Lateral Stability of High-Speed Trains at Unsteady Crosswind

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In memoriam
Christine Schneider
Preface

This thesis summarizes the work carried out during my licentiate studies at the Department of Aeronautical and Vehicle Engineering at the Royal Institute of Technology (KTH) in Stockholm, Sweden.

It is part of the research project "Crosswind Stability and Unsteady Aerodynamics in Vehicle Design" within the VINNOVA Centre of Excellence for ECO² Vehicle Design. The financial support from the centre is gratefully acknowledged.

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Very special thanks to my family in Germany and to my friends, mostly in Germany and Sweden, but now also more distributed around the world in Chile, the USA and Tanzania.

Stockholm, October 2009

Dirk Thomas
The Swedish Licentiate degree may need an explanation for readers outside of Sweden. An intermediate academic degree called Licentiate of Technology can be obtained halfway between an MSc and a PhD. The examination for this degree is less formal than for a PhD but it requires the completion of a thesis and a public seminar.
Abstract

Crosswind stability of rail vehicles has been a research area for several decades, mainly motivated by vehicle overturning accidents and higher speeds, but in recent times also by issues of lower energy consumption and track maintenance costs demanding lower vehicle weights. During everyday operation, rail vehicles are subjected to large lateral influences from track irregularities, track curves and crosswind, leading to large suspension deflections and increased crosswind sensitivity. Also unsteady crosswind like gusts calls for attention. Simulations of possible vehicle overturning are necessary, but need to take large deflections and high shear in the suspension into account. If delivering reasonable results, simulations represent an important tool for overturning prediction of the vehicle.

In the present work, multibody simulations of a high-speed vehicle at large lateral influences from track curves and track irregularities have been carried out, using a half-vehicle model in 2D and a model of a whole vehicle in 3D. The vehicle models also include different suspension models. Corresponding field measurements of the relative lateral and vertical deflections in the secondary suspension have been performed on a fast train and used for validation of the multibody simulations, resulting in good agreement between measurements and simulations.

The 3D vehicle model was further used to study the vehicle response to unsteady crosswind during curve negotiation where aerodynamic loads obtained by unsteady Computational Fluid Dynamics, namely Detached Eddy Simulations, representing three types of gusts were used. In addition, the method of Quasi Transient Gust Modelling was evaluated in terms of overturning risk. Strong lateral and roll responses of the vehicle and influences of the gust duration and the relative difference between mean and maximum wind speed were observed. Further, variations of suspension and mass properties of the vehicle were performed to study the influence on crosswind sensitivity. The position of the centre of mass of the carbody and the lateral bumpstop clearance showed significant influence on the crosswind stability.

Keywords: Rail vehicle dynamics, crosswind stability, overturning risk, multibody simulations, unsteady aerodynamics, CFD, field measurements, suspension modelling.
Outline of thesis

This thesis consists of an introduction to the area of research, a summary of the present work and the following two appended papers:

**Paper A**

Thomas D, Berg M and Stichel S:
*Measurements and simulations of rail vehicle dynamics with respect to overturning risk.*
Accepted for publication in Vehicle System Dynamics.

Planning of the measurements and simulations has been performed by Thomas and Berg. Simulations were carried out by Thomas. The paper was written by Thomas under the supervision of Berg and Stichel.

**Paper B**

Thomas D, Diedrichs B, Berg M and Stichel S:
*Dynamics of a high-speed rail vehicle negotiating curves at unsteady crosswind.*
Presented at 21st International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD’09), Stockholm, Sweden, 17-21 August 2009.
Submitted in extended and revised version for international journal publication.

Multibody simulations have been carried out by Thomas. Detached Eddy Simulations were performed by Diedrichs. Quasi Transient Gust Modelling calculations were done by Thomas and Diedrichs, using a code by Diedrichs. The paper was written by Thomas under discussion with Diedrichs and the supervision of Berg and Stichel.
Contribution of thesis

This thesis presents investigations on the lateral stability of high-speed trains due to large lateral influences from crosswind, track curves and track irregularities.

The thesis is believed to contribute to the present research field as follows:

- A literature survey [30] has been compiled concerning transient crosswind stability of vehicles, covering aerodynamics and vehicle dynamics aspects of crosswind stability of road and rail vehicles, as well as presenting modelling of gusts and risk assessments.

- The response of a high-speed rail vehicle to large lateral influences from track curves and track irregularities has been studied to investigate the possible overturning risk due to large lateral deflections in the secondary suspension. On-track measurements have been performed to validate the correctness of multibody simulations. A detailed model of the secondary suspension is included in the simulation model and shear spring effects are considered. The simulations show good agreement with the measurements.

- Using multibody simulations, a high-speed vehicle has been subjected to aerodynamic loads obtained from unsteady CFD at a curve negotiation. The investigation includes different gust types, the timing of the gusts and curve entry, as well as studies of the influence of mass and suspension properties on the crosswind sensitivity of the vehicle.

- The so-called Quasi Transient Gust Modelling (QTGM) presented in [24] has been evaluated in terms of overturning risk (wheel unloading).
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Paper A

Paper B
1 Introduction

Crosswind stability of rail vehicles has been a research topic during the last decades, mainly motivated by overturning accidents. Reports on crosswind accidents of rail vehicles in fact date back to the 19th century to the current decade [22]. Two examples of accidents of the current decade can be seen in Figure 1.1, showing the most common crosswind accident type for a rail vehicle, which is overturning about one of the rails. In comparison, crosswind accidents of road vehicles are mostly of a different kind, since an initial deviation from the direction of travel is most common. However, even overturning accidents of high lorries have occurred.

In recent times the motivation of studies of crosswind stability of rail vehicles has been extended. The operational speed of trains has increased, also leading to higher aerodynamic loads on the vehicle. Heavier vehicles could improve the crosswind stability but on the contrary issues like lower energy consumption demand lighter vehicles, which at the same time would lead to benefits regarding track deterioration and track maintenance. Furthermore, the traction layout of passenger trains, especially high-speed ones, is changing in recent years going from loco-trains to multiple units with distributed traction. Since the aerodynamic forces are most critical on the leading vehicle of a train, the weight change from a locomotive - as the leading and heaviest vehicle of a loco-train - to a vehicle of a multiple unit increases the demands on crosswind stability of trains. In addition, unsteady crosswind like various gusts is becoming a major concern.

Figure 1.1: Overturning accidents of rail vehicles, (a) on curved track at Uttendorf (Austria) in 2002, (b) on tangent track at Wasserauen (Switzerland) in 2007.
1. Introduction

The rail infrastructure is also important to take into account. Vehicles on narrow gauge lines usually run at lower operational speeds but the overturning stability is less compared to a normal gauge vehicle. Also bridges and embankments involve higher wind speeds due to the atmospheric boundary layer and the accelerated flow at the top of an embankment. In addition, tunnels can be an important factor since the wind speed at a tunnel exit can increase significantly from zero inside the tunnel to the actual wind speed in open field. Curveous railway lines can lead to large lateral suspension deflections of the vehicle in the curves, causing a deterioration of crosswind stability.

Also, a rail vehicle can be subjected to other unsteady wind phenomena in everyday operation, including gusts in open field, gust-like wind conditions due to changes in the housing density and vegetation near the track as well as by-passing vehicles.

Since crosswind stability represents a safety issue, detailed information about the behaviour of the vehicle at crosswind is desirable. However, field tests using a rail vehicle at overturning risk are not practicable due to safety and economic reasons. Therefore, simulations represent a necessary and important tool, but attention has to be paid to the correctness of the simulations at large suspension deflections, since a rail vehicle is a highly nonlinear system.

In the present thesis, the rail vehicle behaviour under large lateral influences from curves and track imperfections is studied by means of measurements and simulations and with respect to overturning risk. In particular, the vehicle response to unsteady crosswind during curve negotiation is investigated.

Chapter 2 gives an overview of lateral rail vehicle dynamics on tangent and curved track, without influence of crosswind. Fundamentals of vehicle aerodynamics in combination with crosswind are presented in Chapter 3. Then Chapter 4 combines the two previous chapters dealing with rail vehicle dynamics and overturning risk of a vehicle at unsteady crosswind. A summary of the present work, in particular the appended papers is given in Chapter 5. Finally, Chapter 6 draws conclusions on the work and proposes future work.


# Lateral stability of high-speed trains at unsteady crosswind

## 2 Lateral rail vehicle dynamics

### 2.1 Fundamentals

A rail vehicle often consists of a carbody supported by two running gears, and high-speed rail vehicles are designed as bogie vehicles. Figure 2.1 shows schematically the setup of a typical rail vehicle including the coordinate system of the carbody and associated motion components.

![Figure 2.1](image.png)

**Figure 2.1**: Side and top views of a bogie rail vehicle. Longitudinal motion $x$, lateral motion $y$, vertical motion $z$, roll motion $\varphi$, pitch motion $\chi$ and yaw motion $\psi$ [2].

The vehicle consists of a carbody supported by the two bogies through the secondary suspension. Each bogie consists of a frame and two wheelsets, connected by the primary suspension. Both the primary and secondary suspensions include spring and damper components. Examples are air springs, coil springs, rubber springs and hydraulic dampers. The type of components is dependent on the desired suspension characteristics. Furthermore, the suspensions include bumpstops, delimiting the suspension motions in vertical and lateral directions. The force transmission in longitudinal direction is usually achieved by traction rods (not shown in Figure 2.1). The secondary suspension is often also equipped with one anti-roll bar per bogie, counteracting roll motion of the carbody (not shown). In Sections 2.2 and 2.3, special emphasis is put on the lateral rail vehicle dynamics since lateral loadings and excitations are of concern in this thesis.
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A vehicle running on a railway track is subjected to lateral influences due to track irregularities. These irregularities represent deviations from the nominal track geometry. They influence the motions of the vehicle due to excitations of the wheelsets and have generally great impact on the wheel-rail forces and the ride comfort. A definition of different kinds of track irregularities is given by Figure 2.2. Lateral (line) and cant irregularities of long wavelength can cause low-frequency lateral and roll motions on the carbody, which may lead to decreased crosswind stability [2].

![Figure 2.2: Definition of track irregularities [2].](image)

2.2 Lateral dynamics on tangent track

On tangent (straight) track a vehicle is beside the track irregularities affected by lateral impacts due to the running behaviour of the vehicle itself. Vehicle ride instability can occur at high speed and in some cases this could also affect the vehicle ability to withstand crosswind.

The running surface of a railway wheel has a conical shape and for wheelsets with two wheels on a common axle this often leads to a laterally self-stabilizing behaviour of the wheelsets when running along the tangent track. But by looking at the middle of a free wheelset from above and following it along the track, one can recognize a sinusoidal lateral motion, see Figure 2.3. This phenomenon is called hunting and was first described in [35]. Thus, assuming an initial lateral displacement $y_0$ of the wheelset in the track, the lateral displacement $y(t)$ of the wheelset centre of gravity relative to the centre of the track can be expressed by

$$y(t) = y_0 \cdot \sin \omega t.$$  \hspace{1cm} (2.1)
Figure 2.3: Hunting motion of a free wheelset [2].

The wavelength $L_w$ of this sinusoidal motion depends on half the distance between the wheel contacts $b_0$, the nominal wheel radius $r_0$ and the so-called equivalent conicity $\lambda$, and can be described by

$$L_w = 2\pi \cdot \frac{v}{\omega} = 2\pi \cdot \sqrt{\frac{b_0 r_0}{\lambda}}, \quad (2.2)$$

which is known as Klingel’s formula. In this approximation, the wavelength is thus considered independent of the speed $v$. Note that this formula applies to a free wheelset. For wheelsets contained in bogie frames, the influences of the suspension and wheel-rail friction forces result in an increasing wavelength for increasing speed.

Now looking at a single bogie and assuming a zero relative motion of the bogie frame, the running stability is depending on the primary suspension properties and represents an eigenvalue problem of a linearized model. The characteristic equation obtained from the equations of motion of the problem, usually contains one conjugated complex solution per degree of freedom. On the basis of the obtained solutions root locus plots can show the critical running speed of the bogie. A horizontally stiffer primary suspension leads to higher critical speeds. However, the steering capability of the wheelsets in curves becomes limited at the same time, carrying other problems along like increased lateral wheel-rail forces, see Section 2.3.

Since rail vehicles are nonlinear systems due to the suspension systems, wheel-rail contacts and the equivalent conicity as function of the lateral wheelset displacement, other effects come into play which are not present for a linear system. This can result in several stable solutions for the same system under the same conditions. The stability limit for the nonlinear system is reached for the lowest speed where a periodic solution, i.e. a constant amplitude oscillation, can occur (cf. $v_{\text{crit, nonlinear}}$ in Figure 2.4). An example of a limit cycle diagram for hunting of a wheelset in
2. Lateral rail vehicle dynamics

a bogie frame is given in Figure 2.4, showing the lateral hunting amplitude $y_0$ as function of the vehicle speed $v$.

![Figure 2.4: Limit cycle diagram of lateral wheelset amplitude $y_0$ as function of vehicle speed $v$ [2].](image)

Beside the suspension properties, the wheelset-track equivalent conicity and the different masses of a vehicle influence its ride stability. However, it may be hard to find an optimum case since the different properties often counteract each other. In the literature often two different periodic lateral motion phenomena causing instability are referred to: high-frequent or wheelset/bogie instability, and low-frequent or carbody instability [2, 33, 36]. High-frequent instability usually occurs in combination with high equivalent conicity at running speeds above 100 km/h at frequencies between 4 and 10 Hz. Low-frequent instability on the other hand also occurs at running speeds above 100 km/h but at frequencies between 1 and 2 Hz and low equivalent conicity. It is a resonance phenomenon and can be observed if a low hunting frequency of a wheelset coincides with a natural frequency of the vehicle.

On tangent track, crosswind usually leads to less vehicle overturning risk as compared to curved track. However, an interaction between carbody ride instability and a crosswind gust may influence the vehicle. Further information about lateral rail vehicle dynamics on tangent track is, for example, given in [2, 33, 36], where detailed explanations about lateral stability of different kinds of bogies and bogie vehicles are given in [36].

2.3 Lateral dynamics at curving

The steering capability of a wheelset described in Section 2.2 also exists on horizontally curved tracks. Looking at a simple wheelset in a curve, see Figure 2.5, the
wheelset will be displaced laterally outwards to achieve a ratio of the outer to inner rolling radii, $r_{out}$ to $r_{in}$, close to the longitudinal travel distance ratio for the outer to inner rails. For perfect radial steering, that is if the wheel axle points towards the centre of the curve, the geometric conditions can thus be written as

$$\frac{r_{out}}{r_{in}} = \frac{R + b_0}{R - b_0},$$

(2.3)

where $R$ is the curve radius. For conical wheels the rolling radii $r_{out}$ and $r_{in}$ can be written as

$$r_{out} = r_0 + \lambda_0 y$$

(2.4a)

$$r_{in} = r_0 - \lambda_0 y$$

(2.4b)

with the nominal rolling radius $r_0$ and the wheel conicity $\lambda_0$. The lateral displacement of the wheelset that is needed for perfect steering is thus

$$y = \frac{r_0 b_0}{\lambda_0 R}$$

(2.5)

Note that Equations 2.3 - 2.5 represent a simplification and neglect friction forces on the wheelset. Ride instability is a minor problem on curved track compared to tangent track. However, carbody instability can occur in curves with large radii. More detailed explanations of curve steering of wheelsets, bogies and vehicles can be found among others in [2, 36].

A rail vehicle negotiating a horizontal track curve is beside track irregularities and
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Figure 2.6: Rear view of rail vehicle carbody at curving, (a) lateral acceleration in horizontal plane, (b) lateral acceleration in track plane [2].

the curve steering subjected to additional lateral influences. Figure 2.6 shows the rear view of the carbody of a rail vehicle at a curving situation. The vehicle at quasi-static curving condition, running at speed $v$ through a curve with radius $R$, is subjected to the centrifugal acceleration $v^2/R$ and the gravity $g$, see Figure 2.6a. Using the ”resulting” acceleration, a transformation into the canted track plane can be made giving the lateral acceleration in the track plane $a_y$ and the vertical acceleration perpendicular to track plane $a_z$, see Figure 2.6b. With the track cant angle $\varphi_t$, the corresponding quasi-static lateral acceleration in the track plane can be expressed as

$$a_y = \frac{v^2}{R} \cdot \cos \varphi_t - g \cdot \sin \varphi_t = \frac{v^2}{R} \cdot \cos \varphi_t - g \cdot \frac{h_t}{2b_0} \tag{2.6}$$

where $h_t$ is the track cant and $b_0$ again half the nominal distance between the wheel-rail contact points of a wheelset. For, say, $v^2/R \leq 0.3$ and small cant angles, Equation 2.6 can be approximated by

$$a_y \approx \frac{v^2}{R} - g \cdot \sin \varphi_t = \frac{v^2}{R} - g \cdot \frac{h_t}{2b_0} \tag{2.7}$$

The track cant that leads to a zero lateral track plane acceleration at a given speed $v$ and curve radius $R$, is called the equilibrium cant $h_{eq}$, cf. Figure 2.7b. It can be expressed as

$$h_{eq} \approx \frac{2b_0}{g} \cdot \frac{v^2}{R}. \tag{2.8}$$
If the cant $h_t$ is less than $h_{eq}$ we get a cant deficiency $h_d$, cf. Figure 2.7a and c,

$$h_d = h_{eq} - h_t \approx \frac{2b_0}{g} \cdot \frac{v^2}{R} - h_t \approx \frac{2b_0}{g} \cdot a_y.$$  \hspace{1cm} (2.9)

\textbf{Figure 2.7:} Rear view of rail vehicle at right-hand curving, (a) no cant but cant deficiency, (b) equilibrium cant, (c) cant and cant deficiency [2].

The roll $\phi_c$ of the carbody relative to the track, see for example Figure 2.7a and c, is also influenced by the vehicle suspension and mass properties. Using the ratio of the carbody roll angle $\phi_c$ to the track cant angle $\phi_t$ at stand-still in a curve, one can define the dimensionless vehicle coefficient of flexibility

$$C_{\phi} = \frac{\phi_c, v=0}{\phi_t}.$$ \hspace{1cm} (2.10)

The roll of an air spring-supported carbody during curve negotiation is shown in Figure 2.8. The relation is nonlinear and simplified using straight lines. The breakpoints for inflated air springs originate from bumpstop contacts in primary and secondary suspensions. For deflated air springs, the carbody is supported by rubber auxiliary springs which are included in the air springs. The auxiliary springs may restrict the suspension lateral movement and yield thus less roll motion of the carbody, and for low cant deficiency/excess, a hysteresis can be observed due to characteristics of the spring.

In the case of cant deficiency, the outer wheels experience higher wheel-rail forces in both lateral and vertical directions, see Figure 2.9. As implied above the distribution of the vertical wheel-rail forces within a wheelset depends also on the suspension deflections and carbody mass properties. The decrease of the vertical
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**Figure 2.8:** Example of roll angle of a carbody suspended by air springs for cant deficiency and cant excess. Positive carbody roll represents roll towards the outside of the curve. After [33].

**Figure 2.9:** Wheel-rail forces during curve negotiation at cant deficiency. Lateral force $Y$, vertical force $Q$. Outer and inner wheels/rails. $Q_{in} < Q_0 < Q_{out}$, where $Q_0$ is the nominal vertical wheel load. The outer wheel-rail contact is close to the wheel flange. If the inner wheel-rail contact is lost the vehicle may overturn about the outer rail [2].
wheel-rail force on the (inner) wheel/rail is often called wheel-unloading. The appearance of crosswind can lead to even lower vertical wheel-rail forces, thus a higher wheel-unloading on the windward wheel/rail. Wheel-unloading can be used as a criterion for vehicle overturning, see Section 4.1.

The lateral track plane acceleration and thus the cant deficiency should be limited due to risk of ride discomfort and lateral track shift. A limit speed can be found using Equation 2.7, thus

\[ v_{\text{lim}} = \sqrt{R(a_{y,\text{lim}} + \frac{g h_t}{2 b_0})} = \sqrt{R(h_{d,\text{lim}} + h_t) \frac{g}{2 b_0}}. \]  

(2.11)

This speed may be further reduced due to strong crosswind.

2.4 Air springs and bumpstops

Air springs have become common suspension elements in the secondary suspension of high-speed rail vehicles, since they offer good ride comfort and their dynamic behaviour is almost independent of the vertical preload of the carbody. Beside the vertical direction, air springs transfer forces in longitudinal and lateral directions. Due to shear, also moments are transferred through the spring. Air springs represent highly non-linear components with hysteresis characteristics. A schematic view of a railway air spring is given in Figure 2.10. The air springs can be mounted using two-point, three-point or four-point mounting. At two-point mounting, the air volumes of both air springs on one bogie are connected to each other, whereas four-point mounting involves four independent air springs on a vehicle. For three-point mounting the air springs are independent only on one bogie. Two-point mounting can be of advantage regarding levelling and roll motion control. It is also used as a simple tilting mechanism [2].


At high cant deficiencies, the vehicle normally reacts with large lateral suspension deflections, in particular in the secondary suspension, and lateral displacement of
2. Lateral rail vehicle dynamics

the carbody relative to the centre of the track. The carbody is also usually rolling towards the outside of the curve, cf. Figure 2.7. In this case the secondary suspension experiences substantial lateral shear, and its behaviour at large deflections becomes of special interest. The lateral deflection is eventually delimited by bumper-stops, cf. Figure 2.11, which also introduce further nonlinear characteristics to the suspension.

![Diagram of carbody, air springs, and bumper-stops](image)

**Figure 2.11:** Secondary suspension deflection on a rail vehicle at high cant deficiency.

The modelling of air springs has been the topic for several studies [12, 32, 38, 42]. From these models one can distinguish two kinds of models, where either the thermodynamic properties of the springs are considered [32, 38, 42] or a mechanical model is established [12]. The difference between the thermodynamic models is found in the modelling of the air flow between the bellow and the auxiliary volume. The flow is either assumed being a constant mass in dynamic motion [32] or a mass flow [38, 42]. The model presented in [42] just considers the vertical direction of motion. In [32,38] the spring lateral characteristics are represented and modelled as linear springs [38] or as a linear spring-damper combination which is connected in parallel [32]. In both models the vertical and lateral characteristics are independent from each other and the lateral forces are derived from the lateral deflection and deflection velocity. The mechanical air spring model presented in [12] considers the lateral characteristics in three parts with elastic, viscous and friction contributions. Here the elastic part also depends on roll rotation/moment between the upper and lower part of the spring.

Different air spring models have been compared in [28].
3 Vehicle aerodynamics and crosswind

3.1 Vehicle aerodynamics

When an object, e.g. a vehicle, is moving in a fluid, e.g. air, the vehicle interacts with the fluid due to its shape and surface. Assuming a control volume around the vehicle, the law of conservation of mass applies, and thus changes in the curvature of the vehicle surface lead to local changes in the flow velocity and the flow pressure. For a non-viscous and incompressible flow the relation is given by Bernoulli’s equation,

\[ p + \frac{\rho}{2} u^2 = \text{const}, \]  

(3.1)

where \( p \) is the static pressure, \( \rho \) the fluid density and \( u \) the flow velocity along a streamline [11,31,44]. The term \( \frac{\rho}{2} u^2 = q \) (3.2)

represents the dynamic pressure \( q \). Due to the flow pressure and the local pressure changes, forces and moments are acting on the vehicle. Figure 3.1 defines the loads using the example of a train. The loads depend on the shape of the vehicle and can

![Aerodynamic forces and moments acting on a train. Drag force \( F_{\text{Drag}} \), side force \( F_{\text{Side}} \), lift force \( F_{\text{Lift}} \), roll moment \( M_{\text{Roll}} \), pitch moment \( M_{\text{Pitch}} \) and yaw moment \( M_{\text{Yaw}} \) [23].](image)

**Figure 3.1:** Aerodynamic forces and moments acting on a train. Drag force \( F_{\text{Drag}} \), side force \( F_{\text{Side}} \), lift force \( F_{\text{Lift}} \), roll moment \( M_{\text{Roll}} \), pitch moment \( M_{\text{Pitch}} \) and yaw moment \( M_{\text{Yaw}} \) [23].
3. Vehicle aerodynamics and crosswind

be expressed as

\[ F_{\text{Drag}} = q \cdot A_t \cdot C_{\text{Drag}} \]  (3.3a)
\[ F_{\text{Side}} = q \cdot A_t \cdot C_{\text{Side}} \]  (3.3b)
\[ F_{\text{Lift}} = q \cdot A_t \cdot C_{\text{Lift}} \]  (3.3c)
\[ M_{\text{Roll}} = q \cdot A_t \cdot l_t \cdot C_{\text{Roll}} \]  (3.3d)
\[ M_{\text{Pitch}} = q \cdot A_t \cdot l_t \cdot C_{\text{Pitch}} \]  (3.3e)
\[ M_{\text{Yaw}} = q \cdot A_t \cdot l_t \cdot C_{\text{Yaw}} \]  (3.3f)

where \( A_t \) is a reference area, \( l_t \) a reference length and \( C \) the aerodynamic coefficients. Several reference areas and length dimensions are used depending on the vehicle. For rail vehicles in Europe, the standard EN 14067-1 applies [17]. For trains, the reference frame for the loads shown in Figure 3.1 is often located at half the bogie distance between the two bogies of the first car and on top of rail level [23]. For road vehicles, a reference frame located at half the axle distance after the first axle is often used [34].

The dimensionless aerodynamic coefficients \( C \) in Equations 3.3a - 3.3f are mainly dependent on the vehicle shape and give information about the aerodynamic characteristics of the vehicle regardless of its size or speed. The coefficients are obtained by either wind tunnel experiments or Computational Fluid Dynamics (CFD). In both cases a vehicle model is standing still and the fluid flows against the model. However, CFD using moving vehicle models has been presented recently [37]. For CFD there are four main modelling technologies available:

- **Direct Numerical Simulations (DNS)** resolve the governing Navier-Stokes equations directly, why this method is very time consuming and mostly applied in research. Due to the required computational effort, DNS cannot be used for crosswind calculations today.

- **Large Eddy Simulations (LES)** resolve the larger turbulence scales by the computational mesh. Smaller, energy dissipating scales, that are unresolved, have to be modelled. Concerning crosswind calculations of trains including high Reynolds numbers, LES also need high computational effort, why LES are not used in industrial context.

- **Detached Eddy Simulations (DES)** represent a relatively new methodology and is a mixture of LES and RANS [43]. It uses LES away from solid walls and applies RANS close to walls. Both LES and DES are methods for unsteady flow calculations [23].

- **The methodology of Reynolds Average Navier Stokes (RANS)** estimates the turbulent flow by a time average and variance of the flow fields, where for the time average \( t \to \infty \) leads to time independent RANS. In addition, turbulence models have to be introduced. RANS often delivers feasible steady-state
solutions for engineering applications. If one separates the time scales for the mean flow and the turbulence, one can instead of the time average $t \rightarrow \infty$ choose a sufficiently long integral time for the turbulence fluctuations to average out. This approach is referred to as Unsteady Reynolds Average Navier Stokes (URANS) [23].

An overview of computational methods in combination with crosswind stability of rail vehicles is given in [22].

### 3.2 Crosswind

For road and rail vehicles in crosswind, the pressure distribution and thus the aerodynamic forces and moments are dependent on several variables that originate from the vehicle and the wind properties. These are the reference area $A_t$, the reference height $h$ and the vehicle speed $v$ (concerning the vehicle properties), the air density $\rho$ and viscosity $\nu$ as well as the wind speed $v_w$, the wind angle relative to the vehicle travel direction $\beta^*$, the turbulence length scale and the standard deviation of the wind speed (concerning the wind properties) [4, 23]. Figure 3.2 shows the connection between the vehicle speed $v$, the wind speed $v_w$ including its yaw angle relative to the track $\beta^*$, as well as the resultant wind speed $v_r$ and its yaw angle $\beta$ using the example of a train.

![Figure 3.2: Wind situation and notation of velocity vectors for a train subjected to crosswind. Top view [23].](image)

Due to ground surface roughness, the vertical wind speed profile is in reality not constant because of the formation of a boundary layer. The vertical wind speed profile and the resultant wind velocity vectors for a crosswind situation is explained in Figure 3.3. However, in spite of the boundary layer effect, also constant vertical velocity profiles are used for train certification [29].

Environmental and infrastructure characteristics also influence the crosswind situation. Changes in the vegetation can lead to suddenly increasing wind speeds [31]. This effect on the resulting responses of a bus has been studied in [34]. Embankments and bridges lead to higher flow velocities due to flow acceleration at an embankment and the atmospheric boundary layer [8,31]. The crosswind stability
3. Vehicle aerodynamics and crosswind

Figure 3.3: Wind velocity profile and resultant wind velocity vectors for a moving car in crosswind [11].

of a (high-speed) train on an embankment was investigated in [26, 45].

Due to the atmospheric boundary layer and the resulting wind speed, wind tunnel tests for crosswind situations should be made using a moving model [4], performed, for example, like in [7, 15, 19]. However, also open field measurements of aerodynamic loads were performed and compared to wind tunnel tests by [10], resulting in good agreement, but showing a discrepancy for the lift coefficient caused by local roughness effects in the wind tunnel tests. A review on ground vehicles in crosswind is given in [4–6], considering both steady and unsteady aerodynamic loads as well as the interaction of the aerodynamic loads and the vehicle suspension system. A recent state-of-the-art review on crosswind stability, mainly from aerodynamics point of view, is given in [9].

Gust modelling

The modelling of gusts can be divided in two approaches. In the first one an ideal gust is represented, where the gust model is of deterministic nature. In the literature and among standards a few examples can be found. Overviews can be found, for example, in [16, 30]. The most common shapes can be distinguished into the following:

- The exponential or mean gust, which was described by [39]. Its characteristics is an exponential shape. The gust is used within [29].
- The 1 – cos shape, which is often also called "Rugby-ball". The gust is very often used within aeronautics.
The step function. The shape is usually used due to its simple mathematical properties.

- The ramp function. The shape was used, for example, in [40].

Figure 3.4 shows the time histories of the deterministic gust shapes named above for an impulse or a step function. Within [20, 29], the time history of the exponential gust of impulse-type and steady-state aerodynamic loads are used to directly derive the aerodynamic loads seen by a vehicle. A smooth $1 - \cos$ shape that should approximate unsteady aerodynamic loads on a vehicle, and steady-state loads were used in [16].

The second possibility of gust modelling is a stochastic approach. The wind is described by its Power Spectrum Density, for instance a von Karman PSD, and the analysis is performed in the frequency domain. The PSD is used together with a time series to describe a stochastic wind field in one dimension for the whole frequency domain [30].

Beside the possibility of CFD discussed in Section 3.1, the aerodynamic loads seen by the vehicle for deterministic and stochastic gusts can be calculated using the so-called aerodynamic admittance [5]. The approach considers in frequency domain the influence of the unsteady flow on the aerodynamic loads seen by the vehicle.

A combination of a deterministic and a stochastic approach has been made by [13, 14], where a deterministic gust is superposed by a turbulent content. This method was used within [41].
4 Rail vehicle dynamics and overturning risk at unsteady crosswind

The failure of rail vehicles subjected to crosswind mostly occurs in terms of vehicle overturning about one of the rails, primarily about the outer rails in curves, cf. Figure 2.9 [2].

4.1 Overturning risk

Several methods and criteria exist to describe the overturning of a rail vehicle, at steady or unsteady crosswind, and have been used in various studies and in standards. Four methods are described here to give a short overview, without claiming completeness.

Wheel unloading

The wheel unloading \((Q_0 - Q)/Q_0\), cf. Figure 2.9, is an accepted quantity to predict the overturning risk of a rail vehicle. This method is used in several studies, for example [16, 48, 49], as well as national and international standards [20, 29]. The wheel unloading is evaluated for the windward wheels and may not exceed a certain percentage of the static force. This percentage is often set to 90\%, thus

\[
\frac{Q_0 - Q}{Q_0} \leq 0.9.
\]

The quotient is often low-pass filtered with 2 Hz or 1.5 Hz [20, 29, 40], motivated by the low-frequency nature of the overturning process, and thus mainly neglecting the influence of the track irregularities. The choice of a rather low cut-off frequency of the filtering can be discussed though. Still there are also standards that completely neglect the effects of track irregularities [29].

It is also possible to take a whole bogie into account by calculating the mean unloading value for the inner wheels of the wheelsets of one bogie [20, 29]. The wheel unloading method can be used both in field measurements and simulations.

Moment method

The moment method calculates moments about the leeward/outer rail. The method requires the aerodynamic loads on the vehicle and compares the stabilizing moment due to the gravity forces of the vehicle with the overturning moment due to the
4. Rail vehicle dynamics and overturning risk at unsteady crosswind aerodynamic and centrifugal loads. If these moments are equal, the vehicle starts to overturn. Usually the method does not take dynamic effects from track irregularities into account. However, Andersson et al. [2] describe a moment method considering dynamic lateral track input. Due to the input requirement of aerodynamic loads, this method can be applied for simulations only.

**Intercept method**

The intercept method uses the vertical and (indirectly) the lateral wheel-rail forces to calculate an overturning risk of the vehicle. The resultant force of the wheel-rail forces is calculated and its point of attack in the track plane, $b_t$, relative to the track centre is compared to half the distance of the wheel-rail contact points on one wheelset, $b_0$, see Figure 4.1.

![Figure 4.1: Definition of quantities for calculation of overturning risk with the intercept method. $l = \text{left}, r = \text{right}$ [2].](image)

The quotient of these values is used as a safety measure:

$$n_{R,\text{int}} = \frac{b_t}{b_0} = \frac{\sum_{\text{bogie}} |Q_l - Q_r|}{\sum_{\text{bogie}} (Q_l + Q_r)}$$

(4.2)

A value between 0.8 and 1 is usually used as limit [40]. Also low-pass filtering with 1.5 Hz is usually applied [2]. The intercept method is possible to use in both field measurements and simulations. For detailed information, see for example [2].
Simulation of real overturning

Another possibility to assess overturning risk is to simulate a vehicle that actually is overturning. Then the simulation model must be able to handle loss of wheel-rail contact, usually at the inner rail in curves, and large vehicle motions at the overturning.

4.2 Modelling and simulation of crosswind stability

The modelling and simulation of crosswind stability from a rail vehicle dynamics point of view has been a research topic in some studies, mostly leading to a risk assessment, for example [3, 16], and also some standards take the rail vehicle dynamics into account [18, 20, 29].

Usually the crosswind stability of a rail vehicle is investigated by applying aerodynamic loads on a vehicle model within dynamic multibody simulations. However, also simpler approaches using quasi-static models have been used [25]. Concerning the aerodynamic loads, it can be distinguished between just temporal gusts and spatio-temporal gusts. The former considers aerodynamic coefficients obtained by wind-tunnel tests or steady-state CFD in combination with a time series of a deterministic gust shape. This is used in [20, 29]. A spatio-temporal gust includes effects of varying aerodynamic loads in space and also in time due the moving vehicle.

The wind scenarios used for the multibody simulations can represent either deterministic gust models or measured transient wind loads. Several deterministic gusts have been proposed, either with a meteorological background or as simpler approaches to study vehicle reactions, see for example [16, 21, 24, 29, 40, 47]. A deterministic gust in combination with superposed turbulent fluctuations has been used by [41, 49]. In recent time unsteady CFD have been used to obtain aerodynamic loads on a vehicle from gusts, cf. Chapter 3. Examples are [24, 37]. The results from [24] have been used in [47] to study the response of a high-speed rail vehicle to unsteady crosswind, including a comparison of a spatio-temporal and a just temporal gust using the TSI gust shape.

For a risk assessment the simulation results are often shown as Characteristic Wind Curves (CWC) of the vehicle, showing, for example, the critical wind speed for a rail vehicle for different cant deficiencies and vehicle speeds, cf. Figure 4.2. The risk evaluation is then made by comparing the results to predefined conditions. Examples of such conditions found in the literature are a number of possible overturning accidents on a certain track segment [3], or a comparison to other vehicles that are known to be safe [20, 29, 46].
4. Rail vehicle dynamics and overturning risk at unsteady crosswind

![Figure 4.2: Characteristic wind curve for a proposed high-speed train [2].](image)

Other approaches of risk assessment calculate the failure probability of the vehicle due to crosswind by taking simulation inputs such as the aerodynamic loads as stochastic and uncertain. By applying reliability methods like the Monte Carlo analysis a failure probability for the vehicle can be calculated [16, 27, 49]. A sensitivity analysis regarding the aerodynamic coefficients of the vehicle as well as the gust amplitude and duration is included in [49].
5 The present work

Rail vehicles can thus experience strong lateral influences during everyday operation caused by curve negotiation, track imperfections and crosswind. This normally results in large suspension deflections and carbody displacements, which makes the vehicle even more sensitive to crosswind. Concerning crosswind stability, simulations for the prediction of a possible overturning risk are desirable, but this requires knowledge of the lateral vehicle dynamics at large suspension deflections, in particular in the secondary suspension. The modelling of the latter is important to achieve feasible simulation results at large shear in the suspension. If the simulations yield reasonable results, they represent an important tool for the prediction of vehicle overturning.

The present work investigates the lateral dynamics of a high-speed rail vehicle due to large lateral influences and at large suspension deflections by means of multibody simulations validated by field measurements. Multibody simulations are then used to study the vehicle response to unsteady crosswind. The work is described in two appended papers, but also summarized below.

5.1 Summary of Paper A

Paper A presents field measurements and multibody simulations of the lateral dynamics of a high-speed rail vehicle at large secondary suspension deflections due to track curves and track irregularities. In this way curve negotiation at different cant deficiencies were studied. The simulations were performed using a half-vehicle model in 2D and a model of a whole vehicle in 3D, both models containing different models of the secondary air spring suspension. The simulations showed good agreement with the measurements concerning relative carbody-bogie lateral displacement evaluated at a level of about 0.5 m above top of rail. At high levels of cant deficiency, the relative roll angle between carbody and bogie frame was overestimated by the simulations due to levelling effects of the air springs. The lack of friction in the air spring model of the 2D-model resulted in higher relative displacements compared to the 3D-model. The 3D simulation results were also compared to an unsteady crosswind case with respect to overturning risk by means of the wheel unloading measure.
5. The present work

5.2 Summary of Paper B

The response of a high-speed vehicle to unsteady crosswind during curve negotiation is studied in Paper B. Using multibody simulations, three different gusts are applied to a vehicle model. The gusts are of deterministic kind and consist of a self-created simple artificial gust, the so-called Chinese hat prescribed in the Technical Specification for Interoperability (TSI) [29], and a crosswind case at a tunnel exit. The aerodynamic loads are obtained from unsteady DES and the so-called QTGM approach, resulting in spatio-temporal gusts that include aerodynamic effects in space and time due to the varying flow along the track and the moving vehicle. The simple artificial gust is used to perform studies on the vehicle response due to different gust properties as well as for parameter variations on suspension and mass properties of the vehicle.

The vehicle showed strong lateral and roll reactions to the different gusts, and an influence of the gust duration and the relative difference between mean wind speed and maximum wind speed was observed. A variation of the ramp distance of the simple artificial gust led to higher wheel-unloading for shorter ramp distances. The leading bogie showed in general higher wheel-unloading, independent of the calculation method of the aerodynamic loads. For the trailing bogie, the loads obtained by the QTGM approach yielded higher wheel-unloading than the DES loads. A comparison of a spatio-temporal and a temporal TSI gust did not show significant differences in the vehicle response in terms of the maximum wheel unloading. However, the carbody showed higher roll motion oscillations due to the temporal gust. Concerning the variation of suspension and mass properties of the vehicle, it was shown that the vertical location of the centre of gravity of the carbody and the lateral bumpstop clearance significantly influence the crosswind stability of the vehicle.
6 Conclusions and future work

The purpose of this study was to investigate the response and lateral stability of a high-speed rail vehicle due to large lateral influences from track irregularities, track curves and unsteady crosswind. The work included studies (Paper A) of high-speed vehicle dynamics at large suspension deflections due to large lateral impact from track curves and track irregularities only, in order to analyse the reliability of multibody simulations at such conditions and with respect to overturning risk of the vehicle. The multibody simulations were performed in 2D and 3D, using different suspension models, and validated by field measurements.

It could be shown that the multibody simulations estimated the relative motions in the secondary suspension well. The multibody simulations showed good agreement with the field measurements in carbody-bogie lateral displacements, whereas the relative roll motion of the carbody was overestimated by the simulations at larger suspension deflections and thus cant deficiencies due to levelling effects of the air springs. The lack of friction in the 2D air spring model resulted in higher displacements.

Furthermore, the response of a high-speed rail vehicle subjected to unsteady crosswind during curve negotiation was investigated (Paper B). This contained the exposure of the vehicle to unsteady aerodynamic loads obtained from unsteady DES and QTGM. The deterministic gusts applied represented gusts in open field, including the so-called Chinese hat of the TSI, and a tunnel exit. Using a simple artificial gust, comparisons of different gust and curve timing and parameter studies on the influence of mass and suspension properties of the vehicle on crosswind sensitivity were performed. It was shown that the vertical location of the centre of mass of the carbody and the lateral bumpstop clearance influences the crosswind stability significantly. The QTGM approach was evaluated in terms of usage within rail vehicle dynamics, leading to higher wheel unloading compared to DES loads, but offering a fast approach for the application of unsteady aerodynamic loads. A comparison of a spatio-temporal and a temporal TSI gust did not show significant differences in the vehicle response. However, further investigations on this topic should be part of future work.

Possible future work can be suggested from both parts of the work. Concerning the modelling effects at large suspension deflections, additional effects concerning air springs could be introduced. This includes the levelling mechanism of the springs as well as possible pneumatic connections of the air springs. Also other existing air spring models could be validated on a vehicle at large suspension deflections.
6. Conclusions and future work

Regarding the vehicle response to unsteady crosswind, further comparisons of transient aerodynamic loads and just temporal or steady state loads could further show the relevance of unsteady approaches. Also, more parameter studies on the vehicle properties could highlight additional possibilities of counteractions to crosswind effects.

In general, the influence of the track irregularities and the applied low-pass filtering within the different overturning criteria would be of interest for further investigations.
Lateral Stability of High-Speed Trains at Unsteady Crosswind

References


References


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Lateral Stability of High-Speed Trains at Unsteady Crosswind
