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On Rail Vehicle Dynamics in Unsteady Crosswind Conditions

Studies Related to Modelling, Model Validation and Active Suspension

by

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Preface

This thesis summarizes the work carried out during my PhD studies at the Department of Aeronautical and Vehicle Engineering at KTH Royal Institute of Technology 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 ECO^2 Vehicle Design, which in addition to Vinnova and KTH also involves the external centre partners Bombardier Transportation, Trafikverket (Swedish Transport Administration), Scania CV, formerly Saab Automobile AB, Volvo AB, Creo Dynamics, Elitkomposit AB, VTI and Yovinn AB. The financial support from the centre is gratefully acknowledged.

I would like to thank my main supervisor Prof. Mats Berg for accepting me as a PhD student and his guidance, support and comments since the beginning of the project as well as in-depth reviews of the manuscripts. In addition, thanks to my co-supervisor Prof. Sebastian Stichel for support and comments on the work. To my other co-authors, Dr. Ben Diedrichs and Dr. Rickard Persson, thank you for fruitful discussions and good collaborations.

Regarding the work on Paper C in this thesis, I would like to make some special acknowlegdments. The measurement work would not have been possible without an enormous support from Bombardier Transportation. Many thanks to Henrik Tengstrand, Jakob Wingren and in particular Camilla Sjöberg at the Department of Vehicle Performance Engineering, and the people at the train workshop *Lokis* at the Västerås site.
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AB Transitio is also acknowlegded for providing the vehicle. As I understand, *Silvret* is running through Bergslagen again, which is great.

Thanks to all my colleagues at the Division of Rail Vehicles and the Centre of ECO^2 Vehicle Design, for discussions, a pleasant working environment as well as great and challenging after-work events. To my colleagues at Vehicle Performance Engineering at Bombardier Transportation, thanks for a nice working environment since I started three years ago. I am looking forward to working full-time with you guys.

Very special thanks to my family, and to all my friends for cheering me up when necessary, but most of all for being friends.

Stockholm, October 2013

Dirk Thomas

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 substantial lateral influences from track curves, track irregularities and crosswind, leading to large suspension deflections and increased crosswind sensitivity. Unsteady crosswind like gusts also 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 they deliver reasonable results, simulations represent an important tool for overturning prediction of rail vehicles.

In the present work, multibody simulations of a high-speed rail vehicle under large lateral influences from track curves and track irregularities have been carried out, using a half-vehicle model in 2D and a full vehicle model in 3D, including different suspension models. Corresponding field measurements of the relative lateral and vertical deflections in the secondary suspension were performed on a fast train and used to validate the multibody simulations.

The 3D vehicle model was further used to study the vehicle response to unsteady crosswind during curve negotiation, including aerodynamic loads obtained from unsteady Computational Fluid Dynamics. In addition, the *Quasi Transient Gust Modelling* method was evaluated. 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. The influence of the vehicle's suspension and mass properties on crosswind sensitivity were studied in addition.

In order to validate modelling and simulation results for gust-like loads on a rail vehicle, full-scale experiments were conducted by exciting the carbody of a stationary rail vehicle, imitating synchronous and asynchronous crosswind-like loads and measuring the vehicle response. The measurements were reflected in multibody simulations, which were in good agreement with the measured responses. Parameter studies of the suspension characteristics were performed additionally. Asynchronous crosswind-like loads were in comparison to synchronous loads observed to result in lower wheel-unloading.

It was further studied whether active secondary suspension can be used to improve crosswind stability. A fast rail vehicle equipped with active secondary suspension for ride comfort purposes is exposed to crosswind loads during curve negotiation by means of simulations. For high crosswind loads, the active suspension is used to reduce the impact of crosswind on the vehicle. The control input is taken from the primary vertical suspension deflection. Three different control cases were studied and compared to the only comfort-oriented active secondary suspension and a passive secondary suspension. The

application of active suspension resulted in significantly improved crosswind stability.

Keywords: Rail vehicle dynamics, crosswind stability, overturning risk, multibody simulations, unsteady aerodynamics, CFD, field measurements, full-scale experiments, model validation, suspension modelling, active suspension.

Sammanfattning

Sidvindstabilitet av spårfordon har varit ett aktivt forskningsområde under flera decennier, vilket huvudsakligen motiverats av olyckor med vältande fordon samt högre hastigheter, men under senare tid även genom kravet på att minska fordonsvikten för att minska energiförbrukningen och spårnedbrytningen. Spårfordon är utsatta för stor lateral påverkan i form av kurvor, spårlägesfel och sidvind under daglig drift, vilket leder till stora förskjutningar i framför allt sekundärfjädringen samt ökad känslighet för sidvind. Även dynamisk sidvind såsom vindbyar kräver uppmärksamhet. För att prediktera en möjlig fordonsvältning behövs simuleringar, som dock behöver ta hänsyn till stora förskjutningar samt skjuvning i fjädringen. Om simuleringarna levererar rimliga resultat representerar dessa ett viktigt verktyg för att prediktera fordonsvältning.

I föreliggade arbete har flerkroppssimuleringar utförts för ett höghastighetsfordon utsatt för stor lateral påverkan pga kurvor och spårlägesfel, där en halvfordonsmodell i 2D och en modell av ett helt fordon i 3D har använts. Respektive modell innehåller även olika fjädringsmodeller. Motsvarande fältmätningar, där relativa vertikala och laterala förskjutningar i sekundärfjädringen mätts på ett snabbtåg, har utförts och använts för validering av flerkroppssimuleringarna.

Fordonsmodellen i 3D har dessutom använts för att studera fordonsresponsen vid kurvgång och transient sidvind, där de aerodynamiska lasterna har tagits fram med hjälp av transient Computational Fluid Dynamics. Dessutom utvärderades metoden *Quasi Transient Gust Modelling*. Starka lateral- och rollresponser på fordonet observerades, och som var beroende av vindbyns längd och relativa skillnaden mellan medelvind och byvind. Dessutom undersöktes inverkan av fordonets fjädrings- och massegenskaper på sidvindsstabiliteten.

For att validera modelleringen samt simuleringsresultaten för vindbyliknande laster har fullskalemätningar utförts, genom att belasta vagnskorgen av ett stillastående fordon, för att imitera sidvindspåverkan och mäta fordonsresponsen. Mätningarna återspeglades med hjälp av flerkroppssimuleringar som visade bra överenstämmelse med uppmätta resultat. Ytterligare parameterstudier gjordes avseende på fjädringsegenskaperna. Asynkrona sidvindsliknande laster resulterade i mindre hjulavlastning jämfört med synkrona.

Dessutom studerades om aktiv sekundärfjädring kan användas för att förbättra sidvindsstabiliteten. Ett höghastighetsfordon, som är utrustat med aktiv sekundärfjädring för komfortändamål, har med hjälp av simuleringar exponerats för sidvind under kurvgång. Den aktiva fjädringen, som regleras med hjälp av vertikalförskjutningen i primärfjädringen, används för att reducera sidvindspåverkan på fordonet. Tre olika regleringsfall studerades och jämfördes med den komfort-orienterade aktiva fjädringen samt en passiv sekundärfjädring. Användningen av den aktiva fjädringen ledde till signifikant förbättrad sidvindsstabilitet.

Nyckelord: Spårfordons dynamik, sidvindsstabilitet, vältningsrisk, flerkroppssimuleringar, MBS, icke-stationär aerodynamik, CFD, fältmätningar, fullskaliga experiment, modellvalidering, fjädringsmodellering, aktiv fjädring.

Dissertation

This thesis consists of two parts. Part I gives an introduction to the area of research and a summary of the present work. Part II contains the following four appended papers:

Paper A

Thomas D, Berg M and Stichel S: *Measurements and simulations of rail vehicle dynamics with respect to overturning risk*. Vehicle System Dynamics **48** 1, pp 97-112, DOI 10.1080/00423110903243216, 2010.

Planning of the measurements and simulations was 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*. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit **224** F6, pp 567-579, DOI 10.1243/09544097JRRT335, 2010.

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

Paper C

Thomas D, Berg M, Stichel S and Diedrichs B: *Rail vehicle response to lateral carbody excitations imitating crosswind*. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, DOI 10.1177/0954409713496765, 2013. Available online, to appear in print.

Planning and execution of the measurements were performed by Thomas, multibody simulations were carried out by Thomas. The paper was written by Thomas under the supervision of Berg and Stichel and under discussion with Diedrichs.

Paper D

Thomas D, Berg M, Persson R and Stichel S: *Improving crosswind stability of fast rail vehicles using active secondary suspension*. Submitted for international journal publication.

Simulations were carried out by Thomas. The paper was written by Thomas under supervision of Berg and Stichel and under discussion with Persson.

Publications not included in the thesis

Parts of the thesis work were presented at conferences and in other publications, including:

Thomas D, Berg M and Stichel S: *Measurements and simulations of rail vehicle dynamics with respect to overturning risk*
Proceedings of the 22nd International Congress of Theoretical and Applied Mechanics (ICTAM 2008), Adelaide, Australia, 24-29 August 2008.

Thomas D, Diedrichs B, Berg M and Stichel S: *Dynamics of a high-speed rail vehicle negotiating curves at unsteady crosswind*
Proceedings of the 21st International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD'09), Stockholm, Sweden, 17-21 August 2009.

Thomas D, Berg M, Diedrichs B and Stichel S: *Rail vehicle response to lateral carbody excitations imitating crosswind*
Proceedings of the 22nd International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD'11), Manchester, UK, 14-19 August 2011.

Thomas D, Berg M, Diedrichs B and Stichel S: *Rail vehicle response to carbody excitations imitating crosswind*
Proceedings of the 23rd International Congress of Theoretical and Applied Mechanics (ICTAM 2012), Beijing, China, 19-24 August 2012.

Thomas D: *Lateral Stability of High-Speed Trains at Unsteady Crosswind*
Licentiate thesis, TRITA-AVE 2009:79, ISSN 1651-7660, ISBN 978-91-7415-473-3, KTH Royal Institute of Technology, Stockholm, Sweden, 2009.

Sima M, Thomas D and Favre T: *Pilot study in Scandinavia, the example of the West Coast Line*
DeuFraKo project "Aerodynamics in Open Air" (AOA) internal report, 080729-AOA-WP2.5, 2008.

Contribution of the thesis

This thesis presents investigations of the dynamics of rail vehicles due to large influences from unsteady crosswind, track curves and track irregularities with respect to modelling, model validation and the use of active secondary suspension.

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

- A literature survey [48] 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 during 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 *Quasi Transient Gust Modelling (QTGM)* presented in [34] has been evaluated in terms of overturning risk (wheel unloading).

- Full-scale experiments have been performed by applying lateral loads to imitate crosswind on the carbody of a stationary rail vehicle and measuring the vehicle responses, in order to validate multibody simulations. Quasi-static and dynamic gust-like loads were applied, both synchronously and asynchronously. The vehicle response was measured by means of relative lateral and vertical deflections between bogie frames and the carbody, lateral accelerations on the carbody floor and vertical wheel-rail forces on the wheelsets of one bogie. The vehicle reacts with a sway response to gust-like loads, including overshoots in the responses. Asynchronous lateral loads were observed to result in less wheel-unloading than synchronous loads.

- Active secondary suspension has been shown by simulations to significantly improve the crosswind stability of a fast rail vehicle. The active secondary suspension, that is originally installed on the vehicle for comfort-oriented purposes, is used to reduce the impact of high crosswind loads. Three different types of control have been studied, using the vertical deflection of the primary suspension as control input, and compared to the original comfort-oriented control of the active suspension as well as to a passive secondary suspension.

Contents

Part I

1 Introduction

Crosswind stability of rail vehicles has been an active research topic for several decades. The first motivation for research were accidents related to crosswind. Reports on crosswind accidents of rail vehicles actually date back to the 19th century [32], and still occur today. Two relatively recent accidents can be seen in Figure 1.1, showing an overturned single diesel unit near Uttendorf (Austria) in 2002, and the overturned first two cars of an electric multiple unit near Wasserauen (Switzerland) in 2007. The latter accident happened during the winter storm Kyrill, leading locally to very high wind speeds, which caused the overturning of the vehicles.

(a) (b)

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

Both accidents represent the most common crosswind accident type for rail vehicles, which is overturning about one of the rails. For road vehicles, by comparison, crosswind accidents are mostly different here and most commonly result in an initial deviation from the direction of travel. However, high lorries have also been known to overturn.

In recent times, the motivation for studies of crosswind stability of rail vehicles has been extended. By building faster rail vehicles as well as new or upgraded railway lines, the operational speeds of trains have increased, leading to higher aerodynamic loads on the vehicle when travelling. Heavier vehicles could improve the crosswind stability but issues such as lower energy consumption on the contrary demand lighter vehicles, which at the same time would lead to benefits regarding wheel maintenance, track deterioration and track maintenance.

Furthermore, the traction layout of passenger trains, especially for high-speed trains but also more and more regional trains, is changing in recent years shifting from loco-hauled trains to multiple units with distributed traction. Since the aerodynamic loads are often 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 multiple unit vehicle increases the demand for trains' crosswind stability of trains. For high-speed vehicles, this has partly resulted in a ballasting of the first running gear. Not only passenger trains, but also freight trains are affected by crosswind when running at tare load conditions.

Unsteady crosswind and the related phenomena have become a major concern in comparison to steady state conditions. A rail vehicle can be subjected to various unsteady wind situations in everyday operation, including gusts in open field, gust-like wind conditions due to changes in housing density and vegetation near the track, as well as effects of passing vehicles.

The railway infrastructure is also important to take into account. Vehicles on narrow gauge lines usually run at lower operational speeds but their overturning stability is less compared to a standard gauge vehicle. Note that both vehicles shown in Figure 1.1 are narrow gauge vehicles. Bridges and embankments also 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 tunnel exits 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 due to cant deficiency, causing a reduction in crosswind stability.

The topic of crosswind stability involves two disciplines, namely aerodynamics and vehicle dynamics, which interact with each other. Most research on crosswind stability of rail vehicles was and still is related to the field of aerodynamics. A good overview of research done up to now can be found in [12]. It is nevertheless necessary to study the vehicle dynamics involved in more detail. Since crosswind stability represents a safety issue, detailed information about the behaviour of the vehicle in crosswinds is desirable. However, measurements including field tests using a rail vehicle at risk of overturning are not practicable for safety and economic reasons. Therefore, simulations represent a necessary and important tool, but attention has to be paid to the accuracy of the simulations at large suspension deflections and to the application of aerodynamic loads, since a rail vehicle with its suspensions and wheel-rail contact is a highly nonlinear system.

In the present thesis, the rail vehicle's behaviour under large lateral influences from curves, track imperfections and crosswind is studied by means of measurements as well as simulations and with respect to overturning risk. In particular, the vehicle response to unsteady crosswind during curve negotiation is investigated by introducing unsteady aerodynamic loads derived by two different CFD techniques. Further, the reponse of a rail vehicle due to gust-like lateral loads is validated by means of full-scale measurements using a stationary vehicle and by means of simulations. The crosswind stability of a vehicle is finally improved by the application of active secondary suspension.

Chapter 2 of the thesis gives an overview of lateral rail vehicle dynamics on tangent and curved track, without the influence of crosswind. Fundamentals of vehicle aerodynamics in combination with crosswind are presented in Chapter 3. Chapter 4 describes modelling aspects of rail vehicle dynamics with respect to crosswind. The assessment of crosswind stability of rail vehicles including existing criteria and treatment in standards is presented in Chapter 5. Chapter 6 gives an overview of the use of active systems on rail vehicles in order to improve their crosswind stability. Chapter 7 gives a summary of the appended papers. Finally, Chapter 8 draws conclusions from the work and proposes future work.

2 Rail vehicle dynamics

As one of the disciplines involved in the thesis topic, the discipline of rail vehicle dynamics is briefly introduced below, giving information on fundamentals and lateral dynamics of a rail vehicle.

2.1 Fundamentals

A rail vehicle often consists of a carbody supported by two sets of running gear. In former passenger vehicles and still partly today's freight vehicles, the carbody is only supported by single-axle running gear. Modern freight and passenger rail vehicles, in particular for fast or high-speed traffic, are mostly designed as bogie vehicles. The setup of a typical bogie rail vehicle is shown schematically in Figure 2.1, including the coordinate system of the carbody and associated motion components. Note that the positive vertical direction is pointing downwards.

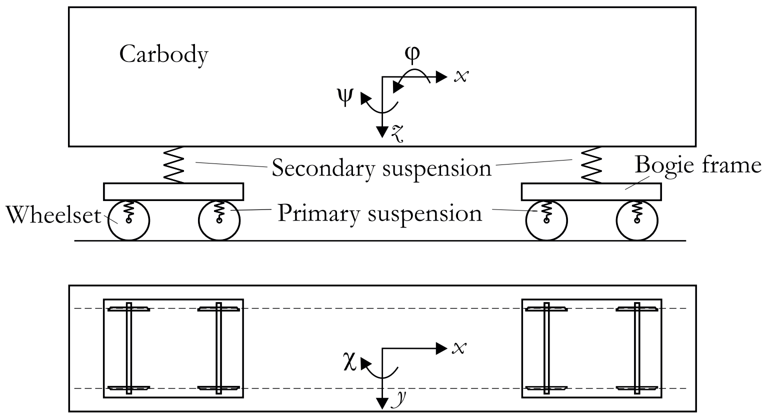

Figure 2.1: Side and top views of a bogie rail vehicle. Longitudinal motion x, lateral motion y, vertical motion z, roll motion φ, pitch motion χ and yaw motion ψ [4].

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 that vary depending on the vehicle type. Examples of such suspension elements are air springs, coil springs, rubber springs and hydraulic dampers. The type of components is dependent on the vehicle operational task and the desired suspension characteristics. Furthermore, the suspensions include bumpstops, delimiting the suspension motions in the vertical and lateral directions. The force transmission in the 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 to counteract the roll motion of the carbody (not shown). The concept of a bogie vehicle follows the idea of decoupling the carbody from the dynamics of the bogies and thus enhancing the running behaviour of the carbody. In Sections 2.2 and 2.3, the special emphasis is on the lateral rail vehicle dynamics since lateral loadings and excitations are primarily of concern in this thesis.

The railway track the vehicle is running on has a nominal geometry, which is among other things defined by the lateral distance between the two rails, i.e. the gauge. The track, however, is never in perfect condition, but includes deviations from the nominal track geometry, which are also known as track irregularities. These imperfections affect the running dynamics of the vehicle. They influence the motions of the vehicle due to excitations of the wheelsets and generally have great impact on the wheel-rail forces and ride comfort. A definition of different kinds of track irregularities is given in Figure 2.2. Note that vertical track defects are here called longitudinal level.

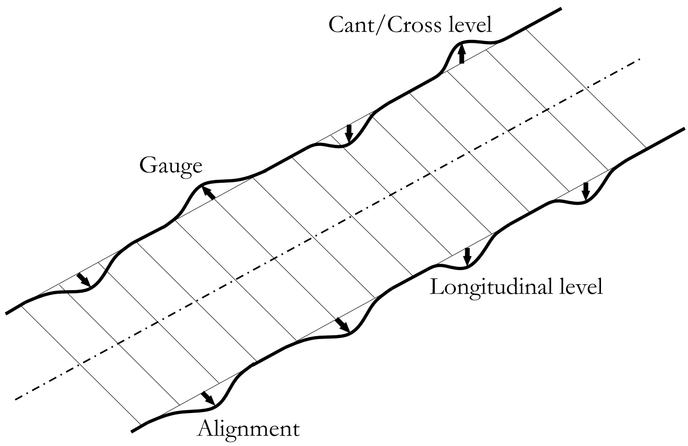

Figure 2.2: Defintion of track irregularities.

The impact of crosswind on a vehicle is mainly of a lateral nature, which is though also influenced by the vehicle speed, see Chapter 3. In the following, some fundamentals of lateral rail vehicle dynamics on tangent and curved track are given.

2.2 Lateral dynamics on tangent track

On tangent, or straight, track, a vehicle is not only affected by the track irregularities, but also by lateral impacts due to the running dynamics of the vehicle itself.
The running surface of a railway wheel has a conical shape and a flange towards the inner side of the wheel. For wheelsets with a rigid axle this leads to a laterally self-stabilizing behaviour of the wheelsets when running along tangent track. The conical shape, however, does not lead to a totally straight running behaviour. If one looks at the middle of a free wheelset from above and follows it along the track, one can recognize a sinusoidal lateral motion, see Figure 2.3. This phenomenon is called hunting and was

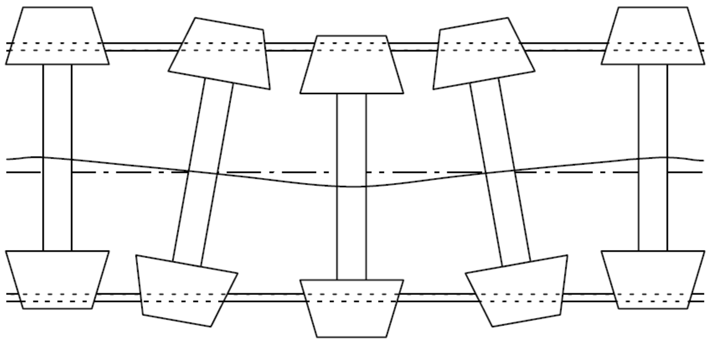

Figure 2.3: Hunting motion of a free wheelset [4].

first described in [60]. 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 thus simply be expressed by

$$y(t) = y_0 \cdot \sin \omega t. \tag{2.1}$$

with ω being the angular frequency of the motion. 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 λ, and can be described by

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

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

Now, looking at a single bogie and assuming a zero relative motion of the bogie frame, the running stability is dependent 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.

In addition to 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, two different periodic lateral motion phenomena causing instability are often referred to: high-frequency or wheelset/bogie instability, and low-frequency or carbody instability [4, 57, 61]. High-frequency instability usually occurs in combination with high equivalent conicity at running speeds above 100 km/h at frequencies between 4 and 10 Hz. Low-frequency 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 that 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, and it must be noted that the vehicle and the suspension system are normally designed to avoid the occurrence of both the instability phenomena mentioned above. Since low-frequency carbody instability is near the frequency range that is of interest in crosswind perpectives, it is still mentioned here.

Further information about lateral rail vehicle dynamics on tangent track can be found, for example in [4, 57, 61].

2.3 Lateral dynamics when 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 2.4, 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, i.e. if the wheel axle is pointing towards the centre of the curve, the geometric conditions can thus be written as

$$\frac{r_{out}}{r_{in}} = \frac{R + b_0}{R - b_0}, \tag{2.3}$$

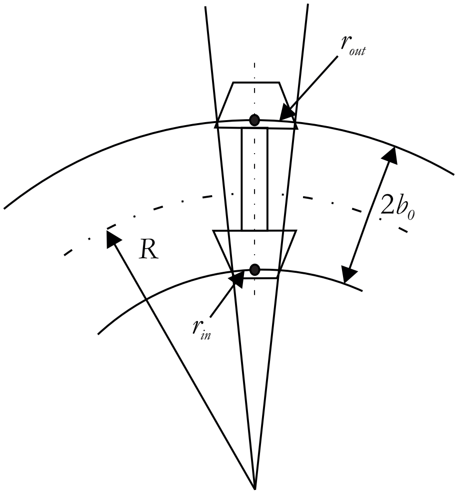

Figure 2.4: Curve steering of a free wheelset with conical wheels.

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

$$r_{out} = r_0 + \lambda_0 y \quad (2.4a)$$
$$r_{in} = r_0 - \lambda_0 y \quad (2.4b)$$

with nominal rolling radius r_0 and wheel conicity λ_0. The lateral displacement of the wheelset that is needed for perfect steering is thus

$$y = \frac{r_0 b_0}{\lambda_0 R} \quad (2.5)$$

Note that Equations 2.3 - 2.5 represent a simplification and ignore friction forces on the wheelset. Ride instability is a minor problem on curved track compared to tangent track. However, low-frequency carbody instability can occur in curves with large radii. More detailed explanations of curve steering of wheelsets, bogies and vehicles can for example be found in [4, 61].

In addition to track irregularities and curve steering, a rail vehicle negotiating a horizontal track curve is also subjected to additional lateral influences. Figure 2.5 shows the rear view of the carbody of a rail vehicle at a curving situation. Under quasi-static curving conditions, running at speed v through a curve with radius R, the vehicle is subjected to centrifugal acceleration v^2/R and acceleration of gravity g, see Figure 2.5a. 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 2.5b. With track cant angle φ_t, the corresponding

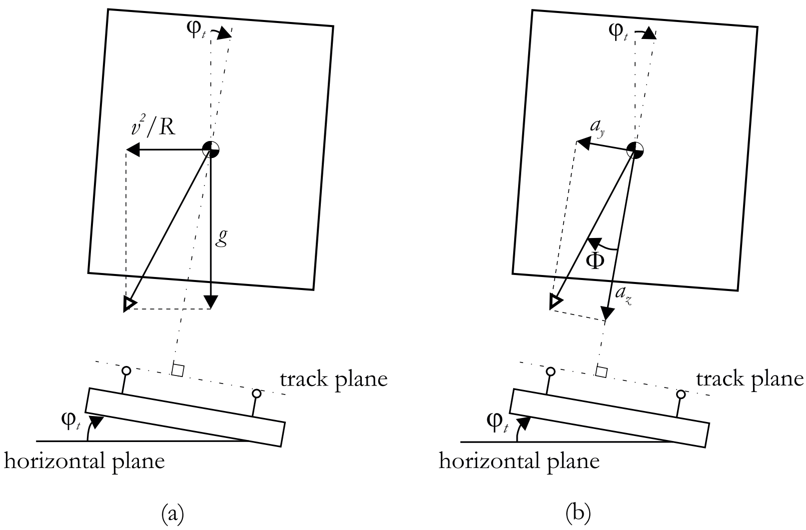

Figure 2.5: Rear view of rail vehicle carbody at curving, (a) lateral acceleration in horizontal plane v^2/R, (b) lateral acceleration in track plane a_y.

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, $v^2/R \leq 0.3\ g$ and small cant angles, Equation 2.6 can be approximated as

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

The track cant that leads to a zero lateral track plane acceleration at a given speed v and curve radius R, is called the equilibium cant h_{eq}, cf. Figure 2.6b. It can be expressed as

$$h_{eq} \approx \frac{2b_0}{g} \cdot \frac{v^2}{R}. \tag{2.8}$$

If cant h_t is less than h_{eq} we get a cant deficiency h_d, cf. Figure 2.6a and c,

$$h_d = h_{eq} - h_t \approx \frac{2b_0}{g} \cdot \frac{v^2}{R} - h_t \approx \frac{2b_0}{g} \cdot a_y. \tag{2.9}$$

Curve negotiation at cant deficiency, depending on suspension characteristics, is usually

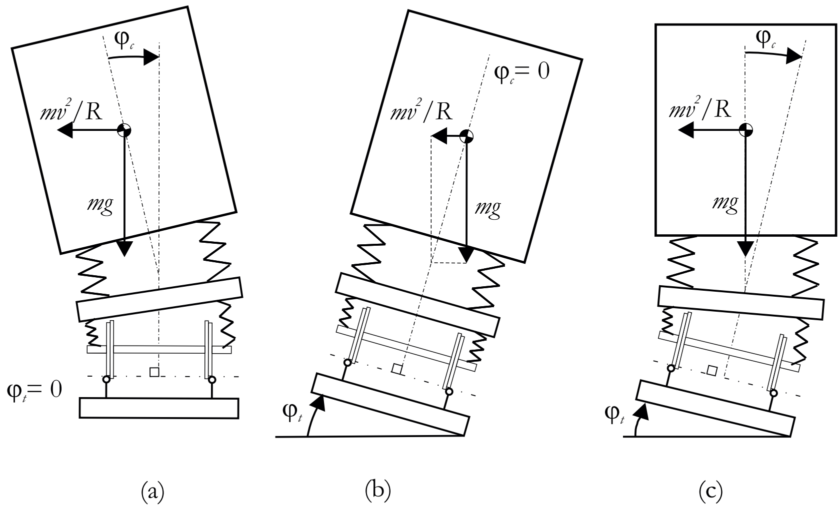

Figure 2.6: Rear view of rail vehicle at right-hand curving, (a) no cant but cant deficiency, (b) equilibrium cant, (c) cant and cant deficiency [4].

accompanied by a combined lateral deflection of the secondary suspension, or a shift of the carbody towards the outer side of the curve, and a roll motion of the carbody out of the curve. The lateral carbody shift, in particular, has a destabilizing influence on the vehicle with respect to crosswind due to the shifted centre of gravity of the carbody and the, in turn deteriorated, restoring moment in case of additional crosswind loads on the carbody.

The roll φ_c of the carbody relative to the track, see Figures 2.6a and c, is also influenced by the vehicle suspension and carbody mass properties. Using the ratio of the carbody roll angle φ_c to the track cant angle φ_t at stand-still in a curve, one can define the dimensionless vehicle coefficient of flexibility

$$C_\varphi = \frac{\varphi_{c,v=0}}{\varphi_t}. \tag{2.10}$$

The roll response of an airspring-supported carbody during curve negotiation is shown in Figure 2.7. The relation is nonlinear and simplified using straight lines. The break-points for inflated (pressurized) air springs originate from bumpstop contacts in primary and secondary suspensions. In the case of 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's lateral movement and thus yield less roll motion of the carbody, and in the case of low cant deficiency/excess, a hysteresis can be observed due to characteristics of the spring.

In the case of cant deficiency, which is typical for fast rail vehicles, the outer wheels expe-

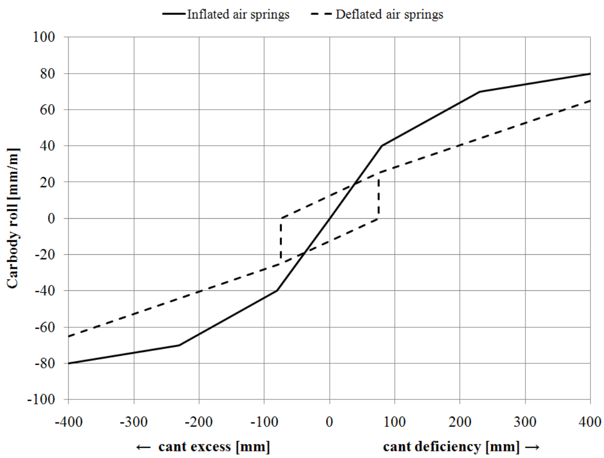

Figure 2.7: Example of roll of a carbody suspended on air springs for cant deficiency and cant excess. Positive carbody roll represents roll towards the outside of the curve. From [57].

rience higher wheel-rail forces in both the lateral and vertical directions, see Figure 2.8. As implied above, the distribution of the vertical wheel-rail forces within a wheelset also

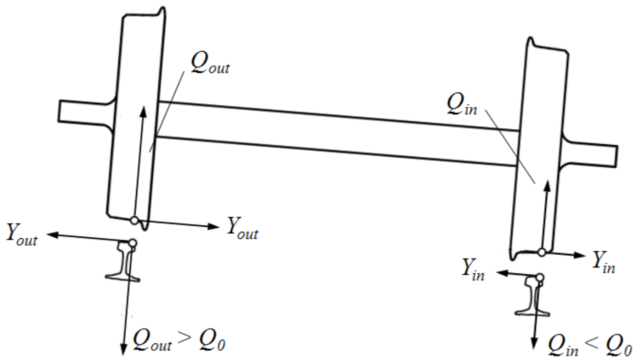

Figure 2.8: Wheel-rail forces during curve negotiation with cant deficiency. Lateral force Y, vertical force Q. Outer and inner wheels/rails. $Q_{in} < Q_0 < Q_{out}$, where Q_0 is the nominal vertical wheel load on horizontal track. The outer wheel-rail contact is close to the wheel flange. If the inner wheel-rail contact is lost, the vehicle may overturn about the outer rail [4].

depends on the suspension deflections and carbody mass properties. The decrease in the vertical wheel-rail force on curve-inner wheels or rail is often termed wheel-unloading. Additional loads on the vehicle from crosswind can additionally decrease the vertical wheel-rail forces, which in extreme cases can also lead to a wheel lift followed by a possible overturning of the vehicle about the outer rail. Wheel-unloading is used as a criterion for crosswind stability of a rail vehicle, see Section 4.1.

The lateral track plane acceleration and thus the cant deficiency is usually limited due to risk of ride discomfort and lateral track shift. Limit values may vary on different networks and depending on vehicle types. A limit speed for curve negotiation can be found using Equation 2.7, thus

$$v_{lim} = \sqrt{R(a_{y,lim} + g\frac{h_t}{2b_0})} = \sqrt{R(h_{d,lim} + h_t)\frac{g}{2b_0}}. \tag{2.11}$$

where $a_{y,lim}$ and $h_{d,lim}$ are the permissible track plane acceleration and the corresponding permissible cant deficiency.

3 Vehicle aerodynamics

To introduce the second discipline involved in the topic of the thesis, some background on vehicle aerodynamics is given below, including fundamentals and information regarding crosswind and gust modelling.

3.1 Fundamentals

An object or body, e.g. a vehicle, that is subjected to a flow of or moving in a Newtonian fluid, e.g. air, 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 flow velocity and flow pressure. For a non-viscous and incompressible flow, the relation is given by Bernoulli's equation,

$$p + \frac{\rho}{2}u^2 = const, \tag{3.1}$$

where p is the static pressure, ρ the fluid density and u the flow velocity along a streamline [15, 55, 78]. The term

$$\frac{\rho}{2}u^2 = q \tag{3.2}$$

represents the dynamic pressure q. Equation 3.1 can also be derived from the Navier-Stokes equations by assuming incompressible, stationary flow without internal friction [78].

Depending on the shape of a body, one can distinguish between so-called streamlined, or slender, and non-streamlined, or bluff, bodies. In the case of a slender body, the flow remains to a larger extent attached to the body, whereas the flow around a bluff body has a massive separation [54]. Rail vehicles can be treated as slender bodies or as bluff bodies, depending on the aerodynamic subject of study. For crosswind conditions, they have to be treated as bluff bodies [21].

Due to the flow pressure and the local pressure gradients, forces and moments are acting on the vehicle. Figure 3.1 defines the loads using the example of a train. The loads

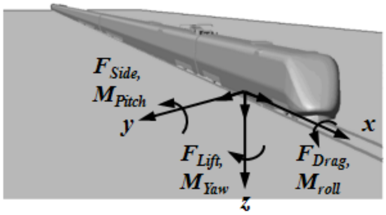

Figure 3.1: Aerodynamic forces and moments acting on a train. Drag force F_{Drag}, side force F_{Side}, lift force F_{Lift}, roll moment M_{Roll}, pitch moment M_{Pitch} and yaw moment M_{Yaw} [33].

depend on the flow situation and the shape of the vehicle, and can be expressed as

$$F_{Drag} = q \cdot A_t \cdot C_{Drag} \tag{3.3a}$$
$$F_{Side} = q \cdot A_t \cdot C_{Side} \tag{3.3b}$$
$$F_{Lift} = q \cdot A_t \cdot C_{Lift} \tag{3.3c}$$
$$M_{Roll} = q \cdot A_t \cdot l_t \cdot C_{Roll} \tag{3.3d}$$
$$M_{Pitch} = q \cdot A_t \cdot l_t \cdot C_{Pitch} \tag{3.3e}$$
$$M_{Yaw} = q \cdot A_t \cdot l_t \cdot C_{Yaw}, \tag{3.3f}$$

where A_t is a reference area, l_t a reference length and C the aerodynamic coefficients for the respective directions. Several reference areas and lengths are used depending on the vehicle. European standard EN 14067-1 [23], for example, defines the reference dimensions to be used as 10 m^2 for the reference area and 3 m for the reference length for all types of rail vehicles, which allows the aerodynamic properties of different vehicles to be compared.
For rail vehicles, 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 at top of rail level [33]. For road vehicles, a reference frame located at half the axle distance behind the first axle is often used [59].

The non-dimensional 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 through 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 recently been presented [62], and wind tunnel experiments involving moving vehicle models have also been performed in crosswind related studies [9, 19].

In CFD, there are four main techniques available to treat the turbulence in the flow:

- In Direct Numerical Simulations (DNS), all scales in the solution of the governing

Navier-Stokes equations are resolved. This method is very time-consuming and mostly applied in research. Due to the required computational effort, DNS cannot be used for applied crosswind calculations today.

- In Large Eddy Simulations (LES), the larger turbulence scales are resolved by means of the computational mesh. Smaller, energy-dissipating scales, that are unresolved, have to be modelled. Concerning crosswind calculations of trains that include high Reynolds numbers, LES also needs high computational effort, which is why LES are not used in an industrial context, but have been used in research; see for example [51, 52, 63].

- Detached Eddy Simulations (DES) represent a relatively new methodology, which is a mix of LES and RANS [76]. It uses LES away from solid walls and applies RANS (see below) close to walls. Both LES and DES are methods for unsteady flow calculations [33] and have been used in research; see for example [37, 49, 74, 82].

- In Reynolds Average Navier Stokes (RANS), the flow is decomposed into a time averaged and variance of the flow fields, where 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 and is an industrial standard. If one separates the time scales for the mean flow and the turbulence, one can instead of the time average $t \to \infty$ 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) [33].

An overview of computational methods in combination with crosswind stability of rail vehicles is also given in [32].

3.2 Crosswind

For road and rail vehicles exposed to crosswind, the pressure distribution and thus the aerodynamic forces and moments on the vehicle 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 ρ and viscosity ν as well as the wind speed v_w, the wind angle relative to the vehicle's direction of travel β^*, the turbulence length scale and the standard deviation of the wind speed (concerning the wind properties) [6, 33]. Figure 3.2 shows the connection between the vehicle speed v, the wind speed v_w including its yaw angle relative to the track β^*, and the resultant wind speed v_r and its yaw angle β using the example of a train.

Due to ground surface roughness, the vertical wind speed profile is in reality not constant because of the formation of an atmospheric boundary layer. The vertical wind

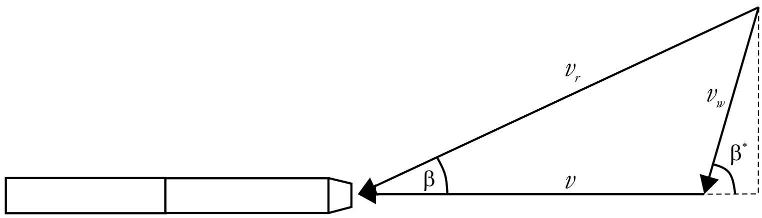

Figure 3.2: Wind situation and notation of velocity vectors for a train subjected to crosswind. Top view [33].

speed profile and the resultant wind velocity vectors for a crosswind situation are explained in Figure 3.3. However, in spite of the boundary layer effect, constant vertical velocity profiles are also used for train certification [43].

Environmental and infrastructure characteristics also influence the crosswind situation.

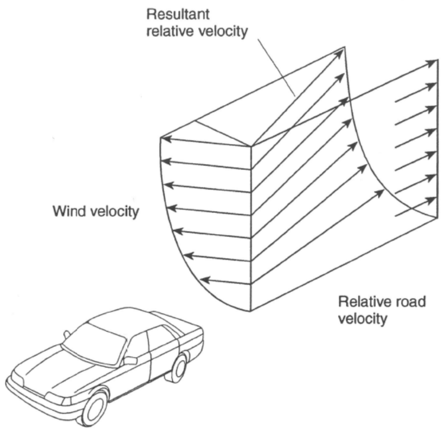

Figure 3.3: Wind velocity profile and resultant wind velocity vectors for a moving car in crosswind [15].

Changes in the vegetation can lead to suddenly increasing wind speeds [55]. This effect on the resulting responses of a bus has been studied in [59]. Embankments and bridges lead to higher flow velocities due to flow acceleration at an embankment and the atmospheric boundary layer [10, 55]. The crosswind stability of a (high-speed) train on an embankment was investigated in [36, 79].

Due to the atmospheric boundary layer and the resulting wind speed, wind tunnel tests for crosswind situations should be made using a moving model, in order to assure the correct wind speed relative to the vehicle [6], and performed as, for example, in [9, 19, 28].

However, open field measurements of aerodynamic loads were also performed and compared to wind tunnel tests by [13], resulting in good agreement but showing a discrepancy for the lift coefficient caused by local roughness effects in the wind tunnel tests. A review of ground vehicles in crosswind can be found in [6–8], considering both steady and unsteady aerodynamic loads as well as the interaction of the aerodynamic loads and the vehicle suspension system. A fairly recent state-of-the-art review on crosswind stability, mainly from an aerodynamics point of view, can be found in [12].

Gust modelling

The modelling of gusts can be divided into two approaches. In the first, an ideal gust is represented, where the gust model is of a deterministic nature. A few examples can be found in the literature and some standards. Overviews can be found, for example, in [21, 48]. The most common shapes can be distinguished as follows:

- An exponential or mean gust, which was described by [65]. Its characteristics are an exponential shape. A gust with a bi-exponential shape, which is due to its form referred to as *Chinese hat*, is used in [43].
- A $1-\cos$ shape, which is often also called a "Rugby-ball". This gust type is very often used in aeronautics contexts.
- A step function. This shape is usually used due to its simple mathematical properties.
- A ramp function. This shape was used, for example, in [66].

Figure 3.4 shows the time histories of the deterministic gust shapes listed above for an impulse or a step function. In [30, 43], the time histories 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 [21].

The second possibility as regards gust modelling is a stochastic approach. The wind is de-

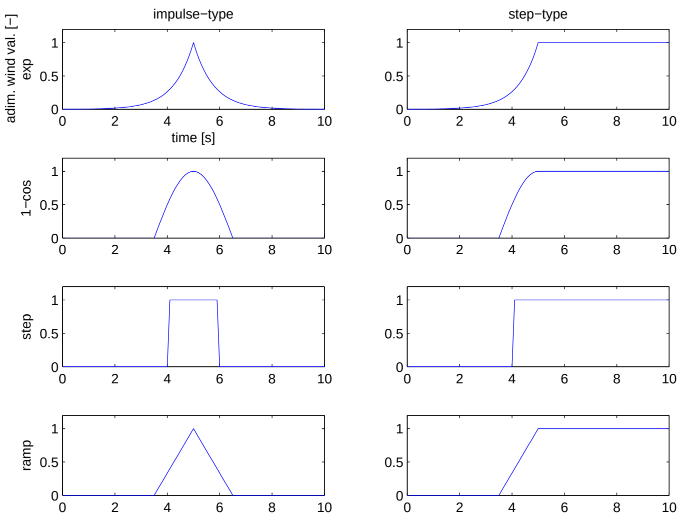

Figure 3.4: Time histories of gust shapes for impulse or step function type. From [48].

scribed 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 [48]. A spectrum is also described in [29], and used to calculate unsteady crosswind forces in [11], where the spectrum relative to train is decomposed into sinusoidal velocity variations of random phase, which are then combined into a velocity time series at the train position.

However, combinations of deterministic and stochastic approaches have also been applied. In [17, 18] a deterministic gust is superposed by a turbulent content. This method was used in [71]. Stochastic wind time series applied to deterministic gust models, for example from [43], have been derived in [27].

Further, unsteady CFD is used for the calculation of crosswind at a tunnel exit in [62], whereas a deterministic gust model in combination with unsteady CFD is applied in [34].

Besides the possibility of CFD, the aerodynamic loads seen by the vehicle for deterministic and stochastic gusts can be calculated using so-called aerodynamic admittance [7], that is used in several studies, for example [11, 14, 27]. This approach considers, in the frequency domain, the influence of the unsteady flow on the aerodynamic loads seen by the vehicle.

4 Modelling aspects of rail vehicle dynamics with respect to crosswind

Rail vehicles that are exposed to strong crosswind experience large lateral forces mostly loaded onto the carbody, and react with large lateral displacement of the carbody relative to the track and a roll motion towards the leeward side, cf. Figure 2.6c. These motions are together also called sway motion and are combined with large suspension deflections, in particular in the secondary suspension. During curve negotiation, this can be even more increased due to cant deficiency. Special attention therefore has to be paid to the modelling of the vehicle, if the model is to be used for crosswind simulations, and some important modelling aspects regarding suspension elements, influences from the track and modelling accuracy are discussed below.

4.1 Air springs

Air springs have become common suspension elements in the secondary suspension of fast rail vehicles, since they offer good ride comfort and their dynamic behaviour is almost independent of the vertical preload of the carbody. Besides the vertical direction, air springs transfer forces in longitudinal and lateral directions, but due to shear, moments are also transferred through the spring. Air springs represent highly non-linear components with hysteresis characteristics. A schematic view of a railway air spring is shown in Figure 4.1. Usually the carbody of a vehicle rests on two air springs per bogie,

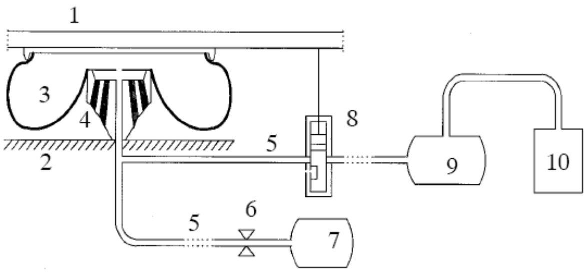

Figure 4.1: Schematic view of a railway air spring. 1. Carbody interface, 2. Bogie interface, 3. Air bag, 4. Auxiliary spring, 5. Air pipe, 6. Orifice, 7. Additional air reservoir, 8. Levelling valve, 9. Air container, 10. Compressor. [16].

which is often also the maximum number per bogie. However, for articulated vehicles with so-called Jacobs-bogies, four air springs may be installed, supporting two carbodies on the same bogie. When mounted on a vehicle, the air springs can be connected to each other via pipes in order to achieve different characteristics regarding the levelling mechanism, for example. Possible solutions here are two-point, three-point or four-point mounting. In the case of 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. In 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 [4]. In the case of large lateral deflections and roll motion influence, as described above, the secondary suspension experiences substantial lateral shear, and its behaviour at large deflections becomes of special interest. The lateral deflection may be delimited by bumpstops, cf. Figure 4.2, which also introduce further non-linear characteristics to the suspension. The modelling of air springs has been the subject of several studies. A good overview

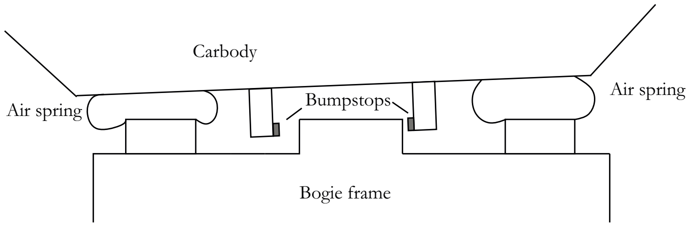

Figure 4.2: Secondary suspension deflection on a rail vehicle at high cant deficiency.

of existing models can be found in [20]. From these models, one can distinguish two kinds of models, where either the thermodynamic properties of the springs are considered [39–41,56,64,68,72] or an equivalent mechanical model is established [16,56,69,87]. The difference between the thermodynamic models is found in the modelling of the air flow between the bellows and the auxiliary volume. The flow is assumed to be a constant mass in dynamic motion [56] or a mass flow [64,72]. The model presented in [72] only considers the vertical direction of motion. In [56, 64], the spring's lateral characteristics are represented and modelled as linear springs [64] or as a linear spring-damper combination which is connected in parallel [56]. In both models, the vertical and lateral characteristics are independent of each other and the lateral forces are derived from the lateral deflection and deflection velocity. The equivalent mechanical air spring models presented in [16,87] consider the lateral characteristics in three parts with elastic, viscous and friction contributions. In the model presented in [16], the elastic part also depends on roll rotation/moment between the upper and lower parts of the spring. Different air spring models have been compared and benchmarked in [2,39,67].

4.2 Influence from the track

Except for the effects of track cant and horizontal curve radii, the influence of the track on crosswind stability is little discussed in the literature; only a few sources can be found. In fact, existing standards exclude track irregularities from the assessment analysis [24, 30, 43]. The reason is most probably to avoid the possibiltiy of influencing the assessment results by a varying application of the track irregularities.

In [4], lateral and cross-level track irregularities with long wavelength are mentioned as being capable of reducing the crosswind stability of a rail vehicle. The study presented in [26] included measured track irregularities, and for speeds above 200 km/h a negative influence due to track irregularities on the crosswind stability of the studied vehicles is concluded. Further information regarding the track data used and the wavelength content of the track irregularities, however, is not given. In [90] it is concluded that an elastic track model compared to a rigid model has only very little influence on crosswind stability. Track irregularities are included in this study as well, but no conclusions are drawn.

The influence of the track layout in terms of transition curves was studied by [66], and also in Papers B and D appended in this thesis [82, 84]. These studies show negative influence from the track layout on the crosswind stability of a vehicle, when a gust-like wind load was applied in conjunction with a transition curve.

4.3 Modelling accuracy

High accuracy in the vehicle modelling is of interest in the case of crosswind stability, since simplifications may have a high impact on simulation results in case of large suspension deflections and possible overturning of the vehicle. Some studies have been made that focus on this aspect.

In Paper A in this thesis [81], the modelling of a vehicle subjected to large secondary suspension deflections during curve negotiation is compared to field measurements by using a simple 2D and a detailed 3D model. The simple model only includes a shear spring in the secondary suspension, but the detailed model includes a full secondary suspension, including the air spring model presented in [16]. It can be concluded from this study that in particular for larger suspension deflections at higher cant deficiencies the simpler model overestimates the measurements, whereas the detailed model including the more precise air spring model shows good agreement with measurements; see Figure 4.3.

Regarding the modelling accuracy of air springs, it is also concluded in [47] that ignoring of the coupling effects between shear and roll deformation of an airspring in case of large deflections, as under high cant deficiency or in the case of crosswind, may result in an underestimation of the maximum vertical track loading during curve negotiation.

The model accuracy of both the vehicle modelling and the aerodynamic forces in case of crosswind is studied in [75] by comparing a simple planar 2D model and a detailed

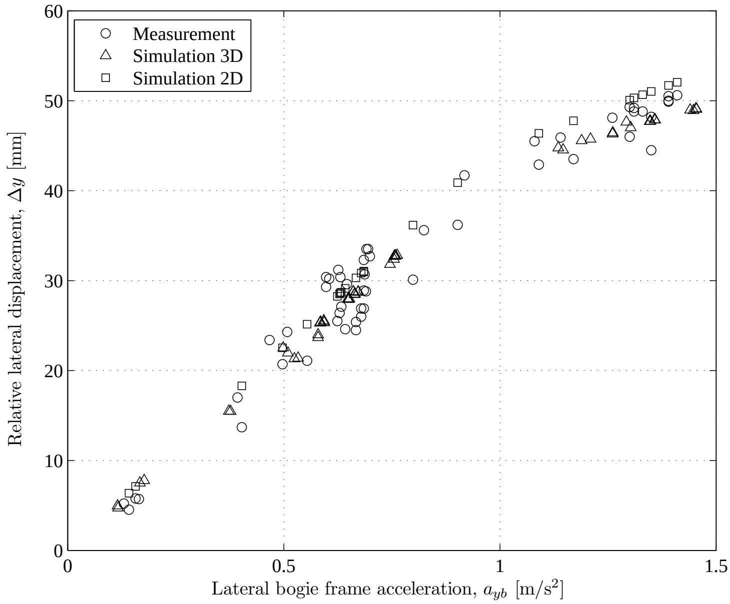

Figure 4.3: Relative lateral carbody-bogie displacement as function of lateral bogie frame acceleration from measured and simulated data in 2D and 3D. From [81].

3D model, and the application of aerodynamic loads including either planar loads with three degrees of freedom or full loads with six degrees of freedom. Regarding the vehicle modelling, the absence of some suspension elements in the 2D model, such as the yaw dampers or the anti-roll bar, was seen to influence the results compared to the 3D model, but both models are considered to represent the vehicle response to crosswind sufficiently well. The accuracy of the aerodynamic loads was found to have a large impact, giving relative differences of up to 3.5 m/s for the critical wind speed, for which reason it is concluded that a planar vehicle model is sufficient regarding the modelling aspect, if only planar aerodynamic loads are available. The study in [75] also compared different wheel-rail contact models, which were however concluded to influence the results regarding crosswind stability only to a minor degree.

The setup of the detailed 3D model in [81] has been used in Paper B in this thesis [82] and validated in Paper C using full-scale experiments [83]. Observations from the experiments regarding the influence of the carbody yaw motion on the wheel unloading due to lateral loads on the carbody have also been made recently in [53], where a very similar experiment is performed and extended by simulations. Additionally, an influence from the carbody sway mode on the vehicle response to lateral loads was concluded in [53].

5 Assessment of rail vehicle crosswind stability

The crosswind stability of rail vehicles can be assessed in several ways, and an overview of different criteria for crosswind stability, modelling and simulation related aspects in assessments, as well as the treatment in standards and regulations is given below.

5.1 Criteria for crosswind stability

Rail vehicles that are exposed to crosswind capable of causing a vehicle failure, most commonly overturn about the leeward rail. Hence, when assessing crosswind stability, the phenomenon of vehicle overturning is often what is considered. Several measures and criteria are available to describe the crosswind stability of a rail vehicle that take the overturning process into account. However, they do not necessarily describe the overturning process itself, but refer to it indirectly in a more or less conservative way. Some examples of such methods are given below, although the list does not claim to be exhaustive.

Wheel unloading

The criterion of wheel unloading $(Q_0 - Q)/Q_0$, cf. Figure 2.8, compares the difference of static and actual with the static vertical wheel-rail force on one or more wheels of a bogie on the windward side of the vehicle. If all windward wheels of the bogies are evaluated, the most affected bogie is usually taken as the measure for the whole vehicle. This criterion is used in many studies, for example [1, 14, 21, 47, 50, 75, 82, 84, 88, 89], as well as in national and international standards [24,30,43] to predict the overturning risk of a rail vehicle. The evaluation is made by comparing the wheel unloading quotient to a limit value, which is set to a certain percentage. This percentage is often set to 90%, thus

$$\frac{Q_0 - Q}{Q_0} \leq 0.9. \tag{5.1}$$

The method can be used with simpler quast-static models or time-dependent MBS calculations [24,30,33]. In the latter the quotient is usually low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 2 Hz or 1.5 Hz [24,30,43,66], motivated by the low-frequency nature of the overturning process, and thus mainly ignoring the influence of the track irregularities. The limit value of 0.9 on the most exposed wheelset or bogie is relatively conservative, as vehicle overturning most probably does not appear at this stage, and the relative status of the other bogies is not taken into account.

Moment method

The moment method calculates moments about the leeward/outer rail and compares the stabilizing moment due to the gravitational forces of the vehicle with the overturning moment due to the aerodynamic and centrifugal loads. If these moments are equal, the vehicle begins to overturn, thus real vehicle overturning is considered. The method does not usually take dynamic effects from track irregularities into account. However, Andersson et al. [4] describe a moment method considering dynamic lateral track input. The method is used on national level for crosswind stability [73].

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 5.1).

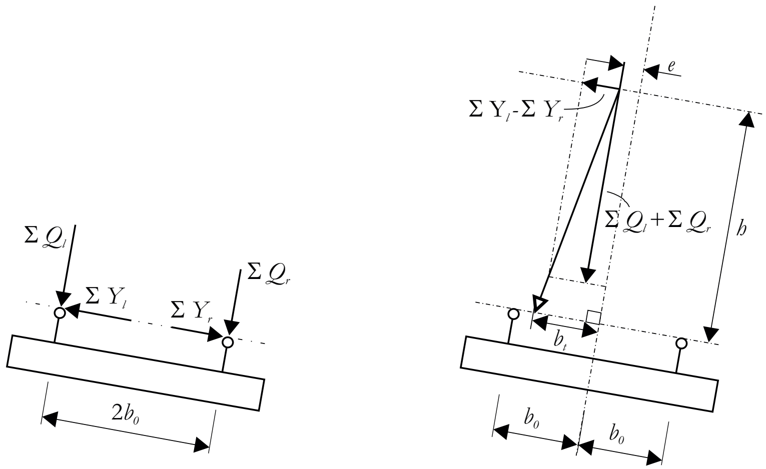

Figure 5.1: Definition of quantities for calculation of overturning risk with the intercept method. l = left, r = right [4].

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

$$n_{R,int} = \frac{b_t}{b_0} = \frac{\Sigma_{bogie} \mid Q_l - Q_r \mid}{\Sigma_{bogie} \left(Q_l + Q_r\right)} \tag{5.2}$$

A value between 0.8 and 1 is usually used as limit [66]. Low-pass filtering with 1.5 Hz is also usually applied [4]. For detailed information, see for example [4].

Besides the methods mentioned above, other criteria that are not related to overturning, but to vehicle safety as the Prud'homme/track shifting criterion or the criterion of safety against derailment Y/Q [25] are also used in some studies to assess crosswind stability [14, 66, 90].

5.2 Modelling and simulation in crosswind stability assessment

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 [5, 21], and also some standards take the rail vehicle dynamics into account [24, 30, 43].

The crosswind stability of a rail vehicle is often investigated by applying aerodynamic loads on a vehicle model in multibody dynamics simulations. However, simpler approaches using quasi-static models have also been used [35] or are available in standards [24, 30, 73]. Concerning aerodynamic loads, a distinction can be made between merely temporal gusts and spatio-temporal gusts. The former consider 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 [30, 43]. A spatio-temporal gust includes effects of varying aerodynamic loads in space and also in time due the moving vehicle, which is used for example in [82].

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 [21, 31, 34, 43, 66, 82]. A deterministic gust in combination with superposed turbulent fluctuations has been used by [71, 89]. Stochastic approaches based on the aerodynamic admittance and stochastic wind-time series have been applied to multibody simulations in [14, 27]. Unsteady CFD have recently been used to obtain aerodynamic loads on a vehicle from gusts; cf. Chapter 3. Examples are [34, 62]. The results from [34] have been used in [82] to study the reponse of a high-speed rail vehicle to unsteady crosswind, including a comparison of a spatio-temporal and a merely temporal gust using the TSI gust shape.
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 at different cant deficiencies and vehicle speeds, cf. Figure 5.2, where critical wind speed refers to the applied assessment criterion for crosswind stability. The risk evaluation or risk assessment 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 [5], or a comparison with other vehicles that are known to be safe [30, 43, 80].

Other approaches to risk assessment calculate the failure probability of the vehicle due to crosswind by taking simulation inputs such as the aerodynamic loads as stochastic and

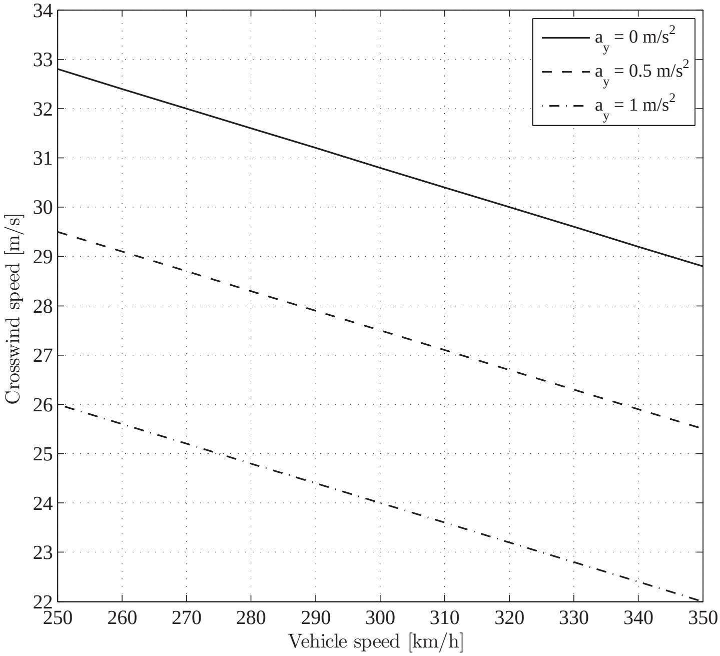

Figure 5.2: Characteristic Wind Curves for a Class 1 high-speed train for different unbalanced lateral accelerations and wind perpendicular to track. Flat ground case [43].

uncertain. By applying reliability methods like Monte Carlo analysis, a failure probability for the vehicle can be calculated [21,38,89]. A sensitivity analysis regarding both the aerodynamic coefficients of the vehicle and the gust amplitude and duration is included in [89].

5.3 Crosswind stability in standards and regulations

European standard EN 14067-6 [24] deals with crosswind stability of rail vehicles and describes assessment methods for crosswind stability. Regarding wind tunnel testing, a ground scenario representing a ballasted single track is introduced. For the assessment of the vehicle dynamics, the standard describes a quasi-static method and time-dependent MBS simulations. As critical limit value, 90% wheel-unloading on the most exposed running gear is prescribed. The standard, however, points out that this is not a limit for overturning. For passenger vehicles and locomotives, the standard presents three speed categories depending on the maximum vehicle speed. These include vehicles with maximum speed up to 140 km/h, from 140 km/h up to 200 km/h, and from 200 km/h up to 360 km/h. No reference CWCs however are given.

In 2002, the first set of Technical Specifications for Interoperability (TSI) was adopted for the trans-European high-speed rail system. These specifications were at that time prepared by the European Association for Railway Interoperability, but are now the responsibility of the European Rail Agency. The latest versions are dated 2008, with amendments in 2012. TSIs were adopted for the trans-European conventional rail system in 2011, with amendments in 2012 [42].

The TSIs for the trans-European high-speed rail system deal with crosswind stability for the rolling stock subsystem (HS RST TSI) [43] and the infrastructure subsystem (HS INF TSI) [44].

The HS RST TSI concerns vehicles with maximum service speeds of 190 km/h and above. Based on the maximum service speed, the vehicles are divided into two classes, where Class 1 includes vehicles with maximum service speeds of 250 km/h and above and Class 2 contains vehicles with maximum service speeds between 190 km/h and less than 250 km/h. For Class 1 vehicles, a set of CWCs is given that the vehicles must fulfil for running speeds between 250 km/h and 350 km/h. These CWCs were derived from the German ICE3, the French TGV Duplex and the Italian ETR 500 trains. The assessment is based on unsteady crosswind including the *Chinese hat* wind gust and 90% wheel-unloading on the most exposed running gear, low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 2 Hz. Two ground scenarios for wind tunnel testing are mentioned, including flat ground with a gap of 235 mm between ground level and the bottom of the wheels, as well as an embankment of 6 m height with ballasted double track. Requirements regarding crosswind for tilting trains of Class 1 as well as Class 2 vehicles are not included in the HS RST TSI, but represent an open point [43].

The HS INF TSI refers to the requirements given in the HS RST TSI regarding crosswind, and demands necessary measures if the requirements cannot be met, for example by locally or temporarily reducing running speeds, or by installing protective equipment [44].

The TSI for both the rolling stock subsystem for conventional rail ‚Locomotives and passenger rolling stock ‘of the trans-European conventional rail system (CR LOC PAS TSI) and for the infrastructure subsystem of the trans-European conventional rail system (CR INF TSI) mention crosswind stability as an open point [45, 46].

In 2009, the European *TrioTrain* project was started, which included three different subprojects, of which one was the subproject *AeroTrain* [86]. One task of *AeroTrain* was to close the open points related to crosswind in the HS RST TSI and CR LOC PAS TSI, which however was not achieved.

On national level in Europe, requirements regarding crosswind stability of rail vehicles in addition to the EN 14067-6 or the TSIs are either non-existent or an open point in many countries. Only a few prescribe further requirements regarding crosswind stability.

In the United Kingdom, the Railway Group Standard GM/RT2142 [73] requires evaluation of the minimum resulting wind speed that leads to an overturning of the vehicle at maximum running speed and presents a limit value the vehicle has to fulfil. The calculation is made by evaluating the overturning moment about the leeward rail. This method applies to vehicles running at up to 140 mph, or approx. 225 km/h.

Germany applies the Ril 80704 standard for vehicles with running speeds of more than 140 km/h, using the CWCs of several reference vehicles, depending on the running speed. For wind tunnel tests, a flat ground with 235 mm gap is prescribed. The vehicle dynamics are assessed by either a quasi-static approach or MBS simulations. Like the HS RST TSI, the latter include the *Chinese hat* wind gust and 90% wheel-unloading on the most exposed running gear, low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 2 Hz as the critical limit [30].

Sweden and Belgium also prescribe national requirements, where for example the CWC of the X61 vehicle is used for assessment in Sweden [77, 85].

6 Active systems for increased crosswind stability of rail vehicles

Active systems installed on a rail vehicle have been the subject of research for some time, see [70] for example. Active systems in this case are mostly actuated suspension elements that are actively controlled in order to fulfil a certain purpose, for example to improve ride comfort for the passengers or to maintain good ride comfort in case of increased vehicle speed or unfavourable track conditions [70]. The general setup of an active suspension system is shown in Figure 6.1. The vehicle responses y in terms of for

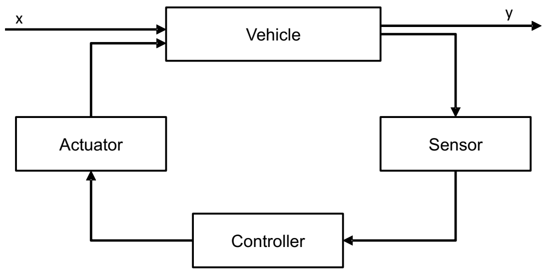

Figure 6.1: Schematic control setup of active suspension, with input measures x and output measures y.

example accelerations, velocities or displacements are measured by sensors installed on the vehicle, and controlled using a closed loop system. External disturbances x in terms of influences from the track or wind, for example, are added to the loop [70].

When active systems are used to improve the crosswind stability of a rail vehicle, different control strategies may be possible, also depending on the control input that is used. Depending on the available information regarding the crosswind situation, two control strategies may be used when the aerodynamic loads are taken into account. If no information regarding the aerodynamic loads is available, a conventional controller may be used, where the control input is based on the state of the vehicle. If information regarding the aerodynamic loads is available, feed-forward control can be applied, which leads to improved results [22]. However, even if the aerodynamic loads are not available directly, feed-forward control may be used to control the vehicle state. This, however, would require more information about disturbances of the vehicle state that are not related to crosswind.

Research has been done recently to study if active systems installed on a rail vehicle are capable of improving the crosswind stability. However, to some extent better crosswind stability was not the main focus of the work, but rather some additional improvement alongside the actual topic of ride comfort.

The beneficial effect of a so-called hold-off device, used to centre the carbody during curve negotiation, regarding crosswind stability is mentioned in [70], but no crosswind-related tests or simulations have been conducted. The effect of such a hold-off device regarding crosswind stability was studied in [1] by means of simulation in combination with active control of the air springs of the secondary suspension. The work focusses on comfort-related purposes by introducing carbody tilt and a hold-off device, but includes a so-called anti-rollover function for the air springs, aimed at reducing the sway and response of the carbody in case of crosswind. This setup is simulated using the *Chinese hat* wind gust. The control input for the feed-forward control is given by the train speed and the resultant wind angle, as it is assumed that the latter can be measured.

The idea of "active ballasting" or of shifting heavy underbelly equipment, for example a transformer, on a vehicle in a longitudinal direction, for example towards the front bogie of a coach, in order to improve crosswind stability, is presented in [22]. This idea originates from comfort-oriented control of lateral vibrations of underbelly equipment presented in [58]. Due to several disadvantages, for example increased lateral wheel-rail forces during curving, the concept has not yet been realised.

The use of active control of an electromagnetic attraction force actuator on a light two-axle vehicle is presented and discussed in [50]. The attraction actuator is controlled by feed-forward control, where the vertical wheel-rail forces are taken as control input. The concept is simulated applying the *Chinese hat* wind gust.

Paper D of the thesis discusses the use of active lateral and vertical secondary suspension to improve the crosswind stability of a fast rail vehicle [84]. Here the active secondary suspension, that is installed on a rail vehicle for the purpose of ride comfort improvement, is used to improve the crosswind stability of the vehicle by changing the control strategy in case of exposure to crosswind. The crosswind control is realised using a conventional controller with the vertical deflection of the primary suspension as control input.

7 The present work

Rail vehicles can be subjected to 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 to predict possible overturning risk are necessary, but this requires knowledge of the vehicle dynamics at large suspension deflection, in particular in the secondary suspension, and unsteady wind loads. The modelling of the secondary suspension is important to achieve feasible simulation results at large lateral shear in the suspension. If the simulations yield reasonable results, they represent an important tool for the prediction of vehicle overturning risk. The impact of crosswind loads on rail vehicles may however be reduced by using active suspension, leading to higher crosswind stability by reducing suspension deflections.

The present PhD thesis work investigates the dynamics of a fast 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 vehicle response to gust-like events is also studied in full-scale measurements giving further validation of the multibody simulations. Finally, active secondary suspension is used to improve the crosswind stability of a fast rail vehicle. The work is described in four appended papers, but is also summarized below.

7.1 Summary of Paper A

Paper A presents field measurements and multibody simulations of the lateral dynamics of a fast rail vehicle at large secondary suspension deflections caused by track curves and track irregularities. In this way, curve negotiation at different cant deficiencies was 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 the 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. In particular for large lateral suspension deflections at high cant deficiencies, the 2D model overestimated the relative displacements of both simulated results from the 3D model and measured results. The

3D simulation results were also compared to an additionally simulated unsteady crosswind case with respect to overturning risk by means of the wheel unloading measure.

7.2 Summary of Paper B

The response of a fast 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 type and consist of a self-created simple artificial gust, the *Chinese hat* prescribed in [43], 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 study the vehicle response to different gust properties as well as for parameter variations on the vehicle's suspension and mass properties.

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 were observed. A variation of the ramp distance of the simple artificial gust led to higher wheel unloading for shorter ramp distances. The leading bogie in general showed higher wheel unloading, regardless of the calculation method for the aerodynamic loads. For the trailing bogie, the loads obtained with 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 vehicle response in terms of the maximum wheel-unloading. However, the carbody showed higher roll motion oscillations from the temporal gust. Concerning the variation of the vehicle's suspension and mass properties, 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.

7.3 Summary of Paper C

Paper C presents full-scale measurements of a stationary vehicle subjected to lateral excitations of the carbody imitating crosswind. Quasi-static and dynamic gust-like loads are applied to the carbody using hydraulic actuators. The vehicle response is measured by means of lateral and vertical secondary suspension deflections, lateral accelerations on the carbody floor and vertical wheel-rail forces on one bogie. A multibody simulation model of the vehicle is validated by the measurements and used for additional parameter studies of suspension characteristics.
The vehicle responded to the carbody excitation from gust-like lateral loads with a strong sway response with overshoots in the measured signals, including the wheel-rail forces at the first culmination of the applied lateral loads. It was observed that the dynamic characteristics of the vehicle influence the results due to the presence of considerable sway oscillations. The introduction of asynchronous lateral loading to the carbody showed significant influence on the corresponding vertical wheel-rail forces for both quasi-static

and dynamic loads, where an asynchronous load resulted in less wheel unloading on the measured wheels.
The simulated parameter study showed significant influences from secondary lateral suspension stiffness on the crosswind stability of the studied vehicle, whereas damping elements had almost no effect.

7.4 Summary of Paper D

Paper D studies the possibility whether active lateral and vertical secondary suspension is able to improve crosswind stability. A fast rail vehicle that is equipped with active secondary suspension for a ride comfort oriented purpose, was exposed to crosswind loads during curve negotiation by means of simulations. For high crosswind loads, the impact of the loads was reduced using the secondary active suspension.
Information regarding the exposure to crosswind was indirectly gathered from the vertical deflection of the primary suspension, which gave indications regarding the status of wheel unloading on the windward wheel on the leading axle and was used as control input. The necessity to react on crosswind was determined using an activation limit corresponding to a certain extension of the vertical primary suspension relative to its static deflection on horizontal track.
Three different control cases were studied and compared to the only ride comfort-oriented setup of active secondary suspension as well as a vehicle with completely passive suspension.
By introducing an additional force actuator on the leading bogie of the vehicle, the application of active secondary suspension for the purpose to increase crosswind stability purposes showed significantly improved stability of the vehicle compared to the passive suspension and the normal, ride comfort oriented, active secondary suspension.
For the application of the different control cases, it was observed that the dynamic control part of the ride-comfort oriented control had beneficial influence on crosswind stability. Regarding track layout, an exposure of crosswind loads during curve transition resulted in less stability than in the circular curve.

8 Conclusions and future work

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

It was 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 higher cant deficiencies due to levelling effects of the air springs. The lack of friction in the 2D air spring model resulted in higher displacements.

The response of a fast rail vehicle subjected to unsteady crosswind during curve negotiation was also investigated. 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 effects of different gust and curve timing as well as parameter studies of the influence of the vehicle's mass and suspension properties 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 influence the crosswind stability significantly. The QTGM approach was evaluated in terms of use in 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 of this topic should be part of future work.

The response of a rail vehicle to crosswind gust-imitating lateral carbody loads were studied in full-scale experiments. The carbody of a stationary rail vehicle was loaded with quasi-static and dynamic lateral loads of both synchronous and asynchronous characteristics. The experiments represented a possibility for the validation of multibody simulations including dynamic lateral loads. Different vehicle responses were observed for synchronous and asynchronous loads, where the asynchronous loads led to less vehicle response in term of changes in the vertical wheel-rail forces and carbody roll motion. For all applied dynamic loads, the vehicle reacts with an overshoot in the transfer of vertical wheel-rail forces, which represents the highest wheel unloading. It was also observed how the dynamics properties influence the response to gust-like lateral loads.

Finally, it was concluded that active secondary suspension is able to significantly improve the crosswind stability of a fast rail vehicle. The active lateral and vertical suspension that was installed on a vehicle for ride comfort related purposes was used in order to stabilize the vehicle against major crosswind loads, using the vertical deflection of the primary suspension as control input. The ride comfort oriented control of the active suspension was found to have a beneficial effect by damping the sway response of the vehicle.

The dynamic treatment of crosswind stability in terms of unsteady wind loads is considered to be important due to the overshoots in both the aerodynamic loads and the vehicle reaction, leading to higher impacts than in steady state conditions.

Possible future work can be suggested from all parts of the present 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.

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.

The approach of using a rail vehicle's active suspension to improve crosswind stability could be extended by introducing stored track data or external information about the wind conditions in order to enhance the control possibilities.

In general, the process of vehicle overturning should be studied in more detail to clarify the process and its requirements from a vehicle dynamics point of view and to study the application and safety margins of today's overturning criteria. This would not least be very valuable with regard to standardization. One possibility for this could be improved stationary full-scale measurements, preferably using a discarded vehicle and including much higher lateral loads. This should also be reflected by simulations for validation before using the simulations in combination with unsteady aerodynamic loads.

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Part II