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Probabilistic Assessment of the Crosswind Stability of Railway Vehicles

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Abstract

The crosswind stability against overturning is a major design criterion for high speed railway vehicles. Due to the increasing interoperability in Europe it has also become an important international task. In recent years efforts have been made to derive an uniform rule in certifying railway vehicles. In this case especially probabilistic methods have been proposed which are common design criteria for wind turbines. A sophisticated method to compute the reliability of railway vehicles under strong crosswind is presented. In consideration of the given stochastic wind excitation the response of a simplified train model and the corresponding probability of failure have been computed. The major failure criterion to determine the reliability is the lowest wheel-rail contact force of the railway vehicle.
In the product development process it is a common goal to calculate the virtual prototype as realistic as possible but it is also essential to minimize the computational efforts. For a probabilistic analysis this means to take only the most significant stochastic variables into account and to neglect the unimportant ones. To isolate the major variables a sensitivity analysis with respect to the stochastic excitation variables has been done.
But not only the knowledge about the influence of the excitation variables is crucial, also the impact of the design parameters of the railway vehicle on the crosswind stability is important to know. To get a deeper insight into the system also a sensitivity analysis with respect to the deterministic design parameters has been done.

Keywords: Crosswind Stability, Railway Vehicles, Stochastic System, Sensitivity Analysis

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1 Introduction

The modern developments in railway engineering have been showing a trend to faster and more energy efficient trains with a higher capacity of passenger transportation. These efforts are directly leading to light-weight cars with distributed actuation. Unfortunately these developments are in contrast to a save use in strong crosswind conditions. Especially the first car of the train is highly endangered as it is exposed by the strongest wind forces and moments.

Figure 1: Switzerland January 2007, courtesy of Schweizer Fernsehen - Schweiz Aktuell.

During the last 140 years about thirty wind-induced accidents have been reported. Most of these accidents happened in Japan on narrow gauges at highly endangered points (e.g. bridges or embankments) in nearly hurricane conditions, Fujii et al.; Gawthorpe (1994). But also in Europe there have been incidents reported that trains turned over while operating in strong winds, Rolén et al. (2004). The last accident which has happened in Europe occurred in Switzerland (figure 1) during the winter storm Kyrill in January 2007.
Consequently the crosswind stability is a major topic which has to be considered during the product development process and which cannot be solved easily as all counter-measures are very expensive. If a railway vehicle fails to be certified, ballasting in the underbelly is often the only adequate way to save the design. It is obvious that ballasting a light-weight construction is not a desired goal. Putting wind-fences along the track at places with a high risk of strong winds also increases the costs dramatically.
Due to the desired interoperability in Europe the European Commission is working on Technical Specifications for Interoperability (TSI) to get a common rule for the certification of railway vehicles. Most of the leading operating companies of trains in Europe are using approval processes which are based on worst case scenarios in which the stochastic nature of the uncertainties are not explicitly modeled but are considered by using safety factors, Matschke et al. (2002); Diedrichs et al. (2004). This approach is an antagonism to the intention to optimize the railway vehicle behavior under strong crosswind. Taking the uncertainties during the computation of the characteristic wind curve into account, Carrarini (2004) for the first time, proposed a probabilistic characteristic wind curve (PCWC) whereas Cooper (1979) was the first to introduce uncertainties by the use of a risk assessment process. The major uncertainties in the railway vehicle-/environmental system (e.g. wind scenario, aerodynamic coefficients) are considered as stochastic variables for which the corresponding probability distributions are taken from available literature.
The first intention of this paper is to introduce a method for computing the failure probability

P_f of a railway vehicle under strong crosswind. In this case failure means the exceedance of a critical value of the so-called wheel unloading

$$\frac{\delta Q}{Q} = 1 - \frac{Q_{\text{dyn}}}{Q_{\text{static}}}, \tag{1}$$

where Q_{dyn} is the wheel-rail contact force in every time step and Q_{static} is the static contact force which is set in the absence of all external forces, Diedrichs et al. (2004). The critical limit of the wheel unloading is usually defined as

$$\frac{\delta Q}{Q} \geq 0.9, \tag{2}$$

which means, that the windward wheels are not yet lifting off the track.

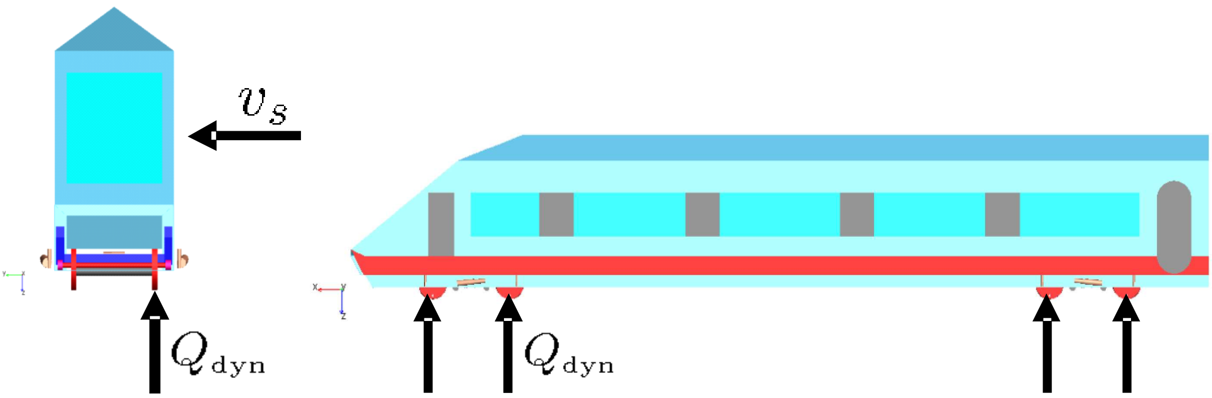

Figure 2: Front and side view with normal wheel force Q_{dyn} and resultant wind velocity v_s.

In a second step sensitivity analyses with respect to the stochastic excitation variables and with respect to deterministic design parameters are performed and the most crucial variables are accentuated.
The paper is structured as follows: In the first section the vehicle and the wind model are introduced. Then the simulation procedures are described and the used software is shown. After that a representative railway car is investigated and the results are briefly stated while section 6 contains the major conclusions.

2 Modeling of the system

The system can be divided into two separate parts: the environmental model and the vehicle model. The environmental model itself consists of two distinct components: the track and the aerodynamic forces and moments.

2.1 Railway vehicle

The railway vehicle is simulated in the commercial MBS-Software ADAMS/Rail. In this code the nonlinear spring and damper forces can be utilized without major problems and also the bump-stops, which have a great influence on the overturning behavior can be included very precisely. The wheel-rail contact forces are simulated using the implemented FASTSIM routine, Kalker (1982). This routine is a good compromise between speed and accuracy to calculate the resultant wheel-rail forces.

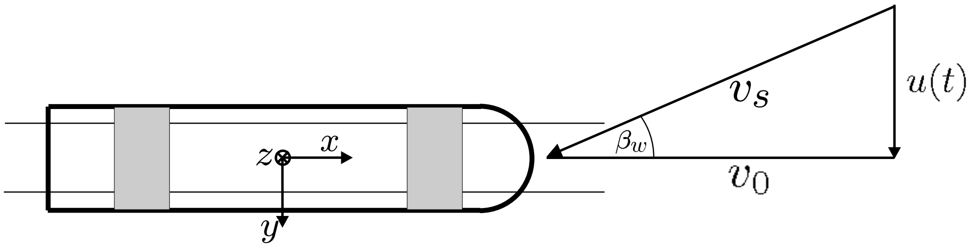

Figure 3: Schematic sketch of the vehicle with coordinate system and wind velocity vector.

2.2 Environmental model

2.2.1 Track model

Straight tracks fitted with UIC 60 rails at standard gauge of 1435 mm have been used. So far no track irregularities have been investigated. The sleepers have been modeled as rigid bodies with an elastic foundation.

2.2.2 Aerodynamic model

The crosswind model $u(t)$ consists of a superposition of the mean wind u_0 and the gust wind $u_B(t)$. As the train speed v_0 is much higher than the velocity of the crosswind the spatial correlation of the wind can be neglected. That means that the wind excitation is modeled in such a way, as if the train would be running through a frozen wind field. Hence, the wind is designed as a function of the track variable s and must be transformed into the time domain by the constant train velocity v_0 as a time integration of the differential equations has to be performed.

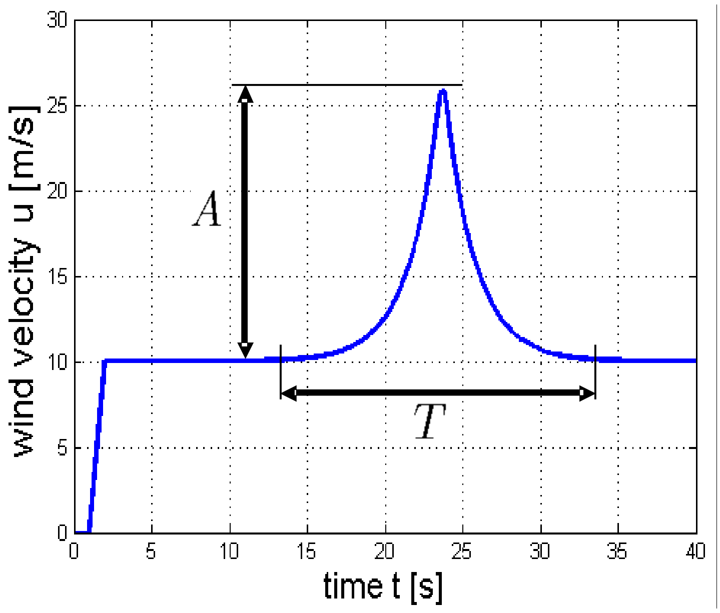

Figure 4: Crosswind characteristic with gust amplitude A and gust duration T.

The exponentially shaped gust characteristic (figure 4) which is utilized in this investigations is often used in wind turbine design and has a strong theoretical foundation, Bierbooms and Cheng (2002); prEN 14067-6 (2007).

The wind loads on the vehicle are modeled as concentrated forces and moments and so they are computed from the acting wind velocity $v_s(t)$ by means of experimentally determined aerodynamic coefficients:

$$F_{y/z}(v_0, u(t)) = C_{\text{side/lift}}(\beta_w)\frac{\rho_L A_t}{2}v_s^2, \tag{3}$$

$$M_{x/y/z}(v_0, u(t)) = C_{\text{roll/pitch/yaw}}(\beta_w)\frac{\rho_L A_t l}{2}v_s^2, \tag{4}$$

as the determination of reliable aerodynamic coefficients by means of computational fluid dynamics (CFD) is still an unsolved topic, Diedrichs et al. (2004); Diedrichs (2003). The parameters A_t and l are the area and the length dimension of the railway car and ρ_L is the constant density of air. The wind forces and moments are therefore functions of the angle

$$\beta_w = \arctan\left(\frac{u_0 + u_B(t)}{v_0}\right) \tag{5}$$

and of the squared resultant wind velocity

$$v_s^2(t) = v_0^2 + (u_0 + u_B(t))^2 \,. \tag{6}$$

As the railway vehicle has a certain dimension in the horizontal and vertical direction the resultant wind forces have to be calculated by an averaging process over the whole area of the carbody. In the time domain this integration transforms to a sliding mean procedure with the time interval $[t - \frac{L_t}{2v_0}, t + \frac{L_t}{2v_0}]$, where L_t describes the length of the carbody.

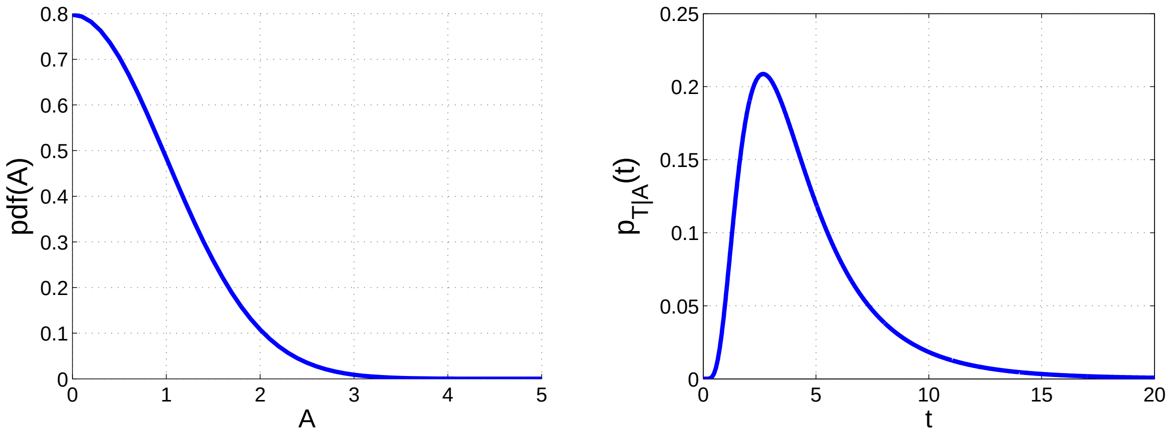

Figure 5: Probability distribution functions of amplitude A and duration T.

The aerodynamic coefficients $C_{\text{side/lift/roll/pitch/yaw}}$, the gust amplitude A and the gust duration T are assumed to be random variables. As not much information about the distributions of the aerodynamic coefficients exists they are fitted by a gaussian distribution with a standard deviation of 10%. The gust amplitude A follows a half gaussian and the gust duration T follows a lognormal distribution as described in Delaunay and Locatelly (1990).

3 Probabilistic analysis of the system

3.1 Reliability analysis

To determine the probability of failure P_f it is necessary to evaluate the high dimensional integral

$$P_f = \int_{\Omega_f} p_{z^*}(\underline{z}^*) d\underline{z}^* \tag{7}$$

over the failure domain Ω_f where $\underline{z}^*$ contains all stochastic variables of the system and $p_{z^*}(\underline{z}^*)$ are the corresponding probability density functions. The failure domain Ω_f is separated from the safe domain Ω_s by the so called limit-state function $g(\underline{z}^*) = 0$ which is defined as:

$$g(\underline{z}^*) = 0.9 - \frac{\delta Q}{Q}. \tag{8}$$

From this definition the failure domain is characterized by $g(\underline{z}^*) \leq 0$ and the safe domain by $g(\underline{z}^*) \geq 0$. For the complex railway vehicle system where a numerical calculation of the function $g(\underline{z}^*)$ lasts about half a minute and where the limit-state function is not known explicitly but can only be evaluated pointwise the computation of the integral 7 is a demanding task. To simplify the calculations the law of conditional probability can be used and equation 7 is reduced to

$$P_f = \int_{u_{0,d}}^{u_{0,t}} P(\underline{z}|u_0) p(u_0) du_0, \tag{9}$$

whereas $\underline{z} = [A, T, C_{\text{side/lift/roll/pitch/yaw}}]$ is the vector of the remaining stochastic variables.
But still the conditional probability $P(\underline{z}|u_0)$ has to be calculated which can be done by semi-analytical procedures such as FORM or SORM or by numerical methods like Monte Carlo Simulation, Proppe et al. (2003); Roos et al. (2006), and eventually also response surface methods can be used, Bucher and Burgound (1990).
The first step in the numerical procedure is always to map all distributions to the standard gaussian space, in which the shortest distance from the origin to the limit-state function, the so called design point, is computed. The FORM results are then verified and improved by importance sampling around the design point, Engelund and Rackwitz (1993); Bucher (1988), to get reliable estimates of the conditional probabilities.

3.2 Sensitivity analysis

The sensitivity analysis is a method to investigate the influence of input parameters on the output of a system. Sensitivity methods are commonly classified in local and global methods and in qualitative and quantitative methods. It is up to the user of these methods which one to take, as they all have their advantages and respectively drawbacks. In general the local and qualitative methods are less computationally expensive but the results gained from these methods are either only valid for a small local region or give only an indication how the dependency between input and output parameters is. On the other side the global and quantitative methods give either results which are valid over the whole parameter space or which show exactly how the input parameters affect the output, but these sensitivity methods require a much higher amount of

computational effort.
In this work the sensitivity analysis is performed to deal with two different kinds of problems. The first one is the impact of the seven stochastic excitation variables on the crosswind stability of the railway vehicle and the second one is to investigate the influence of the deterministic design parameters.
To separate the unimportant excitation variables from the important ones a robustness analysis with latin hypercube sampling (LHS) has been undertaken. From the LHS linear and quadratic correlation coefficients and principal component values from a principal component analysis have been calculated. A comparison of these values show clearly how high the impact of a stochastic variable is. Another good method to decide which variable is important or not is to look at the response surface approximations and to search for high gradients.
The influence of the deterministic design parameters has been extracted by a design of experiment (DoE). In this case the anthill plots of the function $g(\underline{z})$ with respect to the design parameters are good criterions, as these functions directly show the deterministic dependency between these values, optiSLang2007.

4 Workflow

The reliability and sensitivity calculations have been performed under assistance of the commercial code optiSLang. The software optiSlang is specially designed to perfom sensitivity, reliability and optimization tasks. It is platform and solver independent and its advantage lies in its coupling with other software codes as for example Multi-Body- or FE-programs. The implemented powerful algorithms can then be used to investigate the Multi-Body- or FE-models.

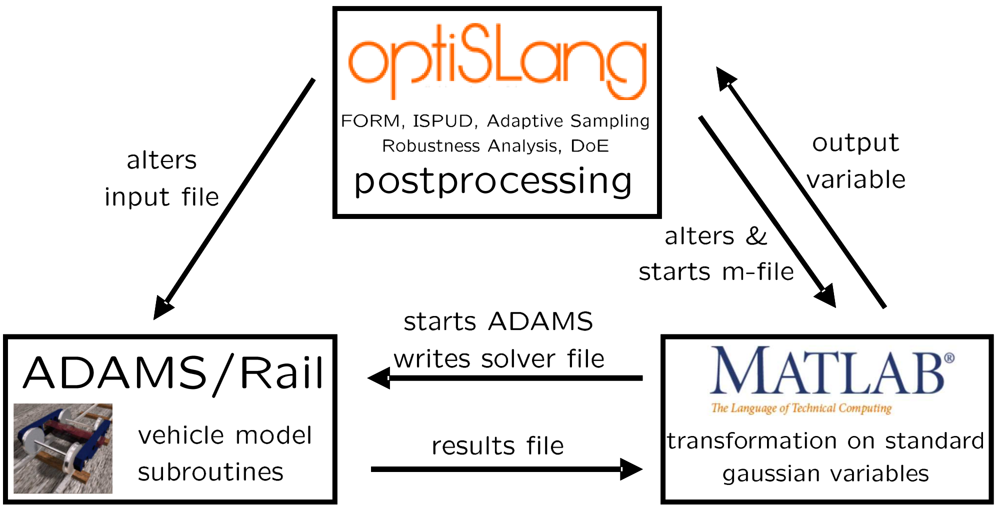

Figure 6: Flowchart between optiSLang, Matlab and ADAMS/Rail.

In this work optiSLang is coupled with the MBS-code ADAMS/Rail and with Matlab. OptiSLang is used for pre-and postprocessing and as master program to control the reliability and sensitivity computations. It alters the ADAMS input-file and the Matlab m-file which is needed to map the distributions to standard gaussian variables and to start ADAMS/Rail in solver mode. The Matlab m-file also writes an output file to pass the resultant values to optiSLang, Fritz (2004).

The postprocessing and the graphical preparation at the end of the computations is again performed with the powerful optiSLang postprocessing routines.

5 Results

5.1 Reliability analysis

As a first result, in figure 7, the normal force $Q_{\text{dyn}}(t)$ of a windward wheel is shown with respect to the simulation time t. In the presented case the critical limit is already exceeded and so the systems parameters are located in the failure domain.

Figure 7: Normal force $Q_{\text{dyn}}(t)$ for $v_0 = 160[\frac{km}{h}]$ and $u_0 = 14[\frac{m}{s}]$ at the design point.

Figure 8 shows the conditional probability of failure $P(\underline{z}|u_0)$ with respect to the mean wind speed u_0 on a straight track for two different vehicle velocities. The failure probability varies about exponentially with increasing mean wind speed.

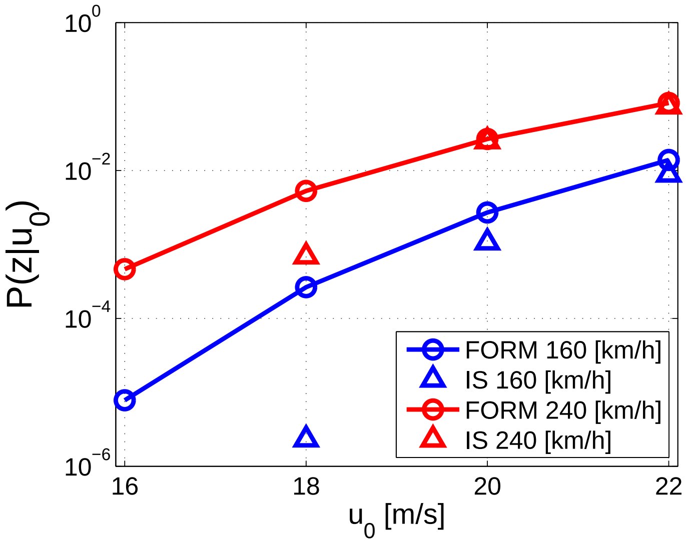

Figure 8: PCWC calculated by a FORM and IS analysis.

To verify and to improve the results of the FORM analysis importance sampling simulations have been carried out. For higher mean wind speeds both results match quite well, as can be

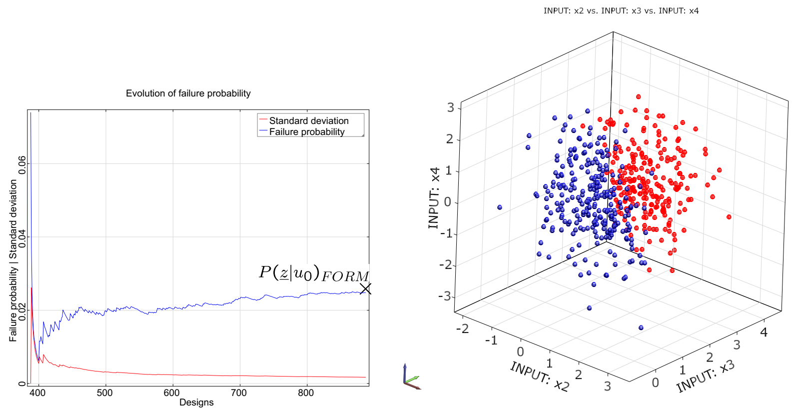

Figure 9: IS result evolution and anthill plot of the failure and safe domain for $v_0 = 240[\frac{km}{h}]$ and $u_0 = 20[\frac{m}{s}]$.

seen in figure 9, but for lower mean wind speeds drastic deviations occur. At a mean wind speed of $16[\frac{m}{s}]$ and a driving velocity of $160[\frac{km}{h}]$ the relative error is about

$$\frac{P(\underline{z}|16)_{FORM}}{P(\underline{z}|16)_{IS}} = 114 \tag{10}$$

which is very high. But as previous response surface computations had shown (see figure 10), that the limit-state function has only a slight curvature it is in the authors opinion acceptable to trust the FORM results and to put the selected adaptive importance sampling strategy into questions. Nevertheless, further investigations have definitely to be done.

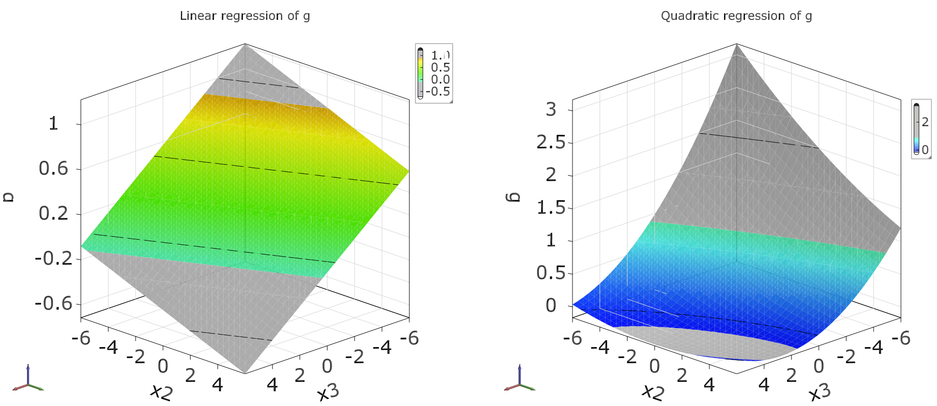

Figure 10: Linear and quadratic response surface approximations for $v_0 = 240[\frac{km}{h}]$ and $u_0 = 20[\frac{m}{s}]$.

5.2 Sensitivity analysis

A Sensitivity analysis with respect to the 7 stochastic variables and with respect to various deterministic design parameters has been performed.

5.2.1 Excitation variables

In all figures the order and assignment of the variables is as follows:

$$\begin{aligned} x_1 &\rightarrow C_{\text{lift}}, \quad x_2 \rightarrow C_{\text{roll}}, \quad x_3 \rightarrow A, \quad x_4 \rightarrow T, \\ x_5 &\rightarrow C_{\text{side}}, \quad x_6 \rightarrow C_{\text{pitch}}, \quad x_7 \rightarrow C_{\text{yaw}}, \quad x_8 \rightarrow g(\underline{z}). \end{aligned}$$

From the linear and quadratic correlations matrices shown in figure 11 (the axes refer to $x_i, i = 1 \ldots 8$) the most crucial variables can be identified. These are the gust amplitude A, the aerody-

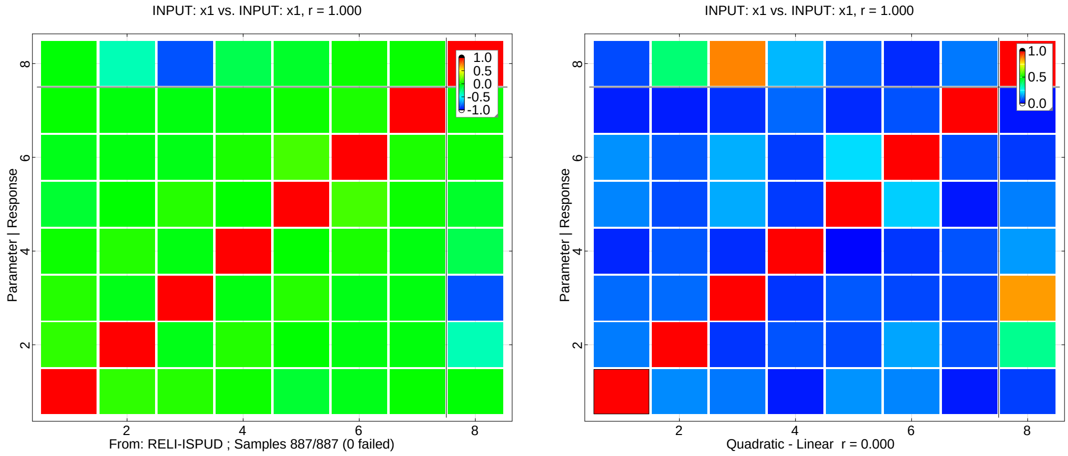

Figure 11: Linear and quadratic correlation coefficients for $v_0 = 240[\frac{km}{h}]$ and $u_0 = 20[\frac{m}{s}]$.

namic roll moment coefficient C_{roll} and the gust duration T, listed in the order of importance. The same result arises form the computation of the principal component vector. From figure 12 it can clearly be seen, that the amplitude and the roll moment coefficient have the highest

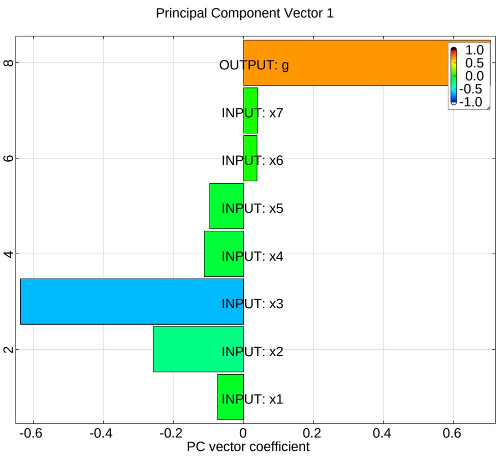

Figure 12: Principal component vector for $v_0 = 240[\frac{km}{h}]$ and $u_0 = 20[\frac{m}{s}]$.

impact. Based on these facts a model reduction could be applied and the unimportant variables could be neglected.

5.2.2 Design parameters

The scanned design parameters are:
the antiroll bar (antiroll), the secondary suspension damper (SS_Damper), the lateral damper (LD), the primary vertical damper (PVD), the primary suspension at the inner (PS_Cz_in) and outer position (PS_Cz_out) and the secondary suspension (SS_Cz). The mass of the carbody and the position of the center of mass which are known to contribute high impacts on the crosswind stability are not considered here because of their certain effects.
The influence of the design parameters has been investigated by means of a Design of Experiment. As for the excitation variables the linear and quadratic correlation coefficients and the principal components can be used to analyze the impact of the design parameters on the function $g(\underline{z})$. Unfortunately the effects of the design parameters are quite low and so only the principal

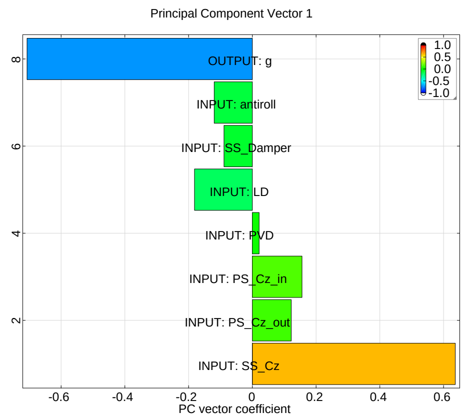

Figure 13: Principal component vector for the investigated design parameters.

component vector gives good results, (see figure 13). Very good insights into the functional dependencies give also the anthill plots of the design parameters. From these plots the designer

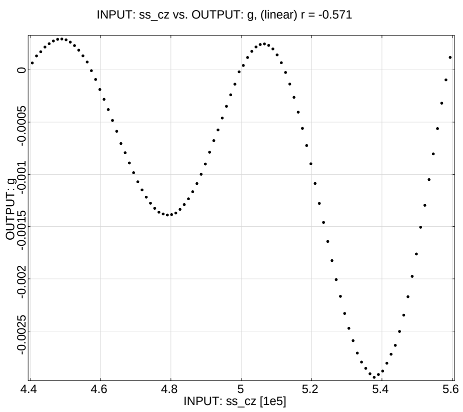

Figure 14: Anthill plot of function $g(\underline{z})$ versus the secondary suspension (SS_Cz).

immediately sees which parameter is worth to vary and which is not and so mistakes could be avoided.
Especially for the important secondary suspension parameter it is interesting to see its effect on the function $g(\underline{z})$ because this function is not monotone but oscillates, figure 14. This means,

that a simple increase or decrease of the secondary suspension parameter could lead to the opposite effect as wanted and so maybe the designer would misleadingly decrease the crosswind stability and not increase it. Here, using a local sensitivity method would have also lead to wrong results and only a global sensitivity analysis can give the complete overview over the system behavior.

6 Conclusion

In this paper a consistent stochastic approach to calculate the crosswind stability of railway vehicles, in which Probabilistic Characteristic Wind Curves (PCWC) have to be computed, is proposed. The stochastic variables in the system result from uncertainties in the wind excitation and from uncertainties in the aerodynamic coefficients of the vehicle. In this approach the crosswind stability is quantified by the probability of failure that a railway vehicle turns over. In a second step the influence of the stochastic variables and the influence of deterministic design parameters have been investigated by means of global sensitivity analyses.

The PCWC have been calculated by FORM approximations and by Monte Carlo simulations with variance reduction. The derived results have been showing a good agreement for higher mean wind velocities but have also been showing relative large errors for lower mean wind velocities.

The sensitivity analyses have been performed by means of latin hypercube sampling (LHS) and by subsequent calculations of linear and quadratic correlation coefficients and principal component values.

From the seven stochastic variables the most crucial variables have been extracted. The gust amplitude A, the aerodynamic roll moment coefficient C_{roll} and the gust duration T have been identified to be most important.

For the design parameters of the railway vehicle such clear results cannot be given. The influences of the considered parameters are, except for one exclusion, almost negligible. And the mentioned exception unfortunately has an oscillating functional dependency on the crosswind stability and can therefore not be used to optimize the railway vehicle.

Optimizing the railway vehicle with the goal to reduce the risk of overturning while operating in strong winds is a crucial issue as it directly leads to multi-criterion optimization. Not only the crosswind stability but other objective functions as for example comfort, costs and limited design space have to be considered. This is an issue which should definitely be investigated in future.

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