Reference-Customer-Spectrum is formed that should contain all relevant loads of partially very different customer operations.

Before execution of the load measurements in the field, the special requirements for the derivation of a relevant loading level are to be considered, e.g.:

- Selection of a representative vehicle type to cover the variety of versions
- Selection of suitable evaluation factors (e.g. measurement channels) for loads
- Consideration of customer expectations from the product
- Consideration of representative customer operations and conditions
- Documentation of influencing parameters to subsequently optimise the product life according to different conditions (e.g. customer expectations, market conditions etc.)

To be able to form a representative Reference-Customer-Spectrum such that customer expectations are met, the use of a data interpretation process based on statistics is of advantage. This process will be explained further in the following chapters.

After a representative spectrum has been formed, there is a need to test the spectrum within an accelerated test procedure. For this purpose, test drives on Rough-Roads are usually executed with a high acceleration factor regarding the test mileage but also with an equivalent damage ratio compared to the customer operations. Therefore, each truck manufacturer uses corresponding Rough-Roads on proving grounds by means of which the loading level can be tested. Depending on the quality of the Rough-Roads and the intensity of the demanded shortening of time, the Reference-Customer-Spectrum and the Target-Load-Spectrum comply with each other more or less.

For the vehicle development of Mercedes-Benz, a series of newly developed Rough-Roads to test heavy duty and upper medium duty trucks are available in the new proving ground in Wörth since the middle of 2007. Due to corresponding combination possibilities of the roads, a good approach of the Target-Load-Spectrum to the Reference-Customer-Spectrum is possible. Meanwhile, this has been confirmed successfully by first tests.

2 INTRODUCTION TO THE TECHNICAL SETTINGS

In finite life design of vehicle components it is assumed, that the component may fail after a certain amount of usage. Usually a failure means a small detectable crack, which might lead to a complete breakdown of the component if used further on.

As a simple example consider the tank mount at the frame of a tractor. Besides the fuel weight the loading depends on many more factors like the road type and quality, the driving conditions, or the total weight of the truck. These factors are governed by some underlying factors like the regional restrictions and properties (market), the mission type (long haulage, distribution or construction site) or the specific customer.

As a measure for the loading of the tank mount we may use the local strain $\varepsilon(t)$ measured with a suitably applied strain gauge. We further assume that we can derive the force signal $S(t)$ from the strain signal using CAE-models of the component.

In that example, we have the typical situation (high cycle fatigue), that the component is able to withstand the load for a short while without any problems, but many repetitions during the life of the truck might lead to failures. The time to failure depends on the number and size of the load cycles. A simple measure of the load D (duty) can be described by

$$\textbf{(1)} \qquad D = \sum_i S_i^k$$

where S_i denotes the load cycles and k is a parameter of the material or of the component. The load cycles S_i can be derived from the force signal $S(t)$ using the rainflow counting. The parameter k is determined from component tests. We refer to (1) for details on rainflow counting and the verification of the model(1).

It is the responsibility of the truck manufacturer to estimate the customer loading D such that the component can be designed to guarantee sufficient reliability and at the same time reduce costs and weight. In order to derive the customer load distribution extensive measurement campaigns need to be performed to cover the manifold factors influencing the load.

The chosen example is simple with respect to the mechanical load path. For example at the cabin or the frame, there are more forces acting on the component, such that the load as a whole is harder to describe in a statistical setting. In these cases more sophisticated multi-axial methods need to be applied, which are not subject of this paper. Here we stick to definition (1), which enables us to derive a scalar value to each measurement and apply univariate statistical methods.

In practice a measurement includes a lot of different quantities (channels) in parallel (accelerations, strains, forces, spring displacements ...). Formula (1) is applied to most of them even if there is no direct relation to the fatigue of a certain component as is the case for the tank mount example. Nevertheless, the duty value gives a condensed measure of the loading and can be used for the statistical analysis.

The concept of the duty D can be combined with the strength C (capacity), which is defined by

$$\textbf{(2)} \qquad N = \frac{C}{D} \quad , \quad D = \sum_i S_i^k$$

where N is the number of repetitions of load D until failure. By definition, each component test until failure gives an observation of the capacity C as can be seen from $N = 1 \Rightarrow C = D = \sum_i S_i^k$. From several observations of duty and capacity, we can estimate distributions for both quantities and use these to calculate the probability of failure under customer loading given by $P(\text{failure}) = P(C < D)$, where the failure distribution function can be derived from the distributions of duty and capacity (see (4) for more details).

In this paper the emphasis is on the distribution of duty, which describes the customer loading variation, and we concentrate on a) modelling the influence quantities including their distribution (section 3), b) deriving the distribution of subpopulations (section 4), and c) combining the partial distributions to a customer load distribution (section 4). Basics about distributions, the estimation of parameters, failure probabilities etc. can be found for example in (2) or (3). Section 5 contains a brief introduction to the process of mapping the Reference-Customer-Spectrum to the proving ground and section 6 summarizes the most important topics.

3 MODELING INFLUENCE QUANTITIES (FACTORS)

In order to determine the customer duty distribution, measurements under typical customer conditions need to be performed. Suitable vehicles are equipped for a measurement campaign and tours on public roads in different regions under realistic payload conditions, driving behaviour etc. are performed. Each channel of each measurement can be evaluated using formula(1) to get observations of the duty D of the corresponding spots in the truck.

Factors, levels, and cells

Such a campaign is an expensive project and requires a large effort during the planning phase. The first task is to list all the variables (factors), which need to be varied during the measurement to analyse their effect on the duty. These are for example

- Road type (city, highway, …)
- Topography (flat, hill, …)
- Payload (empty, full, …)
- Trailer (box, flatbed, …)
- Driving behaviour (aggressive, gentle, …)
- Environmental conditions (icy, wet, hot, …)
- Regional restrictions (speed limit)

As indicated, each of these factors has a certain set of possible levels, which can be two, three ore more discrete levels (highway, country road, or city for the road type) or a range of continuous values (from 0% to 100% for the payload). For practical reasons, the continuous factors usually are divided into a (small) number of levels, for instance the payload levels might be 0%, 60%, and 100%. If there are n_f factors with l_i, $i = 1, ..., n_f$ levels, then the scheme ends up in a matrix of $L = l_1 \cdot l_2 \cdot ... \cdot l_{n_f}$ possible combinations or cells. Of course, there might be restrictions regarding the combination of different factors at certain levels (for example aggressive driving behaviour on icy road) either because they are not allowed or of minor importance. This leads to a reduction of the number of cells to be investigated. A simple example of a possible structure of factors, levels, and cells is shown in Table 1.

<table>
<tr><td colspan="2" rowspan="4">Contribution in %</td><td colspan="4">Trailer type</td></tr>
<tr><td colspan="2">flatbed</td><td colspan="2">box</td></tr>
<tr><td colspan="2">Payload</td><td colspan="2">Payload</td></tr>
<tr><td>60%</td><td>100%</td><td>60%</td><td>100%</td></tr>
<tr><td rowspan="3">Road type</td><td>Highway</td><td>6</td><td>14</td><td>8</td><td>18</td></tr>
<tr><td>Countryroad</td><td>3</td><td>7</td><td>5</td><td>12</td></tr>
<tr><td>City</td><td>3</td><td>7</td><td>5</td><td>12</td></tr>
</table>

Table 1: A 3-factor model with 3*2*2=12 cells

If we look at a specific spot of the truck i.e. a channel, not all factors have the same importance. For instance the tank mount is less influenced by the topography as the drive train. During planning of a measurement campaign this plays a minor role, since it is intended to apply the results of the campaign to the duty evaluation for many different spots of the truck. However, in the statistical evaluation of the duty value for a certain component, the number of factors and levels might be decreased such that we need fewer assumptions on the distribution of the levels and have more measurements in the remaining cells. In the example above we might neglect the factor trailer type for the drive train analysis and work with 6 instead of 12 cells.

Although we don't need specific results from the general theory of Design of Experiments the interested reader is referred to (5) for more details on factors, levels etc.

<u>The distribution of factors</u>

In the following, a population means a certain set of possible customers for a specific truck. In the factor/level model such a population is defined by a multivariate distribution of the factors, which defines the relative contribution of each cell to the entire life of a truck. The number of components of this random vector X is given by the number of cells L. A possible approach for the construction of such a distribution is the following.

First consider one factor only, for example the road type with its 3 levels highway, country road, and city. Let us assume that, for a given population, an estimate for the average percentage p_i as well as for the standard deviation s_i of level i is known. Then we can easily define a random variable R_i in [0,100%] with mean p_i and standard deviation s_i (for example a Beta distribution). Combining these 3 random variables to a 3-variate variable R with the restriction that the sum over all 3 components is 100%, we get a statistical model for the road type distribution. A realization of that distribution corresponds to the road type contributions of a specific customer of that population.

Repeating this step for all factors and combining the factor distributions again with the restriction that the sum over all components is 100%, we arrive at the full distribution X of the factors. Correlations between different factors and levels have not been taken into account so far, but this can be supported during the construction of the multivariate distributions if necessary. In that way a statistical model of a certain desired population can be constructed, which can be used to simulate customers by random selection according to X. In the example of Table 1 we have a 12-dimensional distribution F_X such that one realization of X gives the cell contributions of that specific customer as shown in the table. These procedure does not assign the same contribution (the average over the entire population = the expected value of X) to a cell for all customers, but makes it possible to have a variation as is the case in reality.

Besides the factors described above, there is another set of 'underlying' variables like the market (Western Europe, South America …), the mission (long haulage, distribution …), or the customer type (haulier, building company), that in turn determine the distribution of the levels within each factor. As an example consider the market or the customer type. If we are interested in South America, we will find less highway and more country road or even unpaved sections as in Western Europe and a certain building company will more often drive on bad roads or even off-road as a haulier. During the construction of the population model X these underlying variables need to be taken into account, but here we will concentrate on the factors as described above.

4 ESTIMATING CUSTOMER DISTIBUTIONS

Having set up the factor and level model described in section 3 each cell needs to be filled with data. All available measurements of the truck are assigned to their corresponding cells. As described above, a cell specifies the level of the most important influence quantities. However within that cell, there still is a considerable amount of variation of the duty value. There are different slopes in a hilly environment or different road qualities on the highway etc. To cover this variation, several measurements are needed. If there are too few measurements in a cell, we need to assume that the measurements we have are representative and either ignore the variation or presume a certain variation found from other cells or from experience based considerations.

How to interpret the measured data

If there are enough observations for a cell, a distribution of the duty value can be estimated. The standard procedure is to presume a distribution type (for instance Weibull or Lognormal distribution) and fit the parameters of the distribution using least squares or maximum likelihood methods. However the distribution found in that way does not necessarily represent what we want (especially if the selection of road segments have been stratified).

To explain that, assume that we only have the two factors road type (levels highway, countryside, and city) and payload (50% 100%). It is clear, that the cell (road type = highway, payload = 100%) is very important since a considerable amount of customer kilometres will belong to that cell. We assume that there are sufficiently many measured highway sections such that they cover a representative range of roads of that type. If we now calculate the 95% quantile from the estimated distribution and interpret that value as the duty of the 95% customer, then we implicitly assume, that this customer only drives the 5% hardest roads among the measurements. This interpretation of the 95% quantile is somewhat unrealistic, since the distribution we have found is a model for highway sections, not for customers.

Monte-Carlo approach

Another approach is to simulate customers by randomly drawing measurements (with replacement) from the cell until the desired number of target kilometres is reached. The number of selections λ we have to make here approximately is the target length divided by the average measurement length (typically a much smaller number than the target length), such that λ may be of the order 100 or even more. In Figure 1 both data interpretations are shown where $\lambda = 100$ has been used for illustration.

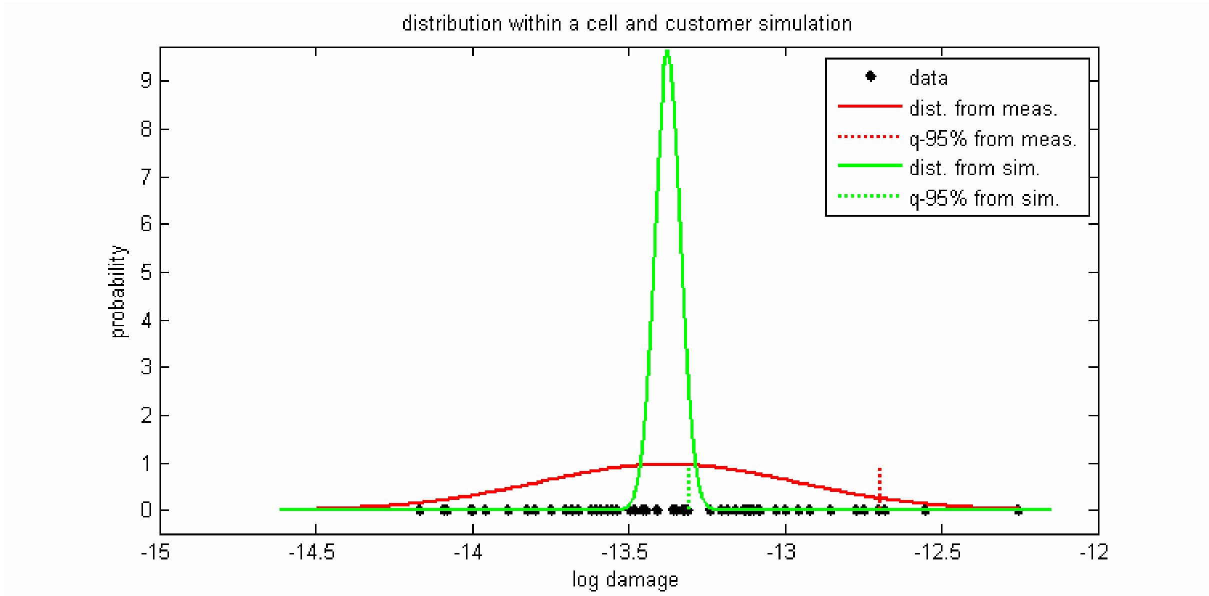

Figure 1: Distribution estimation from 73 measured duty values (black dots). The red curve is the estimated density function and the dotted red line denotes the corresponding 95% quantile. The green curve represents the density estimated from the customer simulation with $\lambda = 100$ and the dotted green line is the corresponding 95% quantile.

The difference in the 95% quantile is large (factor 4 in damage) due to the different interpretations of the data. Since both arguments sound pretty reasonable at a first glance, this simple exercise shows that care has to be taken during interpretation and analysis of the data. The simple random selection as explained above represents a customer as a certain sum of randomly selected measurements. This approach typically leads to a small variance between the simulated customers. This is a consequence of the central limit theorem and can easily be understood from the following example. Let several players throw a dice, each one $\lambda = 100$ times, and add the results. Then the possible results range from 100 to 600, but for most of the players the result will be near to the expected value 350. The variance decreases with increasing number λ.

A more realistic model is somewhere in between the two extreme ones we have shown. In principle, the idea of simulating customers by randomly selecting data out of the measured samples is a reasonable approach since it reflects the fact, that the measured samples do not describe the customer distribution but the road distribution (the distribution of the factor we consider). The selection mechanism has to be extended to take into account, that some customers will drive many different roads (this is the customer we have modelled with the simple sampling) and others will always drive the same small set of roads because of their specific mission. A possible approach is not to use a fixed value of λ for all customers, but to define a certain distribution, which models the fact that there are some 'local' and some 'global' customers. Such models introduce dependencies between the cells, since the property of being a local or a global customer depends on what measurements are assigned to him from all cells, not only within a single cell (see below for further remarks).

The random selection approach (Monte-Carlo method) as such is simple and flexible at the same time. As has been illustrated with the simple example above, the difficult task is to define and justify a good model for the customer behaviour. Applying the Monte-Carlo approach is then a rather simple step to go.

If we decided for the Monte-Carlo approach, then the distribution is not defined by a parametric formula like Weibull or Lognormal but directly by the (arbitrarily) large amount of simulated values. Of course, one may try to fit a parametric distribution to the simulation data in order to compare to former results or for purposes of further analysis. A synthetic example is shown in Figure 2. The histogram gives an idea about the shape of the distribution (symmetry or skewness etc.). In the probability plot one can easily find the quantiles by intersection of the corresponding horizontal line with the data spots. In this example the normal probability plot is used.

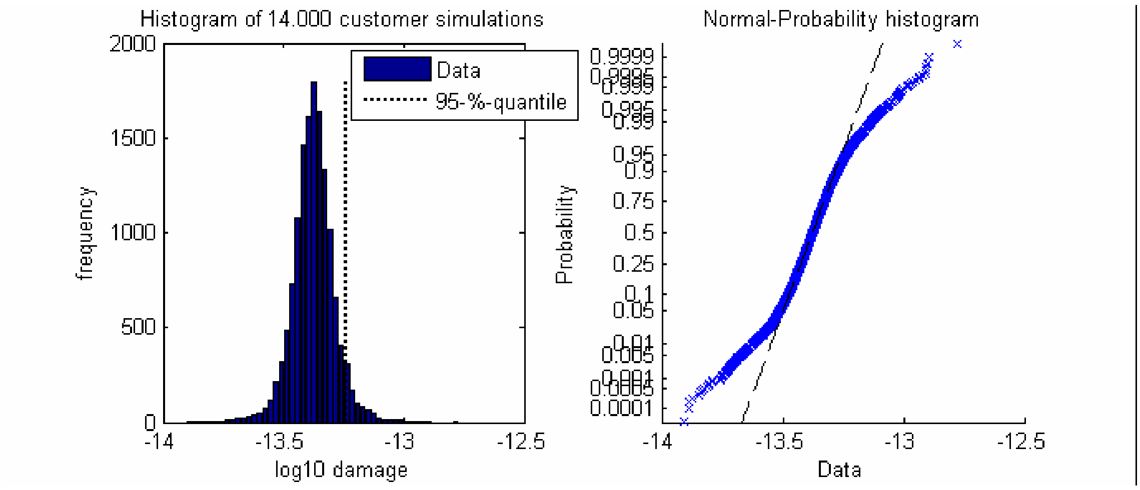

Figure 2: 14.000 simulated customers randomly selected from measurements. To the left, the histogram, to the right the values in Gauss paper are shown.

As can be easily seen, an approximation by a normal distribution would underestimate high quantiles.

Since at that stage of the process we deal only with a single cell, that is a single combination of factor levels, we don't know how large the contribution of that cell to the target mileage will be. Thus, we normalize the duty values to a certain standard length, for example 1 kilometre.

Combining the partial distributions

Once the partial distributions within the cells are known, they must be combined to get a distribution of the population covering all factor levels.

If the Monte-Carlo approach within the cells as sketched above has been taken, we have sub-populations for all cells and can combine these to get the entire population. In order to do this, we randomly select the contributions (weights) for all cells from the factor distribution X, select one of the customers in each cell and scale the normalized duty values according to the weights. However, as has been mentioned above, the idea of having local and global customers makes it hard to perform the customer simulation in each cell independently. Instead, the Monte-Carlo selection mechanism has to be applied to all cells in parallel in order to take the dependencies into account.

If there is a parametric distribution estimation $f_i(x)$, $i = 1,...,L$ for each cell, where f_i denotes the density of cell i, we can combine them in the form $f(x) = \sum_{i=1}^{L} w_i \cdot f_i(x)$, where

$w_i = E(X_i)$ is the expected value of the factor distribution, that is the average contribution of cell i to the desired target length.

In both cases, the most important result will be the 95% customer extracted from the combined distribution.

Further remarks
The advantages of the Monte-Carlo approach are its flexibility with respect to special restrictions or constraints, the lack of assumptions regarding the distribution type, and maybe most important, the fact, that the 95% customer is explicitly given as a certain combination of measurements.

Another property of the Monte-Carlo method is that it delivers a 95% customer specific to the channel (quantile channel) we have used during the distribution estimation. However, since the number of customers in the Monte-Carlo method is arbitrarily large, we should and can make sure that there are many different customers near to the 95% value, such that we even have the possibility to use this freedom for additional purposes (for example controlling spectral properties of the selected measurements). Here, the most interesting thing is to maximize the duty value of the other channels such that the customer is (at least approximately) a 95% customer for several channels.

A disadvantage of the Monte-Carlo method is that it cannot extrapolate to more extreme events than measured, whereas the approach using parametric distributions can. If this is desired, the measured data has to be enlarged by suitably generated synthetic data (extrapolation techniques, see (7) for more details) prior to the Monte-Carlo process.

5 THE CORRELATION BETWEEN TEST TRACK AND CUSTOMER LOADING

Once the Reference-Customer-Spectrum has been derived from the customer loading measurements using the methods described above, the next task is to map this to the test track. We assume that a target damage value for each channel has been derived. For simplicity of notation, we denote that vector of target values by $d^{(T)}$. Measuring a lane of the test track, Rainflow counting the signals and damage calculation leads to the corresponding vector of values for that lane, say $d^{(i)}$. Repeating this step for all lanes and all different driving conditions (several speeds or payloads) we get a large number of damage vectors $d^{(1)},...,d^{(m)}$, where m is the number of different combinations of lanes and driving conditions. The task of finding a driving scenario which best meets the target values is then to find repetition factors $w_1,..,w_m$ such that the differences $d^{(T)} - (w_1 \cdot d^{(1)} + ... + w_m \cdot d^{(m)})$ are small.

This is a standard mathematical optimization problem, which can be solved by corresponding well known algorithms. A lot of refinements and extensions of the method can be introduced. For example we can pay specific attention to the shape of the load spectra for the channels by using not only a single damage value for each channel, but several values corresponding to small, medium, and large cycles for instance. Additionally, constraints on the repetition factors can be taken into account. Examples are lower or upper bounds on the repetition factors, a bound on the total mileage, or a bound on the duration of the scenario.

Depending on the 'richness' of the proving ground, a driving schedule satisfying some, most, or all of the channels can be derived in that way. If we only have straight lanes, then we can hardly expect to match the lateral customer forces. If no braking is foreseen on the proving ground, then we probably will miss high amplitudes in the longitudinal forces. In any case, a compromise between the accuracy of different channels and a compromise between the overall accuracy of damage values on one side and duration, mileage or simplicity of the calculated schedule on the other side has to be made. Here, engineering judgement plays an important role. The load defined by the optimized schedule is called the Target-Load-Spectrum and is used for accelerated testing as explained in the introduction.

Details of that approach can not be given here. Instead, we refer to (6), where the method is described and some applications are shown.

6 SUMMARY

The process of verification of a truck or a component for a final release essentially comprises 3 steps, namely the determination of the duty distribution, the strength distribution and the synthesis of both giving the failure probability. This paper mainly deals with the derivation of the duty distribution. The other two steps are mentioned only briefly in section 2.

The duty depends on many different influence quantities (road, payload, driving behaviour) whose distributions need to be estimated, for example from sales information or questionnaires. This cannot be derived from the mechanical system as such. Instead a model using factors and levels need to be set up, which should be as simple as possible but needs to cover all important effects.

Next, the distributions for specific level combinations (cells) are estimated using either a parametric distribution approach or a Monte-Carlo method. It turns out, that this heavily relies on the correct interpretation of the measured data. In a synthesis step, the factor distributions and the partial cell distributions are combined to get a duty value distribution covering the entire customer population and the Reference-Customer-Spectrum is derived from that.

For the verification in practice it is important to map the Reference-Customer-Spectrum to the Target-Load-Spectrum. This is a driving schedule on the test track, which comes as close as possible to the Reference-Customer-Spectrum and enables accelerated testing. The methods for deriving such target loads are based on mathematical optimization and mentioned here only briefly.

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