Dynamic Analysis of High Speed Rail-Vehicle Collisions

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ABSTRACT
In the event of a collision between a traveling, high speed train and a vehicle, the scale of human fatality and property damage can increase substantially if the train derails from its track after impact. Hence, it is important to identify the conditions and factors that may potentially lead to derailment in the event of a train-vehicle collision incident at a highway-rail grade crossing. This understanding is crucial to the design of safer rail crossings and tracks, and the development of operating standards for rail system, which is the chief purpose of this study. In the present paper, the multi-body dynamic modeling technique is applied to simulate train-vehicle collisions under various scenarios. The derailment coefficient result is calculated to compute the probability of derailment that provides a direct measure of the propensity towards derailment following an impact. Key results of the studies with various parameters are presented.

INTRODUCTION
As trains are operated at higher speeds in part to improve the efficiency of our rail transportation system, the likelihood of highly severe accidents occurring also increases significantly. In accidents involving trains and vehicles at highway-rail grade crossings, the scale of human fatality and property damages rises substantially when the train actually derails from the tracks after impact. To address this important concern, the objective of this project is to gain a more thorough understanding of the conditions and factors affecting derailment in the event of a train colliding with a stationary or moving vehicle. To attain this goal, a computer simulation model applying 3-dimensional multi-body dynamic modeling technique is proposed since actual field testing work is very expensive and dangerous.

In typical traffic accidents involving two or more large bodies, even though the colliding masses may undergo substantial elastic or permanent deformations, the location of the center of gravity is only affected slightly. This type of characteristic permits the simulation of impact occurrences to be based on the laws of mechanics of solid bodies. In the case of train-vehicle collisions, the problem can be accurately modeled by applying multi-body dynamics coupled with 3-dimensional elastic contact theory governing the wheel/rail interaction. This proposed concept forms the fundamental basis for the simulation models used in the present study. The knowledge of the motion of the train and vehicle bodies after impact coupled with the dynamic interactions between the wheel set and rail tracks can be used to predict the probability of derailment.

In the analysis of the train-vehicle collision problem, the derailment coefficient and probability of derailment or climbing probability are two important parameters that can be applied to assess the likelihood of the train leaving its track after impact. The derailment coefficient is defined as the ratio of wheel lateral to vertical forces at the flange–railhead contact surface [1]. These forces can be calculated from the proposed 3-dimensional, multi-body dynamic simulation model. The concept of climbing probability was developed by Tanahasi [2] who introduced the formulation in terms of the statistical parameters of the derailment coefficients for various combinations of rail
and wheel conditions. Note that no earlier study has produced a conclusive threshold value of the derailment coefficient; only the probability of derailment occurrence for a given coefficient is reported thus far. Nevertheless, this concept will be applied here to determine the severity of the derailment in a given train-vehicle collision event. The proposed simulation model is also applied in this study to perform selected parametric studies and examine the effects of critical factors. The overall approach used to formulate the simulation model is given in the flowchart shown in Figure 1 below.

**MODELING APPROACH**

By developing an accurate 3-dimensional multi-body dynamic model, the train-vehicle collision problem can be analyzed without having to conduct physical testing that is both dangerous and costly. Specifically, the proposed simulation model will have following advantages over the actual field testing work:

- Explore the effects of many conditions and factors on the probability of derailment in a more repeatable and controlled manner.
- Analyze design changes quicker for much lower cost and under safe environment.
- Avoid the use of complex test instrumentations, fixtures and procedures typically needed for actual field experiments.
- Study the problem in a secure environment without the fear of losing data from instrument failure or losing testing time because of poor weather conditions.
Based on the requirements of the simulation proposed in this study and detail examination of all the existing dynamic modeling software packages, such as Matlab, Abaqus, Pamcrash, Adams and Dyna3D, it was determined that the Adams/Rail [3] multi-body dynamic modeling software package is the most feasible option for the present train-vehicle collision study. The main structure of the Adams/Rail simulation package is summarized in Figure 2.

![Figure 2: Structure of Adams/Rail modeling package](image)

**Theory**

In general, there are two basic forms of multi-body dynamic model, namely rigid (inelastic) and flexible (elastic) body types. In our approach, a mixed form is applied whereby the train, bogie and vehicle are mostly modeled as rigid bodies, and the connectivity between the adjacent car bodies are done in a flexible manner. Further discussions of the fully assembled train model will be given later. First, the concept of derailment coefficients and climbing probability is presented. In analyzing the train-vehicle collision problem, the derailment coefficient and probability of derailment or climbing probability are two important concepts used to quantify the likelihood of impacts that ultimately lead to the train leaving the rail tracks. The derailment coefficient \( \Gamma \) that is defined as the ratio of the wheel lateral to vertical forces at the flange–railhead contact surface in an earlier discussion is computed from the following equation,

\[
\Gamma_i = \frac{|l_i|}{|V_i|},
\]  

where \( i \) is the specific wheel number, and \( l \) and \( V \) are the lateral and vertical contact forces between the rail and wheel flange. Note that no earlier study has produced a conclusive threshold value of the derailment coefficient; only the probability of derailment occurrence for a given coefficient is reported thus far. In spite of this lack of data, the probability concept will be applied in the present study as it is still a very useful metric in determining the severity of a given train-vehicle collision event from the viewpoint of the wheel set leaving the rail tracks. To further explain the significance of the probability of derailment metric, the background theory of the climbing probability is presented next.

**Climbing probability**

An earlier study on the derailment coefficient by Nadal [1] led to the following derailment criterion:
\[
\Gamma_i \geq \frac{\tan \alpha_i - b_i}{1 + b_i \tan \alpha_i}, \quad \beta_i > 0, \quad (2)
\]

where, \( \beta_i \) is the angle of attack, \( b_i \) is the coefficient of friction at the contact point, and \( \alpha_i \) relates to the attack angle between the horizontal and tangent planes at the flange rail head contact point as shown in Figure 5.2.

The physical interpretation of the Nadal’s criterion for the derailment coefficient \( \Gamma_i \) based on Equation (2) states that for a positive angle of attack, the flange will climb up the rail head when the wheel overcomes the friction between the contact areas. However, the results of Tanahasi’s experiments [2] indicated that derailment did not only occur for \( \Gamma \) greater than the Nadal’s value. In fact, derailment sometimes occurs for \( \Gamma \) less than the Nadal’s value. Based on this observation, Tanahasi introduced the concept of the climbing probability of the wheel flange as a function of various rail and wheel conditions as a means to evaluate the likelihood of derailment occurring. The statistical average (\( m_i \)) and standard deviation (\( \sigma_i \)) of the derailment coefficients for various combinations of rail and wheel conditions are provided by Tanahasi’s [2], which are used in the following probability \( P_i \) estimation formula:

\[
\log_e P_i = 2 - 0.0034 \left[ 3.5 - \frac{\Gamma_i - m_i}{\sigma_i} \right]^4, \quad \frac{\Gamma_i - m_i}{\sigma_i} > 4. \quad (3)
\]

The resultant metric is expected to provide a direct measure of the propensity towards derailment in the event of a collision. This concept is used in the present study to determine conditions and factors most likely to affect derailment as the result of a collision between the train and a vehicle.

**Methodology for Computing the Probability of Derailment**

With the aid of the technical information gathered from the literature survey, a methodology was developed for evaluating the derailment coefficient and probability of derailment using the Nadal and Tanahasi formulations [1-2] as presented in the previous Section. This concept is one of the key ingredients in the determination of the onset of derailment given a specific set of system parameters and dynamic characteristics.

The calculation of probability of derailment is sensitive to the statistical average (\( m_i \)) and standard deviation (\( \sigma_i \)) values of derailment coefficients. Note that in the experiments conducted by Tanahashi [2], typical values of average and standard deviation values for limited number of cases were obtained. In this study, a methodology is developed to compute these statistical parameters numerically. To accomplish this calculation, the derailment coefficient plots for a selected set of analyses are first used to compute the basic statistical parameters. The
numerical answers are then applied to predict the probability of derailment for cases that are not included in the initial set.

To demonstrate the validity of the statistical model, a three-bogie train model with each bogie mass set at 32,000 kg and a stationary 8,000 kg vehicle are used in the simulation. The rail tracks are assumed to be straight. The analysis is repeated for train speed of 5, 10, 15, 20, 30, 40, 50, 60 and 70 m/s to produce the results shown in Figure 4. The average derailment coefficient value \( m_i \) for all speeds except 10 and 50 m/s is then calculated yielding 0.18 with a corresponding standard deviation of 0.017. Using the statistical data, the probability of derailment in percentages for 10 and 50 m/s are then predicted (see Figure 5). The results show that the 50 m/s case derails while the 10 m/s case is found to remain on the track after impact, which is consistent with the other cases.

![Figure 4 – Derailment coefficients for different train speeds.](image)

![Figure 5 – Probability of derailment for different train speeds. Note that the 50 m/s and 10 m/s cases were not used in the calculation of the average and standard deviation](image)
PARAMETRIC STUDIES

In this section, the results of a few set of case studies obtained using the proposed 3-dimensional, multi-body dynamic simulation model are presented. This goal is accomplished by first simulating the dynamics during and after impacts, and then computing the resultant contact force functions at the rail and wheel flange, the contact forces after impacts are then used to compute the derailment coefficients and climbing probabilities that provide a direct measure of the propensity towards derailment. A flowchart summarizing the analysis procedure is given in Figure 6.

![Flowchart](flowchart.png)

**Figure 6** – Analysis flowchart for determining the likelihood of train derails.

Using the above collision analysis process, a range of parametric studies are performed to examine the effects of the vehicle mass, mass of bogies, number of bogies, train and vehicle speeds, and track curvature on the rail and wheel flange contact forces. Each case is simulated for 0.5 second of elapsed time. Few studies are presented in this paper. Results are shown in Figures 7-9 below.

![Graph](graph.png)

**Figure 7** – Effects of train speed (70-180 kmph) and stationary vehicle mass (2000-52000 kg) on the probability of derailment for a 3-bogie train (each bogie is 32000 kg) traveling on a straight track.
CONCLUSIONS

A 3-dimensional, multi-body dynamic model has been developed for simulating the dynamics of a high-speed train colliding with either a stationary or moving vehicle. The proposed model is developed applying the Adams/Rail software package that applies the fundamental mechanics of solid bodies along with elastic contact theory governing the interaction between the wheel set and rail track. The resultant train model comprises of multiple bogies connected to each other via a set of spring elements with nonlinear clearance property. The proposed model has also been verified by testing it on simple limiting cases and known cases. The simulation model is then applied to compute the dynamic contact forces at the wheel/rail, which are used to predict the derailment coefficients and ultimately the probability of derailment. The probability of derailment provides a direct means to assess the likelihood of the train derailing from its track.
The resultant multi-body dynamic model is then applied to perform a series of parametric studies in order to develop a better understanding of the conditions and factors controlling the probability of derailment. The following specific conclusions are obtained from the present analysis:

- Probability of derailment increases with greater vehicle mass, lower train mass, higher vehicle and train speeds, and shorter track curvature radius.
- Train speeds in excess of 100 kmph will most likely lead to derailment of the train after impact.
- For vehicle mass less than 10% of train mass, the likelihood of derailment is very small (less than 10% chance) assuming other factors are not extreme.

REFERENCE

