

# Reliability based analysis of the crosswind stability of railway vehicles

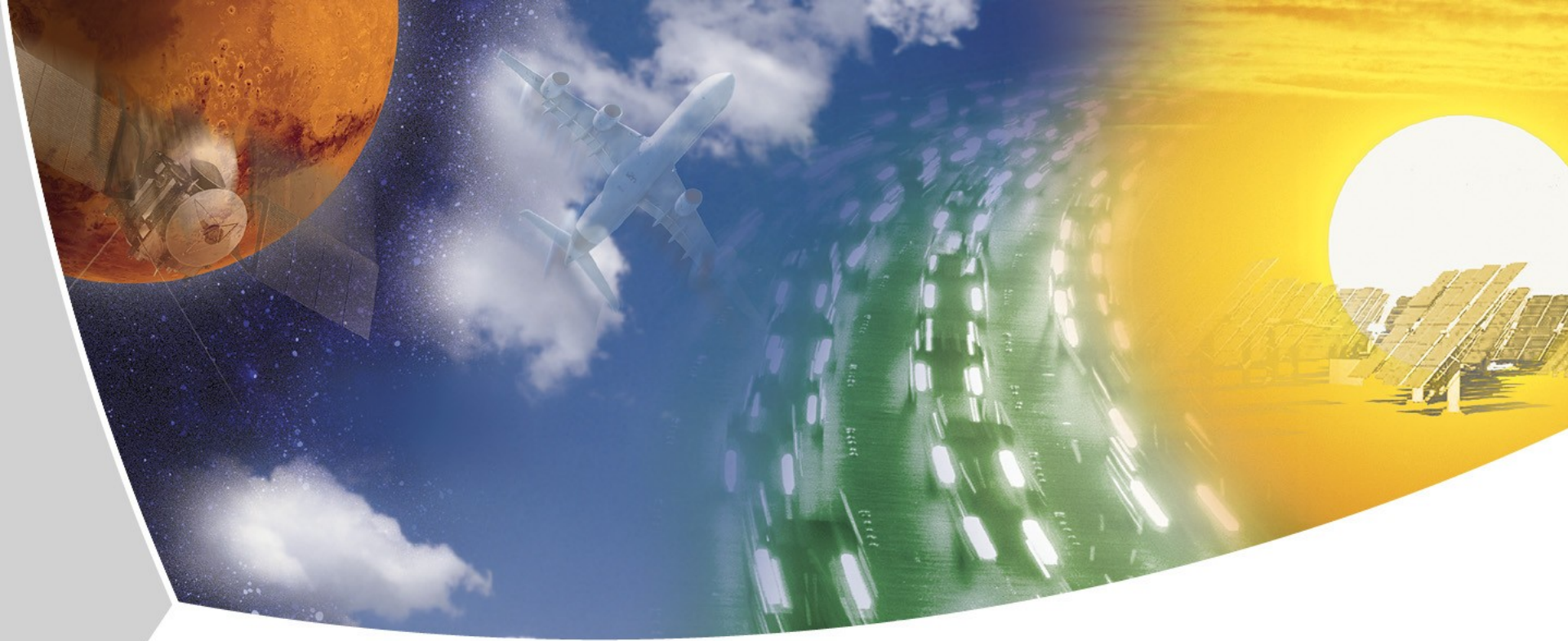
A. Carrarini

DLR (German Aerospace Center)  
Institute of Robotics and Mechatronics  
antonio.carrarini@dlr.de

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## Outline

- Introduction of the crosswind stability problem
- Simulation, parametric uncertainty
- Probabilistic Characteristic Wind Curve
- Reliability analysis
- Application and results

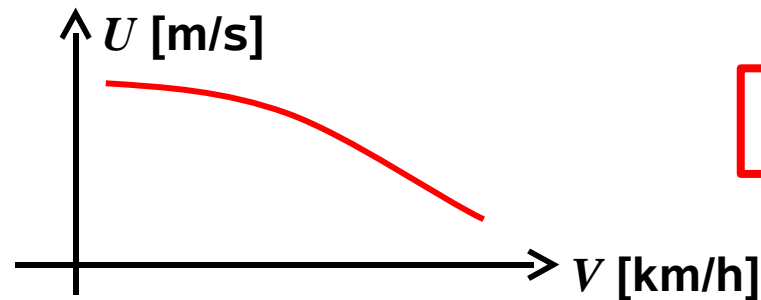


# Crosswind Stability

- Safe-life approach  
(based on returning period)
- Passive safety
- Countermeasures (always) needed:  
ballasting, fencing, etc.
- In Germany:
  - No anemometers
  - Many high speed driving trailers/motor coaches (e.g. ICE2, ICE3)
  - No accidents to date (but some in Austria)
  - Few storms but Föhn



# Characteristic Wind Curve



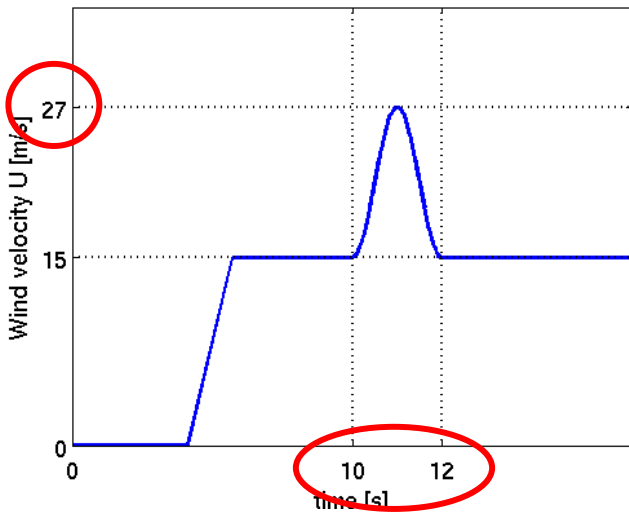
- $U$  is the mean wind velocity
- Overturning is checked by wheel unloading on the wind side:

$$Q_{lim} = 0.1 Q_0$$

- The CWC is computed by series of multibody simulations (fully virtual homologation)

# Simulation

## Unsteady wind

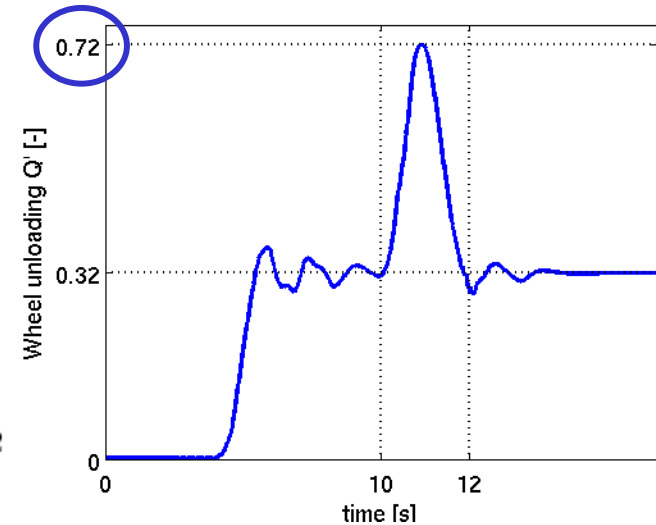


Vehicle (MBS)



$$F(\theta, t) = \frac{1}{2} \rho C(\theta) (U(t))^2$$

## Wheel unloading



Gust factor / duration ?  
Aerodynamic coefficients ?

# Probabilistic Characteristic Wind Curve

Uncertain/Variable Parameters  $\rightarrow$  Stochastic Variables  $X$

The wheel unloading  $Q = Q(U, V, X)$  is also a stochastic variable

$$\cancel{Q < Q_{lim}}$$

$$\Pr_X\{Q < Q_{lim}\} \doteq p_F(U, V)$$

$$U_{overt} = U_{overt}(p_F, V)$$

**Probabilistic** Characteristic Wind Curve (**P**CWC)

$$U_{overt} = U_{overt}(V)$$

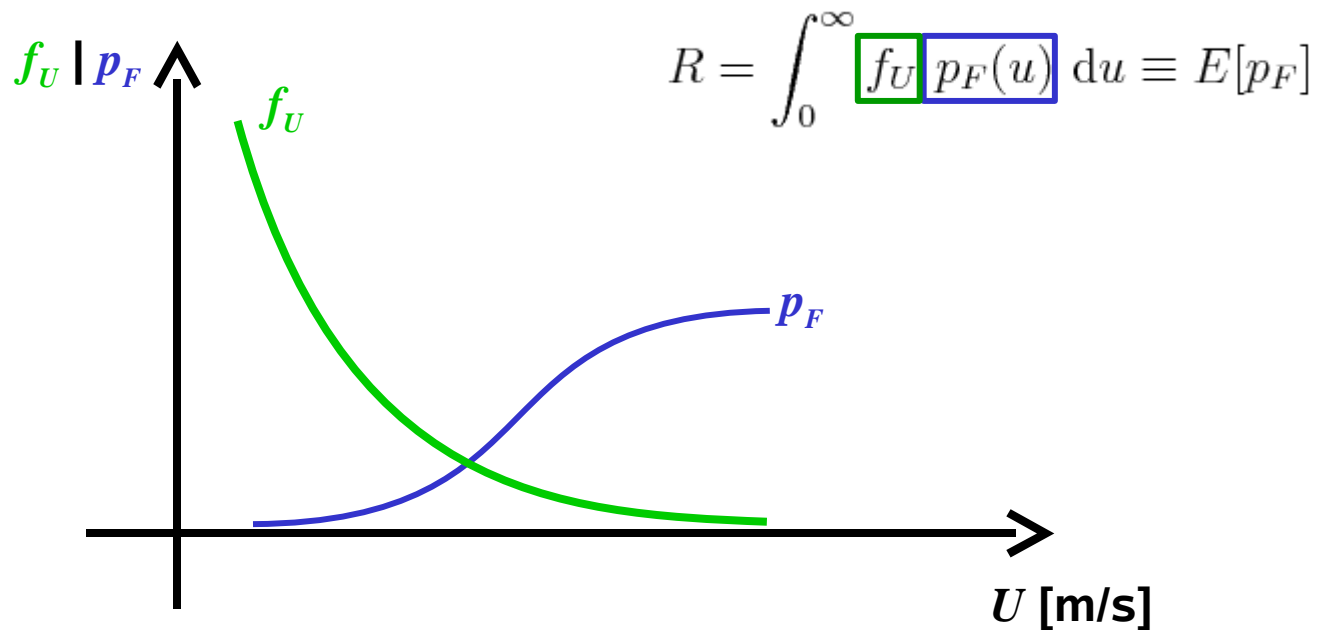
Characteristic Wind Curve (CWC)

# Risk evaluation

Consider the driving velocity  $V$  fixed :

➤  $p_F$  is given by the PCWC

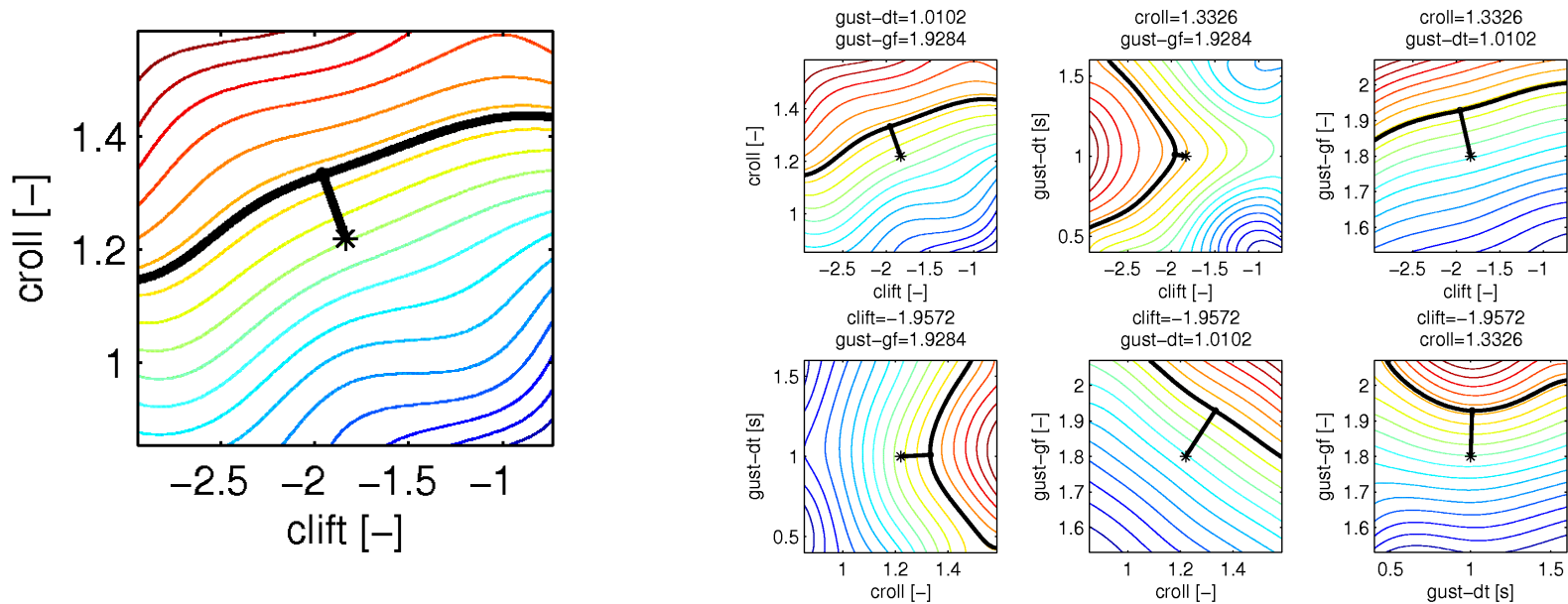
➤  $f_U$  (wind recurrence) is given by the weather service



# How to evaluate $\Pr_X\{Q < Q_{lim}\} \doteq p_F(U, V)$

## Semianalytical techniques

- Well established methods form structural mechanics
- Basic idea:  $Q = Q(U, V, X)$  is approximated (e.g. linearised → MPP)
- For non-gaussian and/or correlated  $X_i$ , further approximations are required
- Computationally a minimization task must be solved



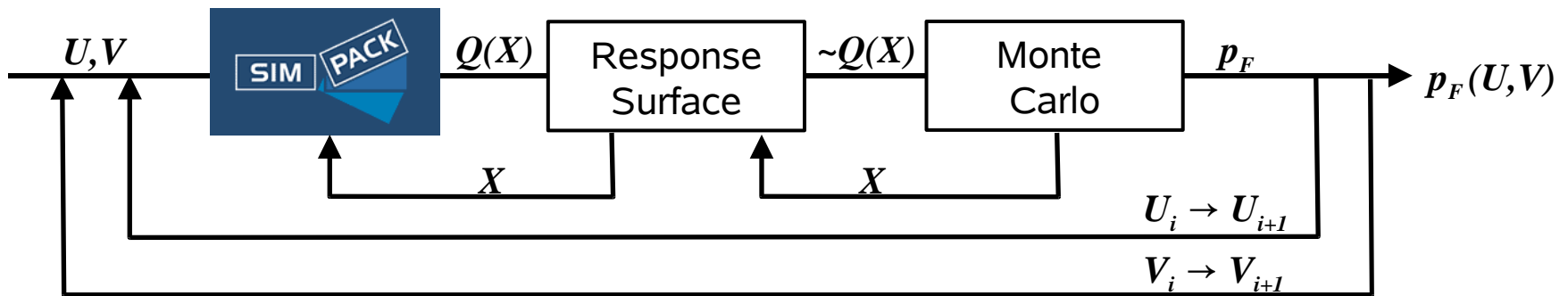
Isolines of  $Q(X)$  with  $U, V$  fixed. The thick line is  $Q = Q_{lim}$ .

# How to evaluate $\Pr_X\{Q < Q_{lim}\} \doteq p_F(U, V)$

## Sampling based techniques

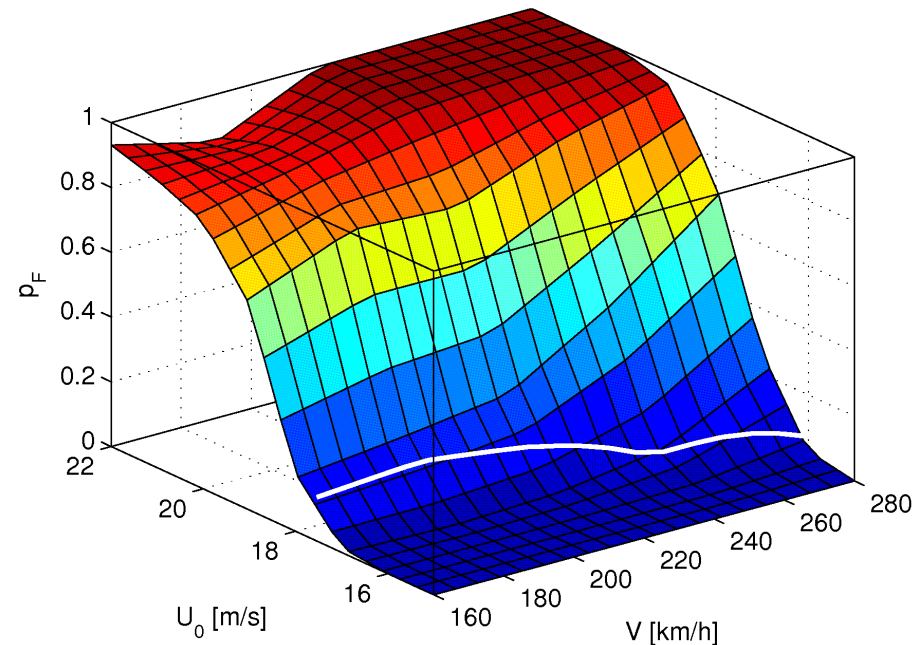
➤  $p_F$  can be also expressed (with  $U, V$  fixed) as  $p_F = \int_{\Omega_F} f_{\mathbf{X}}(\mathbf{x}) d\mathbf{x}$   
 where:  $\Omega_F = \{\mathbf{x} \in \mathbb{R}^n : Q(\mathbf{x}) > Q_L\}$

- But  $\Omega_F$  is only known implicitly by MBS ...
- “Hit or Miss” Monte Carlo + MBS can be used ☺
- But  $p_F \ll 1 \rightarrow$  a huge amount of samples is required ☹
- Importance Sampling etc. can be used ☺
- Anyway:  $Q=Q(X)$  has to be approximated by Response Surfaces



# Finally: the PCWC ( $\Pr_X\{Q < Q_{lim}\} \doteq p_F(U, V)$ )

- Many curves are needed: straight track, curved track with different cant deficiencies, embankment, bridge, etc.
- The PCWC is computed only once (the risk has to be evaluated for each track)
- Filtering of the  $Q$  time histories can have large influence on the results
- Less conservative results are obtained (if compared to the safety factor approach)



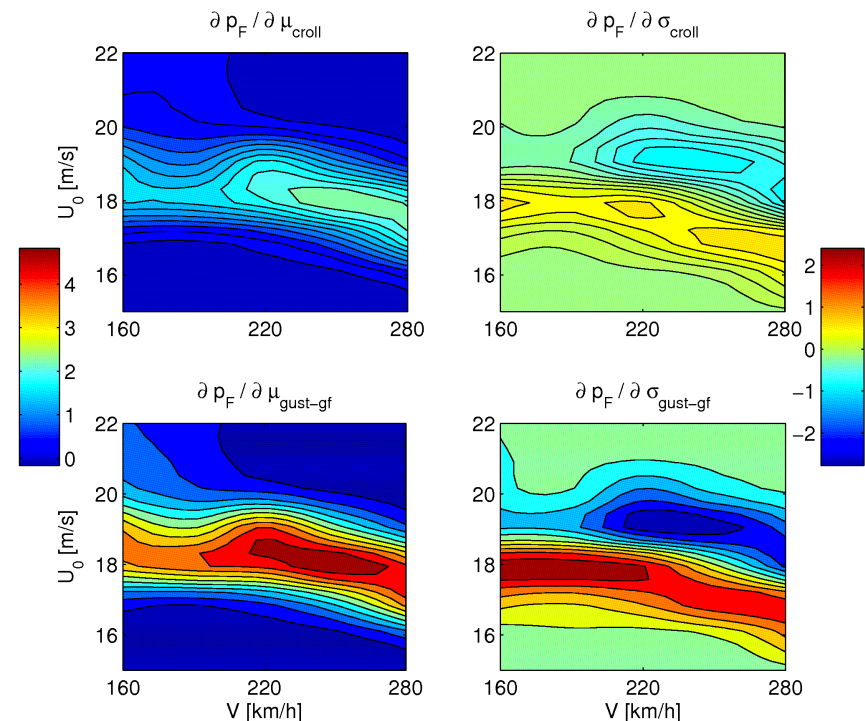
The white line is the conventional CWC

## Further topics

- Sensitivity : if  $U$ ,  $V$  are fixed,  $p_F$  is a function of the statistical properties of the parameters  $X$ , thus:

$$\partial p_F / \partial \mu, \partial p_F / \partial \sigma$$

- Optimization : constrains can / has to be expressed as a function of  $p_F$
- Linearization : SIMPACK can compute a linear model from the original MBS one. Real wind samples instead of ideal gust can be used (linear system analysis).



Sensitivities w.r.t. the aerodynamic roll moment coeff. and the gust factor



## Summary and Outlook

- The risk analysis for the crosswind stability of railway vehicles can be enhanced considering **parametric uncertainties**
- A framework based on the coupling of SIMPACK with **reliability analysis** techniques has been presented
- The computational **effort** is large and much statistical **input** is required but they can be suited to the desired accuracy
- The **statistical models** must be improved (e.g. statistical dependency between gust parameters and wind recurrence  $f_U$ )
- **Time dependent** reliability analysis (upcrossing frequency etc.) based on real wind samples and linearized MBS system could be used