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Frontal collision of trains onto obliquely stuck road trucks at level crossings: Derailment mechanisms and simulation

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A B S T R A C T

Road trucks stuck obliquely across rail tracks in level crossings and collided by trains are common occurrences; such scenarios are used in the assessment of crashworthiness of locomotives. With the ongoing increase in mass of the road trucks, these incidents can lead to derailment without fully exhausting the crush zones of the locomotives, especially in light passenger trains. Understanding the derailment mechanism of trains due to frontal collisions on stuck road trucks is fundamental for the development of advanced devices and/or technologies that can prevent these derailments. This paper presents a study of the dynamic responses and derailment mechanisms of trains for this scenario using a multi-body dynamics simulation method. A fully nonlinear three-dimensional dynamic model to simulate the frontal collision of a passenger train onto an obliquely stuck road truck on a ballasted track is formulated. This nonlinear model is capable of predicting the dynamic response as well as the derailment mechanism of trains. It is shown that the large lateral shift and yaw motion of the longitudinally coupled train vehicle bodies caused by the frontal impact force is the root cause of the derailments.

1. Introduction

Railway level crossing collision is a multi-faceted complex problem affected by the condition of the road vehicle and driver as well as the operational characteristics of the train. According to a report by the Australian Transport Council [1], approximately 100 crashes occur between the trains and the road vehicles at level crossings each year, with an estimated cost of \$32 million and deaths of 37 people on average. Every year hundreds of people across the Europe die in accidents at level crossings, which accounts for one third of all rail fatalities and 1–2% of all road deaths [2]. In the USA, more than 2000 accidents occurred at railway level crossings based on statistics from 2006 to 2010 [3]. With the ongoing increase in the number of heavy road vehicles and level crossings, the risk of level crossing crashes is on the rise.

The dynamic response, stability analyses and energy absorption mechanism of various structures under vehicle impact have attracted extensive research [4–8]. Among all road crashes, those that involve collision between heavy road trucks and passenger trains are the most severe. When a travelling train collides with a heavy road vehicle passing through or stuck at the level crossing, either the locomotive driver cabin would crush and the train stop due to emergency braking or the train derail without fully exhausting the frontal crush zone of the train. There are four collision scenarios defined in EN 15,227 [9], including: 1) A front end impact (head-on collision) between two identical trains; 2) A front end impact onto a buffered rail vehicle; 3) Train front end impact with a heavy obstacle (e.g. stuck truck on road crossing); 4) Train impact onto a low obstacle matter (e.g. car on road crossing, animal, rubbish, etc.). The collision scenario 3 is treated in this paper; this scenario is defined in EN 15,227 [9] mainly focusing on the energy absorption process for crashworthiness assessment of the cabin of the train driver. Although collision induced derailments are real and frequent, the research on this matter is rare; to the best of the knowledge of the authors, and only Koo and Choi [10] have reported derailment of wheelsets under frontal collision.

Theoretical studies on railway vehicle running safety and derailment are reported in [10–16]. Crashworthiness and safety of rail vehicles under frontal collisions are contained in [10,17–18]. Koo and Choi [10] proposed a simplified wheelset model to evaluate the frontal collision-induced derailments. In their studies, different collision scenarios have been used to generate the impact forces causing the wheel derailment. The train vehicle collision deformation, dynamics and specific wheel–rail interactions have not been considered. Sun et al. [17] developed a three-dimensional (3D) nonlinear rigid body model for the investigation of the crashworthiness of a passenger train using the multibody system (MBS) dynamics approach. The results show that it is better to increase the crush length than reducing the crush force in order to retain the low levels

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of the longitudinal deceleration of the passenger vehicles. Zhou et al. [18] investigated the frontal collision safety of a tram vehicle crashing onto a rigid obstacle. Their research shows that the maximum impact angle between the city tram and oblique obstacle should be reduced from 45° to 25° to avoid derailment.

In the present paper, a fully nonlinear 3D train–track model obliquely impacting a road truck stuck at level crossing is presented. Based on the simulation, the dynamic response of a typical train collided with a loosely stuck truck, including the lateral and yaw displacements of the train vehicle body and the wheel/rail lateral displacement, are presented. The derailment mechanisms between the wheels and the rails for a passenger train subjected to frontal oblique impact are analyzed. A concept of derailment boundary line is introduced to evaluate the derailment safety of the trains under different frontal collision scenarios. The key parameters influencing the derailment behavior of the collided trains are presented in detail.

2. Potential train–truck frontal collision scenarios at level crossing

Change in kinetic energy of train vehicles contributes to the derailment [12], and thus a simple energy analysis on the potential train–truck impact scenarios and the derailment risk is proposed firstly. During a train–truck frontal impact process, the energy conservation equation can be given as

$$E_{\mathrm{tvi}} = E_{\mathrm{tvk}} + E_{\mathrm{rtk}} + E_{\mathrm{tvc}} + E_{\mathrm{rtc}} + E_{\mathrm{loss}} \tag{1}$$

where

$$E_{\mathrm{tvi}} = \frac{1}{2} m_{\mathrm{tv}} v_{\mathrm{c}}^2; E_{\mathrm{tvk}} = \frac{1}{2} m_{\mathrm{tv}} v_{\mathrm{tv}}^2; E_{\mathrm{rtk}} = \frac{1}{2} m_{\mathrm{rt}} v_{\mathrm{rt}}^2 \tag{2}$$

where E_{tvi} is the initial kinetic energy of the train vehicles before impact; E_{tvk} is the kinetic energy of the train vehicles after impact; E_{rtk} is the kinetic energy of the road truck after impact; m_{tv} is train mass; m_{rt} is the road truck mass; v_{c} is the train impact velocity; v_{tv} is train residual velocity after impact; v_{rt} is the road truck velocity after impact; E_{tvc} is the energy absorbed by the train vehicle crush zone; E_{rtc} is the energy absorbed by the truck body; and E_{loss} is the energy dissipated by contact friction, damping, etc. It can be expected that E_{loss} is much smaller than other parts of output energy.

Based on the principles of conservation of momentum and energy, the kinetic energy loss of a train–track impact (assumed as a completely inelastic collision) at level crossing can be given as

$$E_{\mathrm{kloss}} = E_{\mathrm{tvc}} + E_{\mathrm{rtc}} + E_{\mathrm{loss}} = \frac{m_{\mathrm{tv}} m_{\mathrm{rt}} v_{\mathrm{c}}^2}{2(m_{\mathrm{tv}} + m_{\mathrm{rt}})} \tag{3}$$

If m_{rt} is much smaller than m_{tv}, the loss of kinetic energy during a train–track collision can be approximately expressed as

$$E_{\mathrm{kloss}} \approx \frac{1}{2} m_{\mathrm{rt}} v_{\mathrm{c}}^2 \tag{4}$$

It shows that the loss of kinetic energy depends mainly on the train impacting speed and the road truck mass. This means that the damage of the train vehicle and the road truck, as well as the train derailment potential, will be increased when a passenger train collided with a heavier truck at higher impacting speed. Several typical scenarios of train–truck collision with different truck weight and stuck state at level crossings are shown in Fig. 1. These scenarios are summarized below:

(a) **Train impacting light truck loosely stuck across track**: As shown in Fig. 1a, when a passenger train impacts a light truck stuck across rails at level crossing due to mechanical breakdown or other factors, it causes largely damage (or even completely braking) of the truck which is swept out of the track region instantly. In such a situations, the kinetic energy loss (E_{kloss}) would not be very large, which will be mainly absorbed by the truck body crushing ($E_{\mathrm{rtc}} \approx E_{\mathrm{kloss}}$). As a result, the train would only suffer minor damage and no derailment will occur due to minimum impact energy absorbed ($E_{\mathrm{tvc}} \approx 0$). For this type of front collision accident, only the passive safety requirement of crashworthiness of passenger trains would be sufficient.

(b) **Train impacting light truck well stuck across track**: This scenario represents a passenger train colliding with a light truck stuck at level crossing due to external factors such as the tires caught in track structure. The kinetic energy loss of a train impacting such a well stuck truck would be larger than that of the Scenario (a). Therefore, the truck kinetic energy (E_{rtk}) existing in Scenario (a) is added to the total kinetic energy loss (E_{kloss}) in Scenario (b). Thus in this type of collision scenario, the light truck would be fully damaged and broken under the passenger train impact, as shown in Fig. 1b. At the same time, the train vehicle damage could also be considerable; therefore, this type of collision scenario can be mitigated through enhanced crashworthiness of the passenger train.

(c) **Train impacting heavy truck loosely stuck across track**: This scenario is likely to cause derailment due to larger kinetic energy loss (E_{kloss}). As shown in Fig. 1c, when a passenger train impacts a heavy truck loosely stuck across track at level crossing, not only the truck would be largely damaged, but also the train vehicle might derail, especially when the impact angle is large. For this type of train–truck collision, the large kinetic energy loss (E_{kloss}) is mainly absorbed by the plastic deformation of the train vehicle crush zone (E_{tvc}) and the truck body (E_{rtc}). Besides, the heavy truck would be swept out of the track region quickly under the large impact force; roll-over could also occur depending on the tire-road contact conditions. The severity of this type of front collision is not only dependent on the train operating speed and the truck mass, but also the emergency braking rate of the train, crash behavior of train vehicle and road truck body, impact angle between the front end of the train vehicle and the truck side wall, collision energy absorption of the train suspensions and the friction between the truck and road surface.

(d) **Train impacting heavy truck well stuck across track:** The scenario represents the most severe front collision accident resulting in heavy damage of road truck and train derailment, as depicted in Fig. 1d. When a passenger train impacts onto a heavy road truck well stuck into the track structure at a level crossing, it could be compared to the scenario of a train crashing into a large deformable wall. If the impact angle is large, it is not possible for the train to consume the large collision energy without derailment. The severity of this type of train–truck collision is also dependent on many factors as discussed in Scenario (c).

There can be many other scenarios. Considering the regular occurrence and the severity of these train–truck collision scenarios, only Scenario (c) is simulated and analyzed in this paper. The detailed modeling of the crash behavior of a passenger train obliquely impacting a heavy road truck stuck at level crossing using MBS approach is presented in Section 3.

3. Modeling of train vehicle and road truck crash behavior

As shown in Fig. 2, the first train vehicle body is assumed to consist of a non-deformable zone and a crush zone. The non-deformable zone is modeled as a lumped mass representing the dynamics behavior of the train vehicle body (described in Section 4.1), while the crush zone is replaced with an elastic-plastic spring element that simulates the crash compression deformation. Generally, the crush zone is composed of three energy absorbing components: (1)