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Effect of Filling Level on the Dynamic Performance and Derailment Risk of a Tank Wagon on Curved Track

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The dynamic stability of partially filled tank wagons presents a critical challenge in the rail industry, where fluid sloshing can significantly impact operational safety. This study utilizes a three-dimensional multi-body simulation in Universal Mechanism (UM) software to investigate this phenomenon. An equivalent pendulum model, with parameters derived for each fill level, is employed to represent fluid behavior at 30%, 60%, and 90% loading on curved tracks. The analysis reveals a complex relationship between fill level and stability. While the quasi-static Nadal (L/V) ratio improves with the added mass of higher fill levels, the dynamic analysis tells a different story. The critical derailment speed paradoxically decreases by up to 20% as filling increases from 30% to 90%. This suggests that while a fuller wagon is more stable against rolling over at low speeds, it is more susceptible to derailment from dynamic oscillations at higher speeds. These findings demonstrate that fluid sloshing has a dominant, non-linear destabilizing effect that must be considered in wagon design and operational guidelines. This model provides a robust framework for optimizing wagon performance and suggests that speed limits may need to be tailored to specific fill ranges to enhance transport safety.

1. Introduction

Tank wagons are a cornerstone of material transportation systems, playing a critical role in various industries. Fluctuations in tank filling levels directly impact the dynamic behavior of wagons, significantly affecting the safety and efficiency of transportation systems. Given its importance, numerous studies have focused on the dynamics of tank wagons. Historically, research has explored design factors related to partially filled tanks, particularly their resistance to rollover [1, 2]. Extensive investigations have also addressed the effects of fluid sloshing and impact in partially filled tanks, leading to the development of simplified models for problem-solving [3]. The significance of sloshing has prompted researchers to conduct parametric studies on both road [4] and rail tank wagons [5], examining the effects of braking and baffle installation. Other studies have focused on the geometric design of tanks, both with and without baffles, under partially filled conditions [6], while some have specifically analyzed longitudinal fluid sloshing during curved movements [7, 8]. Shahrooei et al. [9, 10] investigated sloshing coefficients during braking using both finite element modeling in ADAMS/RAIL and experimental methods. For simplicity, simplified models such as equivalent pendulums or mass-spring systems [11] are often employed to represent fluid sloshing. Younesian et al. [12] introduced a novel strategy to enhance the roll/pitch stability of a tank using a tuned mass damper (TMD) [1]. This study highlights the importance of examining sloshing and lateral dynamic equilibrium in a partially filled tank wagon simulated in Universal Mechanism (UM)

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software. UM, with its comprehensive rail module, has gained significant attention among rail researchers and is highly suitable for freight wagon modeling [13]. Other studies have dynamically modeled partially filled tank wagons using multibody simulation (MBS) [2] software such as SIMPACK [14].

In this research, a three-dimensional model of a tank wagon is developed using UM software to enhance the understanding of its dynamic behavior under real operational conditions. The model considers three filling levels—30%, 60%, and 90%—and simulates a curved track representative of common routes in Iran's rail network. Critical derailment speeds for the wagons are analyzed and compared. The proposed model contributes to the optimized design of tank wagons, enhances rail transportation safety, and facilitates advanced 3D analyses using UM software.

2. Theory and Modeling

Three-dimensional dynamic simulation of tank wagons offers both advantages and challenges. A key advantage is the enhanced accuracy and realism of the results compared to simpler models. One of the primary challenges in such modeling lies in accurately representing the fluid filling behavior within the tank. To study lateral fluid sloshing in tank wagons, simplified models have been developed to capture and simulate certain sloshing characteristics. The tumbling pendulum [1] is one such model. While the tumbling pendulum is not a direct representation of fluid sloshing, it is a dynamic system exhibiting chaotic behavior [2], which shares similarities with certain features of turbulent flows.

2.1. Tank Wagon Model and Equivalent Pendulum Theory

In this section, a numerical analysis of a tank wagon is presented. The modeling was performed using Universal Mechanism (UM) software, leveraging its capabilities to create initial models for tank wagons in full, half-full, and empty states. The specifications of the tank wagon are detailed in Table 1, and a sample of the modeled tank wagon is illustrated in Figure 1.

Table 1. Parameters used for the wagon in the UM software

Car weight (ton)	Wheel Radius (m)	Tank Radius (m)	I_x $(kg.m^2)$	I_y $(kg.m^2)$	I_z $(kg.m^2)$
27.2	0.475	1.5	21,840	74,785	87,666

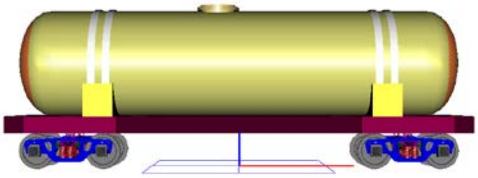

Figure 1. A view of the tank wagon used in the UM software

2.2. Equivalent Pendulum Modeling for a Partially Filled State

To make better use of numerical simulation methods, certain simplifications are employed. For this purpose, to simulate the sloshing force exerted on the partially filled wagon, the Trammel pendulum model has been utilized. Figure (2) shows the model of the tank wagon in a partially filled state.

In this wagon, a pendulum is designed to be placed inside the wagon's tank. The next section will detail the design of this pendulum.

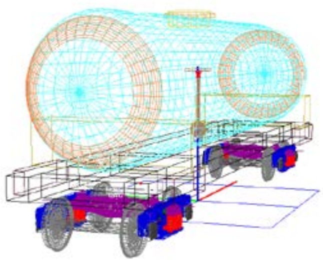

Figure 2. Image of the constructed model of the wagon with the pendulum for the filled state in UM

Subsequently, various calculations must be performed to obtain these parameters, which are described below.

2-2-1- Equivalent Pendulum Mass:

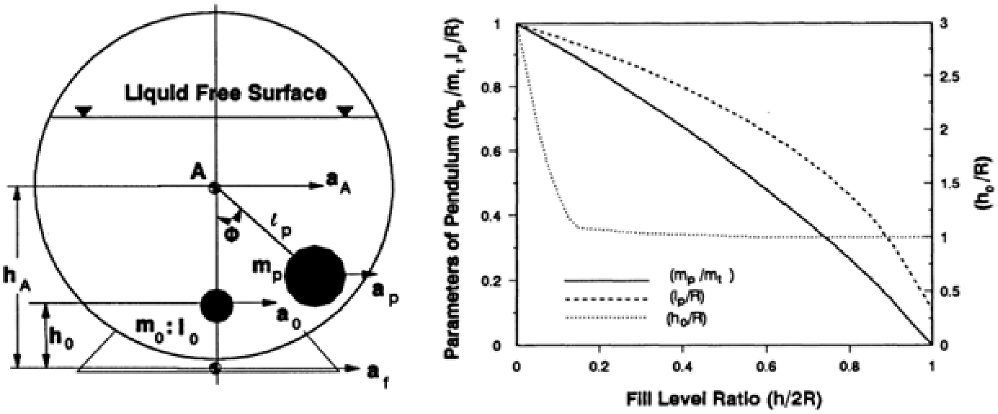

Figure 3. Method of approximating the fluid as a fixed mass and a sloshing [3]

For this section, the method proposed by Ranganathan [3] has been used. The fluid mass is assumed to be divided into two parts: a fixed mass and a moving mass.

Fixed Mass (m_0): This portion of the fluid moves along with the tank without any relative motion with respect to the tank walls. This is the main mass of the fluid that is directly affected by the external forces exerted on the tank.

Sloshing Mass (m_1): This portion of the fluid mass is considered the part that performs an oscillatory or "sloshing" motion in response to the tank's movement. This part represents the motion of the fluid's free surface and the creation of waves and vortices. This mass is virtually modeled as a pendulum or a spring attached to the fixed mass. The required parameters are adapted from Figure (3) and listed in Table (2).

Table 2. Parameters obtained from the chart in Figure 3

Fill Ratio (%)	m_p/m_t	h_0/R	l_p/R
30	0.747	1.373	0.829
60	0.448	1.039	0.571
90	0.133	0.824	0.295

In the table above, R is the tank radius, h_0 is the distance of the fluid's center of mass from the bottom of the tank, m_p and l_p are the mass and length of the pendulum, respectively, and mt is the total mass.

2.2.2. Calculation of Volume, Mass, and Filled Mass in the Wagon Tank:

To calculate the filled mass at various filling percentages of the tank, it is first necessary to determine the total volume. Then, by assuming a specific fluid, the total mass is calculated.

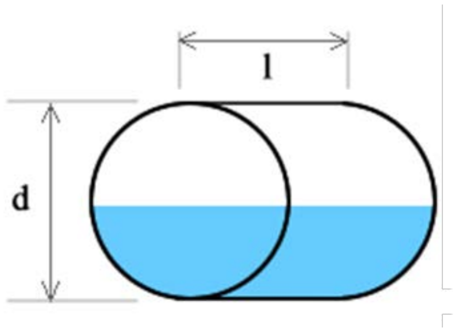

Figure 4. A partially filled tank with its parameters

Finally, using the tank's filling percentage, the total filled mass (m_t) is obtained.

The total volume of the tank, with a length of 10.65 m and a radius of 1.5 m, is obtained using Equation (1) below:

$$V_{tank} = \pi r^2 l = \pi (1.5)^2 (10.65) \cong 75.31\, m^3 \quad (1)$$

The volume of the fluid inside the tank is calculated using Equation (2) below:

$$V_{fluid} = V_{tank} \times \%fill \quad (2)$$

Assuming the fluid is water, with a density of ρ=1000kg/m^3, the total mass of the fluid can be estimated using Equations (3) and (4):

$$m_t = m_{fluid}(kg) = 1000 \times V_{fluid} \quad (3)$$

$$m_t = m_o + m_p \quad (4)$$

In Equations (3) and (4), mt is the total mass. Using the equations above and the coefficients from Table 2, the calculated masses for each of the filling percentages are listed in Table (3):

Table 3. Filled fluid volume and the calculated mass for the fixed and sloshing parts

Fill Ratio (%)	Fill ratio	$V_{fluid}\ (m^3)$	$m_t\ (kg)$	$m_o\ (kg)$	$m_p\ (kg)$
30	0.3	22.593	22593	16722.2	5870.798
60	0.6	45.186	45186	20031.26	25154.74
90	0.9	67.779	67779	9927.18	57851.82

2-3-3- Calculation of the Tank's Fill Height and the Position of the Fluid's Center of Mass in the Equivalent Pendulum Method for a Given Filling Percentage:

For this purpose, the area of the gray section in Figure (5) must first be calculated, and then by using trigonometric relations, the height *h* can be obtained. From the relation below, at any angle θ, the cross-sectional area of the fluid (Aw) is calculated as follows:

$$A_{fluid} = \pi \frac{r^2}{2}(\theta - \sin\theta) \quad (5)$$

In the above equation, the angle θ is calculated in radians.

$$\theta = 2\cos^{-1}(\frac{m}{r}) \quad (6)$$

By multiplying the cross-sectional area by the tank's length, the fluid volume at each filling percentage is calculated; in this manner, the height *h* can be determined.

It is worth noting that when the tank is more than half full, this calculation will be based on

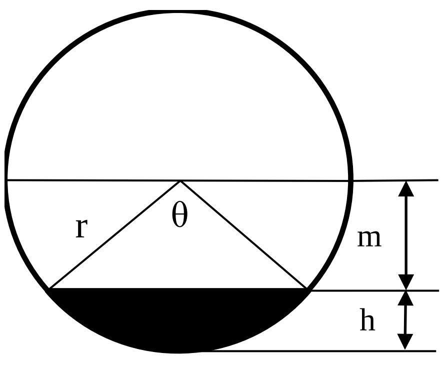

Figure 5. Schematic diagram of the tank's cross-section with a fill height of *h*

the empty space above the tank, and slight modifications to the equations will be introduced.

Using what was stated in the section above, the height *h* has been estimated from the fluid volume for the given filling percentages. Furthermore, by knowing the fluid mass at different filling percentages, as well as the estimated fluid height in the tank, the position of the center of mass (C_g) for each filling percentage was estimated using MATLAB software and is listed in Table (4).

Table 4. Filled fluid volume and the calculated mass for the fixed and sloshing parts

Fill Ratio (%)	$h\ (m)$	$h_{cg}\ (m)$
30	1.02	0.5971
60	1.74	0.9909
90	2.53	1.3641

Effective Pendulum Length (L):

The effective pendulum length is defined as the vertical distance between the center of rotation and the fluid's center of mass, which is given in Equation (7).

$$L_p = h_{cg} \quad (7)$$

Based on the above calculations and the obtained data, the software modeling is performed in the next section.

3. Modeling in UM Software

3.1. Introduction

In the "Theory and Modeling" section, the geometry of the tank wagon was described within the software environment, and a mechanical equivalent model was introduced to analyze the dynamics of the fluid inside the tank. Subsequently, using this equivalent model, the pendulum parameters (including length, mass, and point of attachment) were determined to simulate fluid sloshing at various tank filling percentages. In this section, utilizing the wagon model and the calculated pendulum parameters, a dynamic simulation of the multi-body system (comprising the wagon and the equivalent pendulums for various filling percentages) is performed in the UM software. The objective of this simulation is to investigate the influence of changes in the tank's filling percentage on the dynamic behavior of the wagon and to analyze the interaction between the wagon's motion and the fluid oscillations within it. This approach enables a more detailed examination of the influence of various parameters on the stability and performance of the wagon under diverse operating conditions.

3.2. Modeling the Pendulum and Fixed Mass in the Software

As the wagon used in the software model was described at the beginning of Section 2.1, the pendulum is similarly designed in this section according to the calculated specifications. For the fixed mass, a point mass is considered, which is equal to the calculated fixed mass; this point mass is located at the fluid's center of mass. Due to the large number of filling percentages, the details for the 30%, 60%, and 90% fill levels will be presented in Table (5).

Table 5. Filled fluid volume and the calculated mass for the fixed and sloshing parts

Fill Ratio (%)	Pendulum weight (kg)	Pendulum Effective Length (m)
30	213	0.295
60	201	0.307
90	170	0.321

3.3.Track Modeling:

To investigate the effect of sloshing, a curved track has been considered. As shown in Figure (6) and Table (5), this track is analyzed with a

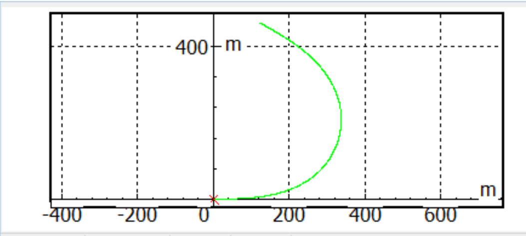

Figure 6. Schematic of the tank wagon's travel track in UM

constant radius of 190 m and a length of 350 m. A schematic of the track can also be seen in Figure (6).

Table 6. Filled fluid volume and the calculated mass for the fixed and sloshing parts

Parameter	Symbol	Value
The stable length of the curve	S	200 (m)
Curve radius	R	190 (m)
Cant	h	0.09 (m)
The entire length of the route	L	800 (m)
Friction coefficient	μ	0.25

4. Results

Considering the previous sections and using the parameters obtained in the design of the empty and filled wagon with the equivalent pendulum model, the simulation results from the UM software will be examined in this part. In the analysis process, the results of the empty model are first extracted and then compared with the

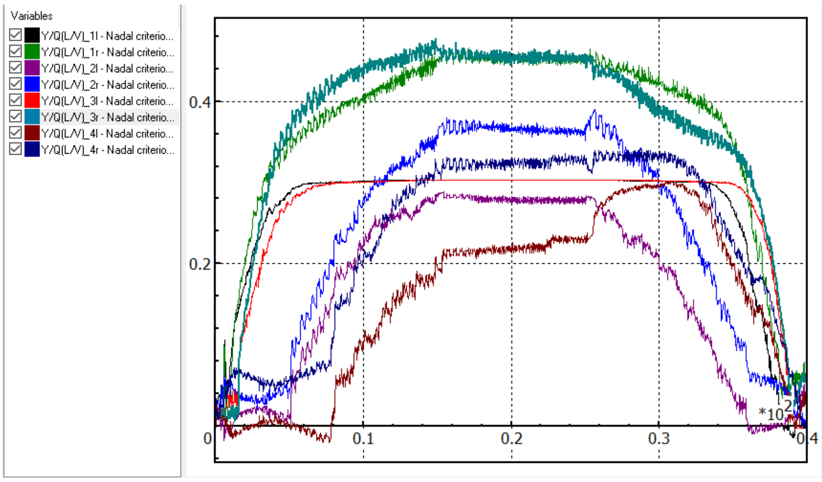

Figure 7: Nadal's criterion, the L/V(Y/Q) ratio in the empty tank wagon, used to determine the critical wheel.

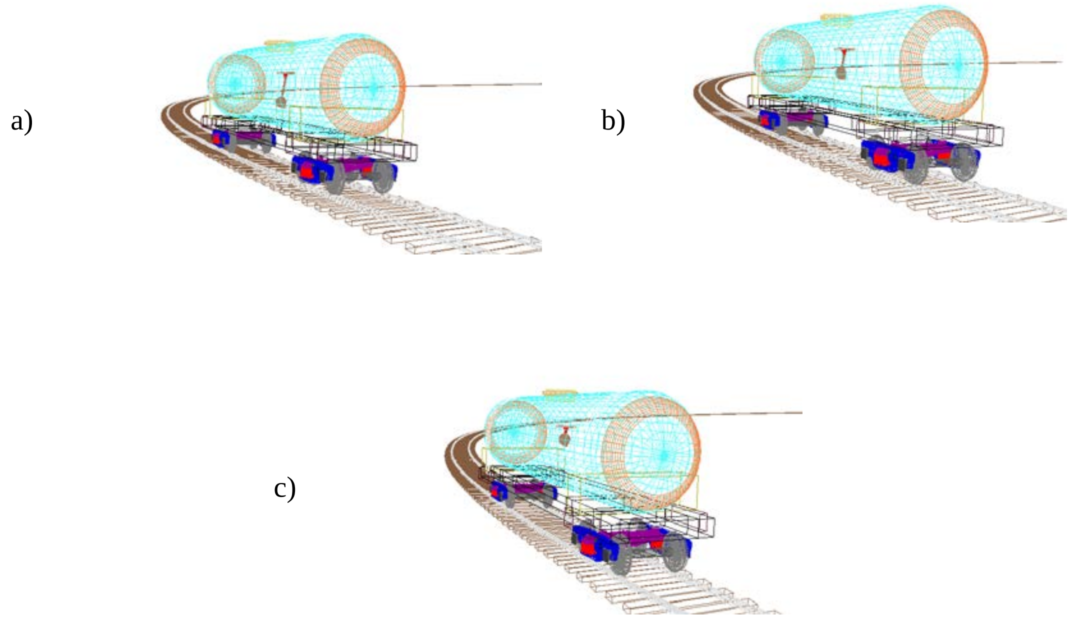

Figure 8: Schematic of the wagon, its equivalent pendulum, and the curved track created in UM; a) 30% filled, b) 60% filled and c) 90% filled

results of the partially filled models. A constant travel speed of 20 m/s (equivalent to 72 km/h) is considered, and the travel time is assumed to be 40 seconds. The parameters of lateral force, vertical force, and the ratio of these two parameters for the critical wheel have been selected as the comparison criteria.

4.1. Analysis of the Critical Wheel in Empty and Partially Filled Wagons

For this purpose, the method from [13] will be used. By using Nadal's criterion, which is the ratio of the lateral force to the vertical force acting on the wheel (L/V), calculated for all wheels, the critical wheel will be identified. According to Figure (7), the third axle's right wheel was the most critical wheel in the empty wagon for this track; therefore, the calculations will be performed for this wheel.

Using the method above, the critical wheel was evaluated in each of the partially filled tanks. The result for all three filling percentages—30%, 60%, and 90%—was that the right wheel of the third wheelset had the highest L/V ratio. In all filling percentages, the wheel with approximately the highest Nadal value was identified as the critical wheel with the highest risk of derailment, and its data has been evaluated. Table (7) and figure (8) displays a schematic of the model built for the aforementioned percentages and also identifies the critical wheel in each case.

Table 7. Critical wheel for different filling percentages

Fill Ratio (%)	**Pendulum weight (kg)**
30	Axle number 3 right wheel
60	Axle number 3 right wheel
90	Axle number 3 right wheel

4.2. Analysis of Maximum Nadal Coefficient, Sloshing Mass, and Fixed Mass with Tank Filling Percentage:

In this section, after analyzing the created models, the results, the effect of the filling percentage, and the change in the Nadal coefficient at a constant speed for a tank wagon will be discussed. This model investigates how the filling percentage affects the reduction of derailment risk for a tank wagon on a standard curved track. As shown in the graph in Figure (9), the maximum L/V ratio, which is the Nadal risk coefficient, decreases as the wagon is filled (simulated using the pendulum model).

As stated, this chart was generated by calculating the maximum value in Excel software; that is, for the entire duration of the

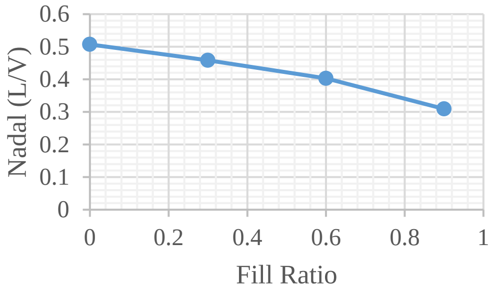

Figure 9: Graph of the maximum Nadal coefficient versus filling ratio for the empty, 30%, 60%, and 90% filled wagon.

run, the single instant with the maximum L/V ratio was selected, and its value was recorded. Approaching this simply, given the constant track and speed conditions, the primary reason for the decrease in the Nadal coefficient is the increased weight of the wagon at higher filling ratios. As the weight increases, the vertical force increases more significantly, leading to a higher vertical force relative to the lateral force, which results in a reduction of the Nadal coefficient.

A point of discussion in this modeling is the slope of the decrease in the Nadal index. According to Table (8), when the wagon goes from completely empty to 30% filled, the Nadal coefficient decreases by 9.6%. However, when the filling changes from 60% to 90%, this decrease in the Nadal coefficient reaches 16.3%. This non-linearity in the reduction of the Nadal coefficient could be related to the direct impact of the sloshing effect at lower filling percentages, which requires further modeling and more detailed investigations. For a more precise analysis, the values obtained from this simulation are presented in Table (8).

Table 8. The maximum Nadal coefficient obtained for empty, 30%, 60%, and 90% filling percentages

Fill Ratio (%)	Max Nadal (L/V)
0	0.507113
30	0.458300
60	0.402871
90	0.337224

The second topic investigated in this research was the critical derailment speed for these three models with the aforementioned filling percentages. Specifically, the derailment speed on the analyzed track was determined using the advanced analysis method in the UM software. The results of this analysis are also presented below.

As shown in Figure (10), in the case where the wagon's tank is 30% full, the RMS (Root Mean Square) index of lateral displacement shows significant changes in the 29-30 m/s speed range, which indicates derailment at a speed of 30 m/s.

As can be seen in Figure (11), and consistent with the previous explanations, in the case where the wagon's tank is 60% full, the speed of 26-27 m/s is the critical speed range, and 27 m/s was the derailment speed. The noteworthy point is

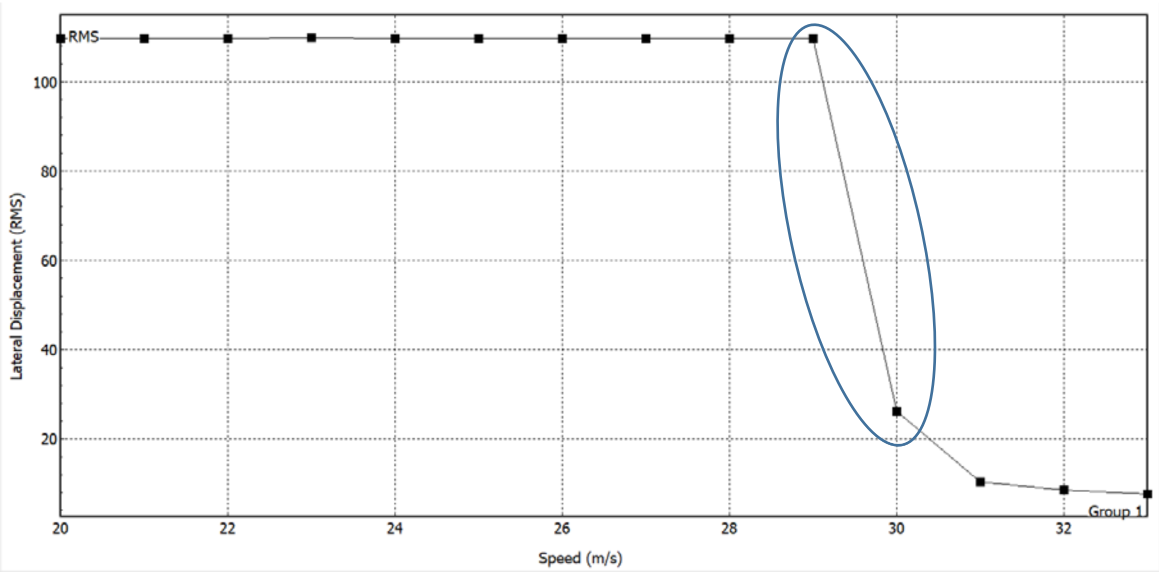

Figure 10: Graph for the critical speed analysis of the 30% filled wagon

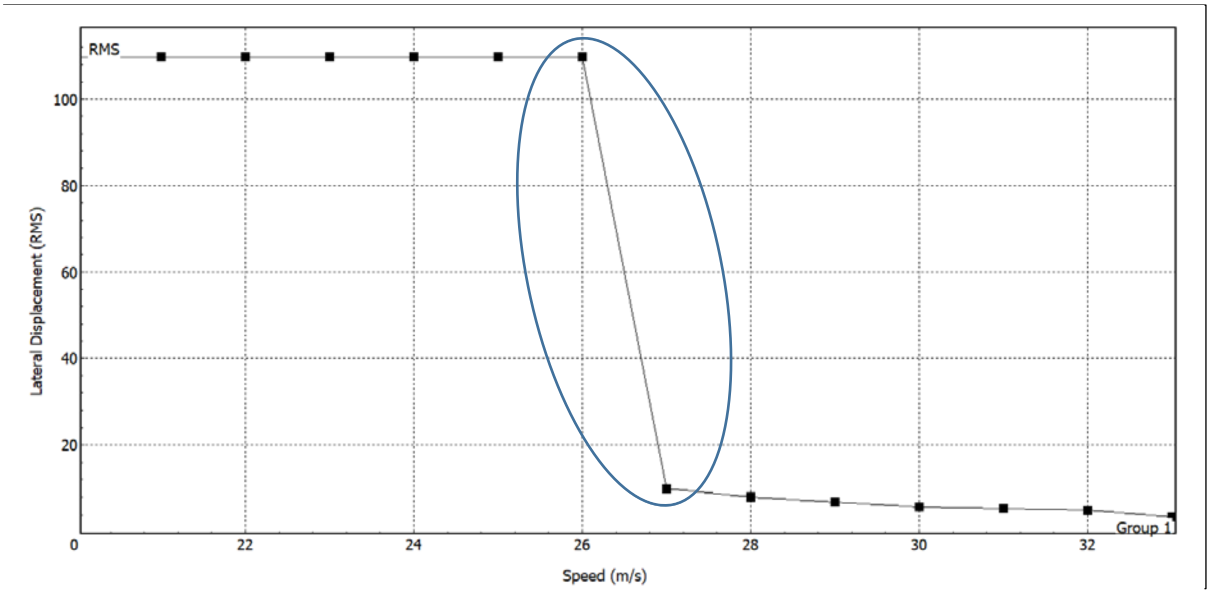

Figure 11: Graph for the critical speed analysis of the 60% filled wagon

that by increasing the filling percentage from 30% to 60%, the derailment speed decreased by 3 m/s, which is a 10% reduction.

Finally, according to Figure (12), in the case where the wagon's tank is 90% full, it is observed that the speed of 23-24 m/s is the critical speed range, and 24 m/s is the derailment speed. This means that by increasing the filling from 60% to 90%, the derailment speed has decreased by 3 m/s, which is equivalent to an 11% reduction.

5- Discussion and Conclusion:

This study has investigated the effect of tank filling percentage on the dynamic behavior of tank wagons using multi-body dynamic simulation in UM software. The results show that the tank's fill level has a significant impact on the wagon's derailment risk.

Analysis of the Nadal criterion (Q/V) indicated that at a constant, non-critical speed of 20 m/s, the critical wheel in the modeled wagons is the right wheel of the third axle. As the tank filling increases to 90%, this wheel remains the critical one. The plot of the Nadal coefficient versus filling percentage (Figure 8), under non-critical speed and constant track conditions, shows that increasing the fill level generally reduces the derailment risk, primarily due to the increase in vertical force (V) resulting from the added weight. This plot illustrates a 9.6% decrease in

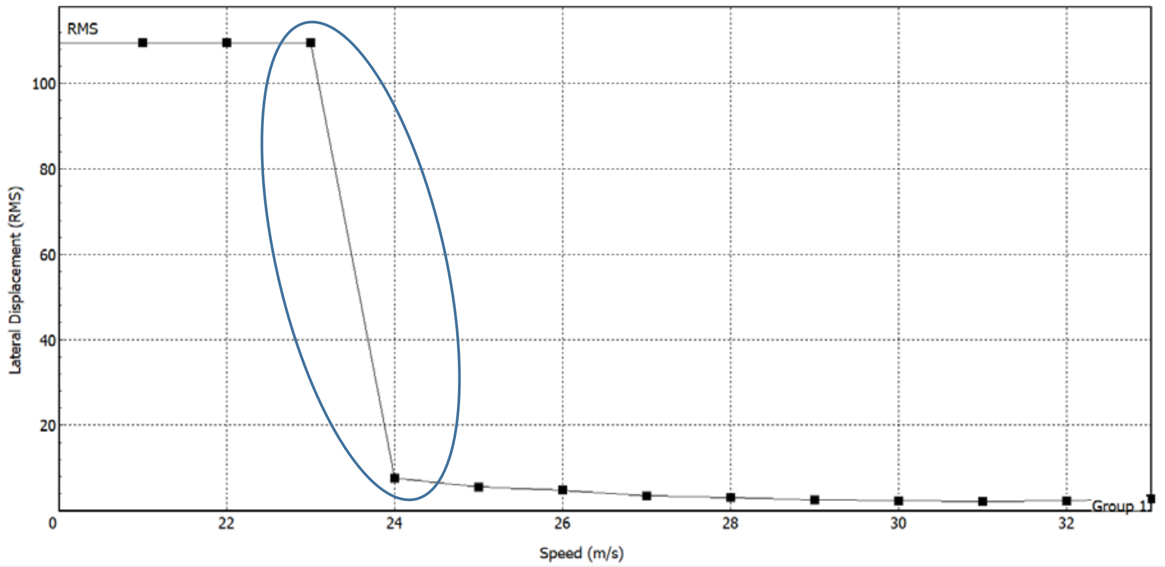

Figure 12: Graph for the critical speed analysis of the 90% filled wagon

the Nadal coefficient when filling the tank from 0 to 30% and a 16.3% decrease when filling from 60% to 90%. This finding underscores the importance of considering the dynamic effects of the fluid at low fill levels.

Furthermore, by analyzing Figures 9, 10, and 11, the critical derailment speeds for the modeled wagons were determined to be in the ranges of 29–30 m/s (for 30% filling), 26–27 m/s (for 60% filling), and 23–24 m/s (for 90% filling), respectively. The results indicate a 20% decrease in the critical derailment speed as the tank filling increases from 30% to 90%.

As a recommendation for future studies, the influence of parameters such as train speed and fluid properties (viscosity and density) on wagon dynamics and derailment risk could be investigated. Additionally, for a more precise understanding of transient effects and oscillations, it is suggested that the system's behavior during curve entry, travel along the curve, and curve exit be analyzed in greater detail.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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