High-speed Train Derailments - Minimizing Consequences through Innovative Design

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Abstract

In the current paper, various possibilities of minimizing consequences of high-speed rail vehicle derailments have been studied through a combination of empirical observations and multi body system (MBS) simulations. In order to assess the appropriate measures and features for an increased derailment-worthy design, a comprehensive MBS model is developed to predict the pre and post-derailment vehicle behaviour. Preventing wheel flange climbing derailment after axle journal failures on curved track is accomplished by implementing mechanical restrictions in the bogie frame. Three alternative substitute guidance mechanisms are presented and a systematic feasibility analysis for one of them, a low-reaching axle journal box, is presented. Three conventionally coupled passenger trailing cars are investigated after derailments on tangent and curved track as a function of the maximum centre coupler yaw angle, carbody height of centre of gravity, coupler and bogie transversal beam height. Furthermore, the articulated train concept is investigated as a function of different inter-carbody damper characteristics.

1 Introduction

Over the years, advancements in active and passive safety have reduced considerably the accident risk, making rail travel to one of the safest modes of transportation. The introduction of active safety measures to reduce the probability of unwanted events has practically eliminated derailments caused by over-speeding or high-speed train collisions [10]. However, derailments due to mechanical failures affecting the wheelset guidance on rails continue to occur, despite refined inspection techniques as well as more reliable vehicles [15]. Moreover, certain types of derailment causes such as vandalism-terrorism or environmental factors are not likely to be eliminated by active measures in the near future.

In this respect, passive safety, aiming at minimizing the consequences once an accident or incident does occur, has received much attention in recent years, especially in the European Union. The main research area of passive safety has been concentrated on vehicle crashworthiness, i.e. the structural capability of the carbody to protect passengers or crew following collisions. In this respect, two standards exist or are under completion in Europe that mainly cover longitudinal impacts. Vehicle derailment-worthiness, i.e. the capability of a vehicle to avoid collisions and/or overturning of vehicles following derailments, has not received much attention. Consequently, the vehicle behaviour immediately following a derailment is not considered in any standard or in engineering practice.

Nevertheless, empirical evidence from some recent events has lead to an increased awareness in the railway community over the possibility to regain control over a derailed vehicle. For example, the Shinkansen derailment at Niigata in 2004 [9], see Figure 1a, has determined the Japanese railway JR-East to start mounting lateral guidance devices on the axle boxes on all Shinkansen bogies in order to minimise the deviation after derailment [8]. In conjunction with a derailment in 2005 at Moy in UK, see Figure 1b, the Rail Accident Investigation Branch (RAIB) made a recommendation to Rail Safety and Standard Board (RSSB) to commence studies of design elements that would limit the degree of deviation from the track [13].

In Sweden, the favourable behaviour of the tilting X 2000 train after a couple of incidents (Figure 2a), as well as other ‘successful’ derailments from abroad (Figure 2b), have in 2002 initiated the research programme entitled ‘Robust Safety Systems for Trains’ at the Royal Institute of Technology (KTH), Sweden. Passenger trains derailing at relatively high speeds have been considered, due to various mechanical failures close to the wheel-track interface as well as other causes that would ultimately affect a wheelset’s guidance on rails.

Although various accidental circumstances make each train derailment a unique event, certain patterns appeared to emerge after analyzing the collected empirical evidence in the initial phase of the project. In this manner, several critical vehicle parameters have been identified as capable of influencing the outcome of a derailment or preventing a derailment to occur [3]. It is rather straightforward to realise that field experiments involving derailing trains at 100 to 200 km/h are essentially impossible to perform, so computer simulations tools had to be developed.
The current paper summarises some key findings from the project and also gives an insight into the adopted methodologies.

![Diagram](image1.png)

Figure 1: a) Low-reaching axle journal parts that may have prevented large lateral deviations in the Shinkansen earthquake derailment in 2004, b) Clear evidence of lateral contact between the AWS support bracket and inner rail side that may have prevented further lateral deviation at Moy, UK in 2005.

![Diagram](image2.png)

Figure 2: a) The forward section of the low-reaching X 2000 bogie frame that guided the vehicle on curved track and through three switches at Lindekullen, Sweden in 2001 [14], b) The leading Eurostar power car with the derailed trailing bogie at Croisilles, France in 2000 [12].

2 Simulation methodology and validation

In order to perform a systematic analysis on the effect of various vehicle design parameters on the derailment process, an interactive process of empirical observations and computer simulations studies is employed. The available research dealing with tools and methodology for train derailment simulations is very limited. Accordingly, a pre- and post-derailment module has been developed for implementation in the general-purpose MBS software GENSYS [11].

2.1 Pre-derailment

A typical four-axle conventional vehicle considered in the MBS simulation model consists of one carbody, two bogies and four wheelsets, comprising six degrees of freedom (DoF) each. In the articulated design, adjacent carbody ends share the same bogie. The following derailment causes are considered and modeled in the MBS software:

- **Axle journal failure (AJF):** The failure of the trailing wheelset journal (inner wheel), affects the leading bogie of a passenger car. As a result, the leading wheelset starts to deviate laterally on the high rail of a circular curve section, following flange climbing.
- **Wheel flange on rail (WFOR):** Such a hypothetical condition is initiated on the leading wheelset of a rail vehicle by an initial lateral displacement of 80 mm in combination with a yaw angle of 1.58°. The leading bogie and carbody midpoints are also displaced laterally. No defects, neither to the vehicle nor to the track, are considered. This derailment scenario would correspond to sequence of events subsequent to the vehicle encountering relatively small objects on the track, as well as other possible running gear or track malfunctions that would lead to wheel flange climbing.
• **High rail failure** (HRF): Failure of the high (outer) rail in a curve is automatically a dangerous situation as the wheelsets lose all lateral guidance. The failure is modelled by removing subsequently the lateral and vertical wheel to rail contact elements once the train reaches the start of a circular curve section.

The above-mentioned derailment causes are simulated on scenarios including tangent and curved track at speeds of 100 and 200 km/h with cant deficiency $D$ varying from 0 to 245 mm (lateral track plane acceleration $a_y$ of 0 to 1.6 m/s$^2$).

Vehicle models in the simulation package GENSYN have been validated on numerous occasions previously, for normal operating conditions. The model describing the AJF derailment cause has been validated successfully by comparing the pre-derailment sequence of events with two authentic Swedish incidents from 2001 [2, 4].

### 2.2 Post-derailment

Once derailed, the forces exerted on the rolling wheels on concrete sleepers are calculated first by employing the finite element (FE) analysis tool LS-DYNA, in which a wheel impacting a concrete sleeper is modelled. A multitude of simulations are performed by combinations of various values for the following five initial impact state parameters: wheel's vertical position relative to the sleeper, wheel's three velocity components and wheelset yaw angle. The results are stored in a look-up table from which data are taken through interpolation during the continued MBS simulation. The FE model as well as the whole MBS simulation has - as a first step - been validated successfully by comparing the indentation marks with one photograph from an authentic derailment [1].

A mathematical MBS model detects any wheel-sleeper contact and generates compatible impact forces based on linear interpolation as a function of the initial impact state parameters mentioned above. The model can also take into consideration the impact situations between wheels and rail fasteners arising in the initial derailment phase.

A recent Swedish derailment incident with a loco-hauled passenger train facilitated a further successful validation of the model by comparing the vertical and lateral trajectory of the derailed wheelset over 10 consecutive sleepers with field measurements [5]. In this case, rail fasteners where involved in the impact sequences.

Briefly, the MBS post-derailment module is valid under the following premises:

- derailment on ballasted track with equally spaced undamaged concrete sleepers of constant properties
- constant post-derailment train speed (no applied braking)
- wheel to ballast contact is not considered
- impact with rail fastening system of Pandrol type; currently valid only for situations where the fastening system orientation and the train’s direction of travel coincide in such a manner that the front arch of the clip is pushed out of the centre leg upon impact
- additional impact with other infrastructure parts such as switches and crossings, signalling devices etc. are not considered.

### 3 Preventing derailment after an axle journal failure

Although not the most frequent derailment cause, an axle failure at the journal bearings, i.e. on the outside of the wheel, possess an imminent danger to vehicle safety. Empirical observations involving the X 2000 power car in combination with a technical report [16] and on-train measurements indicated that mechanical restrictions limiting the wheelset’s motion relative to the bogie frame might limit the consequences following the failure.

A parameter analysis has been performed for alternative axle failure locations in a bogie, in order to test the feasibility of minimizing the derailment tendency after such events. In this respect, failures are initiated on each of the four axle journals outside the adjacent wheel in the leading bogie. The vehicle models used have general characteristics resembling the X 2000 power and passenger trailer cars.

The analysis includes various conditional parameters such as: cant deficiency in the curve ($D = 110$ and $140$ mm at a speed of $V = 200$ and $180$ km/h, respectively), track irregularities, friction coefficients wheel to rail and axle to bogie frame.

The results are presented in Figure 3 as derailment maps for the two vehicle types. Each line corresponds to the location of the axle failure, denoted relative to the closest wheel position in the bogie and in the curve. The lines indicate the *lowest* combination of mechanical restrictions at which a derailment occurs, out of all tested conditional parameters. Each line in the diagrams corresponds to a set containing 600 MBS simulations.
Consequently, in order to avoid a derailment after an axle journal failure for the studied vehicle model, a combination of mechanical restrictions below the lowest line in the diagram should be chosen.

Figure 3: Derailment maps for an X 2000 a) power car and b) trailer car for different axle failure locations in the leading bogie; the lowest combination of mechanical restrictions that lead to a derailment.

4 Minimizing consequences after derailment

4.1 Substitute guidance mechanisms

For low-reaching mechanisms connected to the vehicle, at least three different possibilities can be identified: bogie frame (Figure 4a), brake disc and axle journal box (Figure 5a). The intended purpose of the substitute guidance mechanisms is to guide laterally and stabilise a derailed running gear by simply engaging with the appropriate rail according to Figure 4b and 5b. In order to initiate as well as to maintain a successful lateral guidance, geometrical and strength requirements need to be fulfilled. In addition, mechanisms should be able to cope with track discontinuities, i.e. traversing switches and crossings, in a derailed condition so that a further aggravating situation is avoided.

Figure 4: Low-reaching bogie frame: a) geometrical feasibility parameters essential for b) the intended guidance condition once derailed.

Figure 5: Low-reaching brake disc and axle journal box: a) geometrical feasibility parameters essential for b) the intended guidance condition once derailed.
The study has been mainly focused on the geometrical feasibility requirements. In this respect, the mechanism should be positioned sufficiently low relative to top of the rails \((h, H, H_{ajb})\) as to overcome the vertical dynamic motions induced by the derailed running gear in combination with a sufficient lateral gap \((b, B, B_{ajb})\) to accommodate the width of the rail. Moreover, the positioning of the guidance mechanisms should not interfere with applicable gauging standards for low-reaching parts.

Figure 6 shows the geometrical feasibility results for a low-reaching axle journal box attached to conventionally coupled four-axle vehicles after two different derailment causes at speeds of 100 and 200 km/h. Each line indicates the highest vertical distance \(H_{ajb}\) for different lateral gaps \(B_{ajb}\) that lead to a successful engagement with the rail. Furthermore, the lines actually indicate an averaged successful vertical distance which is computed among the results of an additional simulation set containing four different initial sleeper locations relative to the first derailing wheelset. Accordingly, a sensitivity analysis is also performed for one of the parameters that seriously affects the wheel’s vertical motion on sleepers, namely the vertical distance between the wheel’s lowest point and the sleepers upper surface at the initial impact with a sleeper.

The diagrams also show the approximately lowest possible vertical distance according to the Swedish and the more restricting interoperable European gauging standards. It is assumed that all parts of the wheelset (except the wheels themselves) must comply with gauging requirements for low-reaching parts, even if the wheelset is lowered 30 mm due to wheel wear. It is also assumed that all parts mounted on the bogie frame must nominally be located a further 30 mm higher due to possible vertical motions in the primary suspension.

![Figure 6: Feasible geometrical parameters of an axle journal box part in order to obtain a guidance condition after a derailment on curved track cause due to a) axle journal failure and b) high rail failure; ballasted track, concrete sleeper at 0.65 m, Pandrol rail fasteners, UIC60 rails (worn 14 mm).](image)

Additional results for a low-reaching bogie frame and brake disc can be found in reference [6]. In the vertical direction, guidance mechanisms should generally be located as close as possible to the top of the rail, without violating the permissible gauging standards. In the lateral direction, guidance mechanisms should be located further away from the adjacent wheel, so that the initial vertical movements, or ‘bouncing’, are attenuated by the time a lateral engagement with the rail is attempted.

### 4.2 Centre coupler restrictions (conventional train design)

For conventional vehicle trains with centre couplers, additional means of minimizing the lateral deviation after single bogie derailments on an intermediate car are by utilizing the inter-vehicle couplers. In particular, the possibility of maintaining a limited bogie lateral deviation is investigated, so that wheels can continue to roll on the relatively ‘safe’ sleeper area, and not fall into the ballast.

A standard (‘Std’) trailer car centre coupler configuration is assumed, that permits a maximum yaw rotation at the pivot centre of ±13°. This implies a maximum lateral deflection between two adjacent carbodies of approximately 0.64 m. An additional coupler configuration is modelled and labelled ‘Restricted’ which limits the maximum yaw angle by approximately 60% relative to the assumed
standard value. In the MBS computer simulation model, the semi-permanent centre coupler is modelled as a rigid beam, and consequently, carbody-coupler separation can not occur. For modern semi-permanent couplers involved in the derailment scenarios considered here, this assumption is considered viable, although not further investigated in the present study.

The feasibility of restraining the coupler as intended is addressed, in terms of permissible lateral track shift forces and derailment criteria according to UIC 518 [17] and EN 14363 [7]. In this respect, computer simulations are preformed for a “worst-case” track geometry consisting of a so-called ‘S-curve’ with two circular sections with radii $R_S = 190$ m in opposite directions and with no intermediate section. According to the results, the restriction is feasible in terms of maximum track shift forces and derailment ratio for vehicles equipped with both flexible and stiff wheelset guidance at an axle load of 131 kN.

The maximum lateral displacement of the leading and trailing wheelset of the leading derailing bogie is shown in Figure 7a and 7b, for different derailment scenarios on tangent and curved track, respectively.

All values below the horizontal line imply that the wheel’s flange rolls on the sleeper surface, corresponding to a sleeper length of 2.53 m. On tangent track, i.e. zero cant deficiency, the derailing leading wheelset and subsequently even the trailing wheelset continue to deviate laterally until the carbody reaches the limits imposed by the coupler. For the ‘Restrained’ configuration, both wheelsets are maintained on the sleeper surface. This is not the case for the derailment scenario on curved track (AJF), where the leading wheelset in both coupler configurations leaves the sleeper surface and starts to plough through ballast. For such situations, any additional aggravating sequence of events could be alleviated by bogies equipped with low-reaching transversal beams. The transversal beam may then contact the rail and act as a substitute vertical guidance mechanism. In this manner, the potentially aggravating forces arising from wheel to ballast contact are minimised.

**Figure 7:** Maximum lateral displacement of the leading and trailing wheelset in a leading bogie after derailment on **a)** tangent track due to ‘Wheel flange on rail’ and **b)** curved track due to axle journal failure.

### 4.3 Carbody height of centre of gravity

Without any lateral substitute guidance mechanisms or restrained couplers, a derailed bogie might deviate laterally. Once a wheel loses the vertical support imposed by the sleepers, there is an imminent danger of overturning. The need of such studies have emerged primarily from empirical observations involving North American double-decker cars that would appear more predisposed to overturn after derailments [3].

A standard, i.e. baseline, carbody height of centre of gravity (CoG) $h_{	ext{ccg}}$ and coupler height relative to the top of the rails $h_{	ext{cpl}}$ are assumed of 1.61 and 1.025 m, respectively. The simulations are performed with the standard coupler configuration ‘Std’, see sections 4.2, in terms of its maximum yaw angle relative to the carbody.

The maximum carbody roll angle, measured relative to the track plane and towards the outside of the track, is shown in Figure 8a and 8b for two different bogie transversal beam heights $h_{tb} = 370$ and 170 mm, respectively. The vertical location of the transversal beam in the bogie, $h_{tb}$, has a significant influence on the overturning tendency, particularly for cases of high carbody height of CoG in combination with a low coupler height. Once the vehicle’s lateral deviation starts to be obstructed by
the coupler, a roll moment is generated on the carbody towards the outside of the track. For cases of relatively large vertical distances between the carbody height of CoG and the coupler, the increased rolling moment overturns the carbody. For bogies equipped with low-reaching transversal beams, the carbody roll angle is less sensitive to the variation of carbody height of CoG and coupler height. It is concluded that a low CoG and a low-reaching transversal beam in the bogie are favourable vehicle features with respect to carbody roll angle, in particular, for railway systems with a relatively low coupler height. For such cases, a low-reaching bogie transversal beam provides a vertical substitute guidance mechanism that greatly reduces the risk of vehicle overturning.

**Figure 8: Maximum carbody roll angle after derailment on tangent track as a function of different coupler height and carbody height of CoG for a bogie transversal beam height of a) 370 and b) 170 mm.**

### 4.4 Inter-carbody longitudinal dampers (articulated train design)

A trainset consisting of five carbodies with an articulated configuration according to Figure 9 has been modelled in the MBS software according to the “3-point” principle. Each median bogie supports one carbody end, i.e. the “supported end”, which in turn carries the adjacent carbody, i.e. the “carrying end”. Accordingly, each carbody in the articulated section of the train is supported by three points, two at the “carrying end” and one at the “supported end”. For the trainset modelled here, the choice of support points can also be seen in Figure 9.

![Figure 9: Sketch of the modelled articulated trainset.](image)

The carbodies of the articulated configuration are inter-connected by one anti-roll damper acting primarily in the lateral direction and positioned in the middle of the upper corners of the carbodies. Additionally, four longitudinal dampers link the two adjacent carbodies and they are located at each carbody corner. A standard such inter-longitudinal damper is assumed and labelled “Std” with characteristics according to Figure 10.
The maximum lateral displacements of the leading and trailing wheelsets of the derailing median bogie, the fifth in the trainset, are presented in Figure 11a for a choice of transversal beam vertical position $h_{tb}$ of 270 mm. The results correspond to a derailment scenario on tangent track at a speed of $V = 200$ km/h. Stronger inter-vehicle longitudinal dampers than the assumed standard configuration, provide a sufficient resistance against adjacent car bodies’ relative yaw motion, that keep the bogie rolling on the sleepers’ surface at a substantial safety margin from the sleeper edge. For the case corresponding to the ‘-100%’ damper characteristic, i.e. no dampers are present, the derailing median bogie is relatively “free” to deviate laterally, which leads to overturning.

The maximum car body roll angle towards the outside of the track of the third vehicle in the trainset, ‘Car 3’, is presented in Figure 11b, for the same derailment scenario. In case that no dampers are present (‘-100%’), the car body overturns, as mentioned above. For such cases, the derailing median bogie exhibits a considerable roll angle once the wheels leave the sleeper area. This has a direct negative effect on ‘Car 3’ as its car body is only attached at one support point at the front-end, i.e. the “supported end”. In order to mitigate such relatively large car body roll angles, certain mechanical restrictions could possibly be incorporated at the bogie frame to car body interface, at the “supported end”. In the current articulated train model, such restrictions have not been considered. For stronger inter-car body damper configurations than the assumed ‘Std’ value, the car body roll angle is kept to a minimum as the wheels of the derailing bogie remain on sleepers.

It should be further emphasized that the employed MBS post-derailment module does not take into account the possible interaction occurring between ballast and parts of the running gear. In the conventional configuration, it is believed that this limitation has minor implications for the studied
derailment scenarios, as the coupler provides most of the vertical support once wheels deviate outside the sleeper area. Due to the nature of the articulated configuration, the derailing median bogie sinks deeper into the ballast. For such situations, the ballast might, however, provide some vertical support. In this respect, the maximum carbody roll angle results might be overestimated. The general trend, however, should still be valid.

5 Conclusions

Based on the computational results obtained in the current study, further supported by empirical observations, the following features are perceived as capable of improving a rail vehicle’s derailment-worthy design:

- mechanical restrictions that limit the wheelset’s longitudinal and vertical movements relative to the bogie frame
- low-reaching lateral guidance mechanisms attached on to the bogie frame (bogie frame parts or transversal beams with a staggered design) or the axles (journal boxes or brake discs)
- low-reaching vertical support mechanisms (transversal beams or bogie frame parts)
- small vertical distance between carbody height of CoG and centre coupler pivot centre
- small centre coupler yaw angle for the conventional train configuration
- powerful inter-vehicle longitudinal dampers for the articulated train configuration

It should be emphasized that the present study is performed under the assumption of a number of vehicle and design parameters as well as derailment scenarios that might not always be generally applicable. For a correct assessment of the post-derailment vehicle behaviour, a detailed MBS model of the vehicle under investigation is necessary, including a correct description of all low-reaching features in the running gear, restrictions in suspension, coupler deflections etc. Furthermore, some conclusions drawn here are based on vehicle features and parts with sufficiently high strength capabilities. Such assumptions might not either be generally applicable. Nevertheless, the principal influence of the vehicle features and parameters under study should still be valid.

At this stage, it is also worth pointing out that the insight gained from this research provides a relatively cost-neutral approach to reduce accident risks by decreasing the negative consequences associated with derailments at high speed. In a longer perspective, this would ultimately lead to improved safety and be beneficial for the rail industry as a whole (operators, crew, manufactures, regulatory bodies, infrastructure managers) and for passengers and the general public.

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