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Research Article

An Analysis of Fuel Oil Sloshing in Partially Filled Cargo Tanker Trucks under Cornering Conditions Using Various Baffle Systems

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Ethiopia imports all fuel and crude oils from abroad at high cost, and transportation of these fluids has been carried out by using various capacity of road transportation heavy-duty truck vehicle. Most tanker truck accidents happen during turning because of the fluid splashing in partially loaded tanks and of the uniqueness of the carrying liquids. This is a result of the fact that current baffle configurations are effective at reducing sloshing when braking or accelerating but ineffective at doing so when turning. Consequently, the primary goal of this thesis work is to investigate how different baffle systems affect lateral sloshing reduction. In this work, the optimal baffle configuration and its arrangements for modified oval tanks at 50% and 80% fill levels were tried, and the dynamic analysis of tanker trucks was researched. The tanker truck and baffle system are designed in CATIA V5 for the numerical analysis, and the CFD study is completed in ANSYS Fluent 2021. R2 and the dynamic analysis are carried out in ANSYS LS-DYNA to study the stability of truck. The computational simulation is carried out as a tank with eight types of baffle systems such as existing baffles (TB), TB with BMLB, UMLB, CLB, 2HLB, 2VHLB, 4HLB, and 4VHLB with similar meshing resolution, similar turbulence modeling, similar boundary conditions, and also similar solution strategies. Transverse baffles with bottom-mounted four holes longitudinal baffle with hole-varying position (4VHLB) are discovered to be the best baffle type after evaluating all baffle designs. This suggests that the quantity of sloshing is reduced as the number of holes with small diameters increases. Maximum lateral force and roll moment are reduced by the most, by 47.76% and 58.66%, respectively, at 50% fill level and by 58.08% and 22.52%, at 80% fill level. Consequently, the case tanker truck's use of this revised design baffle will be crucial for enhancing rollover stability while cornering.

1. Introduction

Sloshing is the phenomena that occur in the partial filled tanker due to the external disturbances [1]. In the 1950s and 1960s, fluid sloshing inside partially full tankers was intensively studied in the aerospace area [2]. The goal was to see how partially full fuel tanks of various geometries affected the stability of rockets and planes [3]. In the late 1970s, researchers began to investigate the consequences of fluid slosh in partially filled road containers [2]. The sloshing of bulk fluid in tanker trucks can have a substantial impact on the vehicle's driving dynamics and stability [4]. Low rollover threshold is caused by lateral fluid sloshing during turning and rapid line changes, whereas longitudinal fluid sloshing caused by braking or accelerating actions can induce yaw instability or loss of directional control. If there are no transverse walls partitioning the tank, internal fuel motions can be more severe longitudinally than laterally in traditional tankers where the length is significantly greater than the width.

The longitudinal acceleration peaks might be greater than the lateral maximums because of more length than width. Hence, legislation has till now concentrated only on reducing the longitudinal slosh requiring transverse walls in tankers. But the stability can be more sensitive to lateral sloshing because wheel load transfer and overturning tendency can be more dominating laterally than longitudinally [5]. Longitudinal sloshing in itself is more abrupt and easily perceivable to the driver even if it occurs in the trailer. However, lateral sloshing is less abrupt and more difficult to perceive when it occurs in the trailer.

As a result, it is unlikely that the driver will be able to adjust the steering in complex maneuvers to prevent lateral sloshing forces in the tank [5]. Instabilities caused by maneuvers, such as roll and yaw instability, cause the majority of heavy vehicle accidents. The fill volume directly relates with the fluid inertia, center of gravity height and the load shift potential, and thus the associated forces and moments [6]. The most deadly mode of instability is rollover, which is caused by centrifugal forces and can occur while turning, changing lanes, or braking in a turn maneuver [7]. Because of their high center of gravity and dynamic sloshing of the liquid payload, partially loaded heavy-duty tanker trucks with constant radius turns or lane change movements have a lower rollover threshold than other vehicles [5]. One of the most common causes of fatalities and economic losses among commercial truck vehicles is overturning of tanker trucks during turning maneuvers [4]. Figure 1 shows accidents on a country road with a diesel tanker truck overturned in a curve.

There are various factors that contribute to tanker truck accidents, according to an Ethiopian accident data source. The cornering condition caused 49.8%, 66.09%, and 67.58% of these incidents to happen in the years 2018, 2019, and 2020, respectively, while other causes caused the remaining percentage to happen. Also, as indicated in Figure 2, the accident indicates an upward trend from year to year. Therefore, a partially filled tanker truck is one of the causes of an overturn in a curve. The outcomes of accidents that result in human mortality and property loss are depicted in Figure 2. Accident type is depicted on the horizontal axis.

Researchers characterized the accident as a rollover, rear-end collision, crash, or over-speeding accident depending on what caused it. There were also 45.16 percent, 25.81 percent, 17.74 percent, and 11.29 percent relative frequencies for each cause. Consequently, rollover and rear-end collisions are the two main forms of tanker accidents [8]. Tanker accidents can occur for a variety of reasons, but the most prevalent is liquid sloshing in partially loaded tanks [9].

Tanker accidents can occur for a variety of reasons, including environmental variables, driver error, excessive speeding, and tire bursts; however, overturning in a curve is more common than other causes (Figure 2). The most frequent cause of this is fluid sloshing in partially full tanks. Internal obstructions known as baffles are employed to stop the fluid from freely moving or to lessen the effect of sloshing [10]. The intensity of liquid sloshing inside a moving tank is influenced by a number of factors including liquid fill volume, tank geometry, fluid properties, and tank motion [1]. Some people have done experimental analysis while some have done computational analysis or analytical methods to describe the liquid slosh behavior within a partial filled tank. Some major studies related to this study are presented. The efficiency of several baffle designs is examined, including conventional, partial, and oblique baffles, in minimizing maneuver-induced transient and steady-state fluid slosh forces and moments in a partially filled tank vehicle [11]. The effect of the vertical baffle heights on the liquid sloshing in a three-dimensional rectangular tank with 70% water fill level condition is investigated [12].

Figure 1: Accidents in Ethiopia.

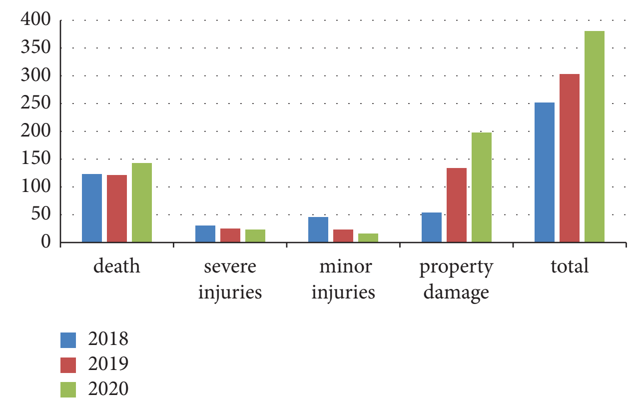


Figure 2: Accidents in Ethiopia caused by tanker truck (source: federal police commission).

In this study, the VOF method provided in the commercial code STAR-CCM+ is used for the two-phase flow problem [13]. The effects of filled volume changes on different parameters and conditions such as roll angle and fluid center of gravity coordinates are studied, resulting fluid force and center of gravity accelerations for two different steer inputs. This work employed CFD and the volume of fluid (VOF) approach to build and simulate the 3-D geometry of a fuel tank method considering multiphase fluid flow predicting fuel slosh movement at a specific capacity within a definite fixed volume [14]. To simulate the behavior of car gasoline tanks in sloshing experiments, a finite element model using the smoothed particle hydrodynamics (SPH) technique in LS-DYNA was constructed [15]. The usage of baffles in various locations across the fuel tank to prevent fuel sloshing is focused [16]. When a partially loaded tank vehicle is subjected to rapid braking, the liquid cargo sloshes, causing liquid stresses to be applied to the tank wall, affect its structural integrity [17]. In this study, cylindrical partially filled container was modelled in 3D using ALE (arbitrary Lagrangian–Eulerian) method in LS-DYNA software. 3D computational simulation of sloshing in liquid-filled level container under dynamic loads in LS-DYNA software using the arbitrary Lagrangian–Eulerian method is focused [18]. Experiments were conducted without any baffles, and series of experiments were incorporated by two horizontal and one vertical baffle, and three vertical baffles were done to validate the results of CFD analysis [19]. They used a transparent automotive fuel tank filled with colored water, a high-speed camera with computer interface, a mounting table, and a counterweight to study the sloshing behavior of the liquid in the tank [20]. The free surface displacement, pressure distribution, and horizontal and vertical forces produced on rectangular and trapezoidal storage tanks due to sloshing were calculated using a numerical code. The result shows the maximum pressure fluctuation, and horizontal and vertical forces were less in trapezoidal tank [21].

As it is discussed from the above literature review, it is concluded that almost all researches have been studied the reduction of sloshing effect on fuel tanker vehicle at different filling level as well as at different baffle configuration during braking or acceleration. In Ethiopia, the existing fuel oil carrying tanker trucks have transverse baffles to reduce the sloshing effect only during braking or accelerating. But the existing baffles are inefficient to reduce fuel sloshing during cornering because of all fuels that come to one side wall, and this is one of the reasons why fuel tanker trucks overturned occurs at a curve since our country has many curvature roads. Therefore, in order to reduce the lateral fuel sloshing effect during cornering, the improvement of baffle design is needed. This paper focuses on studying the effect of various baffle system designs during cornering to reduce lateral sloshing.

2. Modeling and Analysis of Fuel Oil Tanker Truck

2.1. Dimension of Modified Oval Tanker Body. The upper and lower bounds of the radius (R1), the side walls (R2), the blend arcs of the radius (R3), the overall height (2B), and the overall width (2H), which are obtained from eight arcs, are the five parameters that define this modified oval cross section (Figure 3). Each circular arc's radius and center coordinates are used to express it [5]. The following equation is used to construct the shape of modified oval shape:

$$\left(y - C_{yn}\right)^2 + \left(Z - C_{zn}\right)^2 = R_n^2, \quad (1)$$

where $n = 1, 2, \ldots, 8$, c_{yn} and c_{zn} are the coordinates of the center of arc n, and R_n is the radius of the n^{th} arc. Intersection points of adjacent arcs are obtained through solving equations for arc n and arc $(n+1)$ simultaneously.

2.2. Geometry of Transverse Baffles. The existing tank is modelled with four transverse baffles with orifice and one bulkhead which have two partitions: transverse baffles are considered equally spaced mounted. The longitudinal distance among baffles is around 2 meters. And the bulkhead is partitioned the tank equally at 6 m, and its thickness and manhole size are 4 mm and 500 mm, respectively (Figure 4).

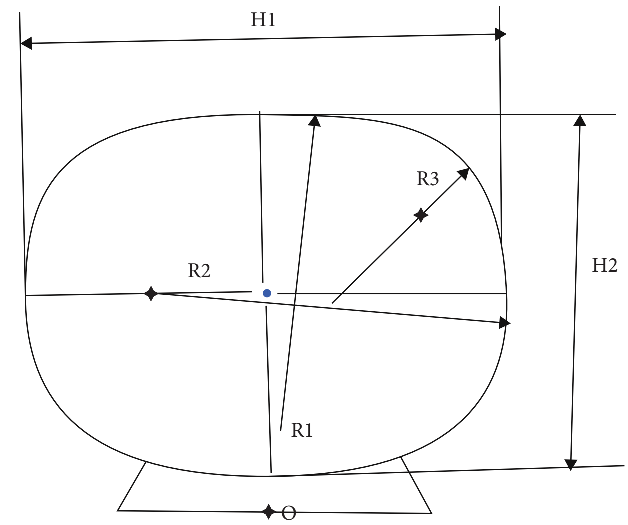


FIGURE 3: Dimensions of modified oval tanker body.

The following baffle designs are new design which is used to reduce the lateral sloshing effect.

2.3. Geometry of Longitudinal Baffles. This baffle is mounted or arranged longitudinally to the center of the tanker. Whose dimension is as follows: the length of the baffle is the same as the length of the tanker, it is 12 m, and its thickness is 4 mm. The height of this baffle considered 75% of the total height of the tanker body not fully equal as height of tanker because it increases additional weight of the tanker. Generally, with this longitudinal baffle system, different factors such as shape and mounting of baffles, numbers, arrangements, and sizing (dimension) of holes are considered.

2.3.1. Baffles with Different Mounting. In this study, two ways of mounting are considered as follows:

(i) Bottom-mounted longitudinal baffles (Figure 5)

(ii) Upper-mounted longitudinal baffles (Figure 6).

2.3.2. Baffles with Different Shapes. In this analysis, two types of baffle shapes are studied. One is straight longitudinal baffles, and the other is curved longitudinal baffles. The straight types are explained in the previous section.

(1) Geometry of Curved-Longitudinal Baffles. This baffle is arranged longitudinally like bottom-mounted longitudinal baffles. The difference is only angle. The tanker's baffles are 1.4 meters tall and 9°degrees slanted from the center. Its hole is placed at the bottom of the tanker with 0.5 m diameter (Figure 7).

2.3.3. Baffles with Different Number of Holes and Dimensions

(1) Longitudinal Baffle with Single Hole: This baffle has single hole in each partition, and in general, it has 6

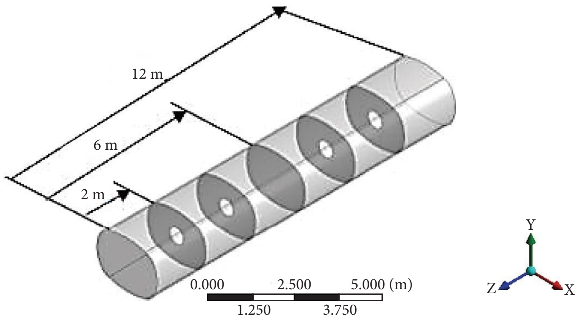


Figure 4: Modeling of tanker body with existing baffles.

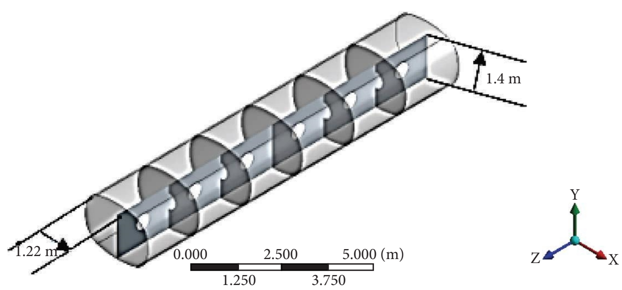


Figure 5: Modeling tanker body with bottom-mounted longitudinal baffles.

holes and also considered center hole of 0.5 m diameter. These baffles are mentioned as shown in Figures 4–6.

(2) Longitudinal Baffle with Two Holes: This analysis considered two holes in each compartment with bottom-mounted arrangements, and the total number of holes is 12 with each 0.5 m diameter (Figure 8).

(3) Longitudinal Baffle with Multiholes: This baffle has four holes in each compartment and totally 24 holes with 0.25 m diameter and arranged in bottom-mounted (Figure 9).

2.3.4. Baffles with Different Hole Arrangements. In this case, two ways of hole arrangements are considered. These are inline and staggered hole arrangements (varying) (Figures 10–13).

All baffle models need to be coded for simplicity and easy comparison and discussion of result. The coded names of baffle models are given in Table 1.

2.4. Mesh Generation. Mesh generation is carried out in a meshing tool after geometry construction. In this instance, a uniform tetrahedral mesh is produced in every situation. For the proposed simulation, the mesh file is converted to polyhedral cells for better result accuracy.

2.5. Grid In-Dependence Test. The most important aspect that affects computing time and result accuracy is the grid independency test. Therefore, picking the best mesh size is

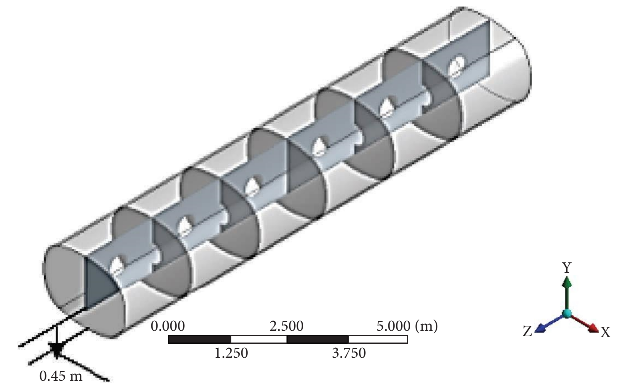


Figure 6: Modeling of tanker body with upper-mounted longitudinal baffles.

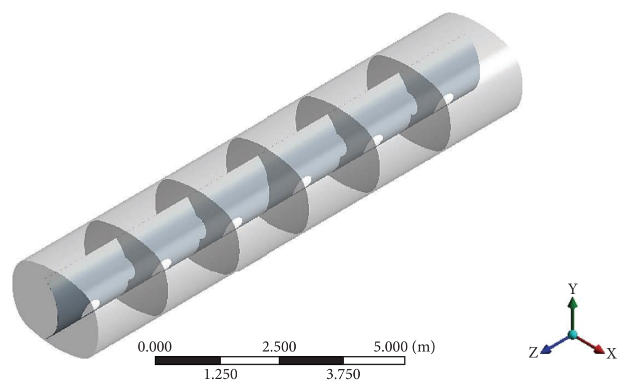


Figure 7: Modeling of tanker body with curved-longitudinal baffles.

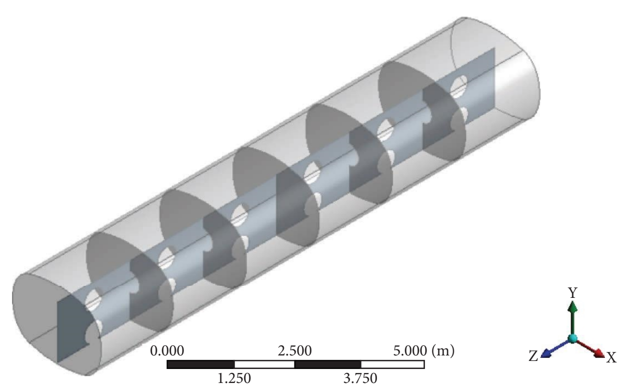


Figure 8: Longitudinal baffle with two holes.

crucial. In this instance, a mesh dependency test is conducted utilizing four different grid sizes, including 40 mm, 50 mm, 60 mm, and 70 mm. In each case, the same sized mesh is utilized for all baffle design types. The differences between the results obtained in meshes 50 mm and 40 mm are 1.02%, 1.38%, 0.84%, 0.82%, 0.51%, 0.85%, 0.86%, and 1.06%, respectively. The difference between 70 mm and 60 mm and also 60 mm and 50 mm is high. Mesh 40 mm is used in all situations because the variation is very small, demonstrating that the outcome is independent of the mesh.

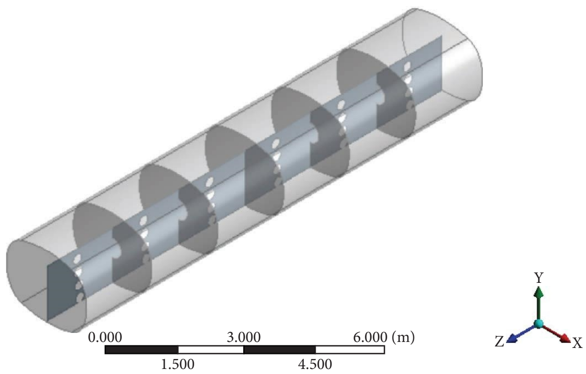


Figure 9: Longitudinal baffle with four holes.

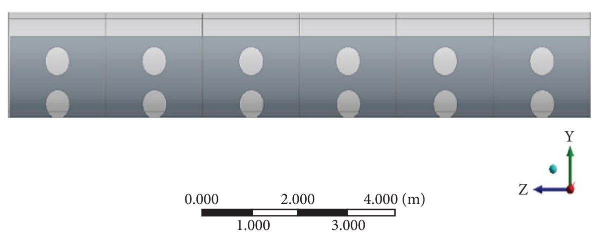


Figure 10: Two holes with inline hole position.

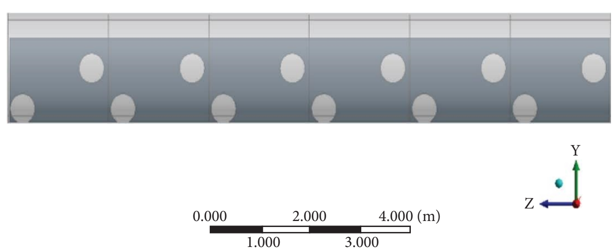


Figure 11: Two holes with staggered hole arrangements.

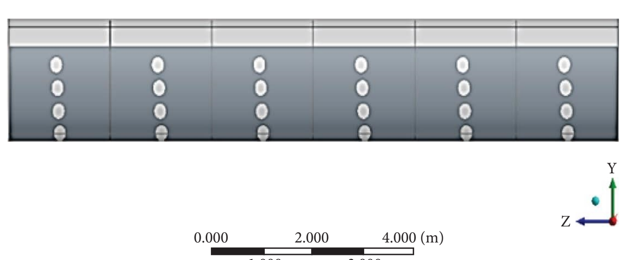


Figure 12: Four holes with inline hole position.

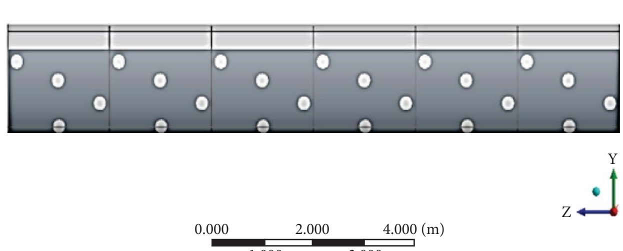


Figure 13: Four holes with staggered hole arrangements.

2.6. Volume of Fluids. The multiphase model panel has the VOF free surface model activated. Volume of fluid (VOF) multiphase model in ANSYS FLUENT is used to track the changes of fluid motion rather than the movement of particles on free oil liquid surface surface. Free oil liquid surface is determined by analyzing the ratio of fluid volume and grid volume in the grid element. This method may extract distinctive parameters during the powerful nonlinear sloshing process, which provides the fundamental framework for further study [10]. Currently, the VOF approach is the most effective way to track free surface area. Explicit formulation for time dependent solution is used. The number of phases in this model is specified as two. It is stated that the primary phase is air, and the secondary phase is diesel. After VOF is activated, the material properties for each phase from the Fluent database are set. The properties are given in Table 2.

2.7. Turbulence Modelling. After multiphase model specifying the next step is specifying the turbulence model. The Reynolds-averaged Navier–Stokes equation is closed in this work using eddy viscosity models. The traditional k-model is taken into account in this investigation. The standard k-model is a semiempirical model that is based on model transport equations for the kinetic energy of the turbulence (k) and its rate of dissipation (ε) [10].

The following equation yields the turbulence viscosity:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \quad (2)$$

where k is turbulent kinetic energy, ε is turbulence dissipation rate, C_μ is constant of proportionality whose default value is 0.09 in fluent, and ρ is density of fluid.

2.8. Boundary Condition. The boundaries in the computational domain are named as LB, BMLB, UMLB, CLB, 2HLB, 2VHLB, 4HLB, and 4VHLB for baffles and tanker body. The boundary type for these considered as a wall while doing the analysis and fluid domain is chosen for the interior of the tank. The boundary conditions considered are given in Table 3.

The operational condition is required after the boundary condition has been established. Assume that the tanker truck is uniformly accelerating at 2.65 m/s^2 on a critical radius curve of 30.48 m, and that its speed should be 9 m/s. This assumption is based on data collected from tanker truck drivers during a survey, and the data are also consistent with results of an experimental test performed by [3]. To approximate a turn with a set radius, a key constant acceleration of 2.65 m/s^2 is used for all tanks. This constant lateral acceleration simulates a transient state turn curvature acting as the centripetal acceleration given by

$$a = \frac{V^2}{R}, \quad (3)$$

where a is centripetal acceleration, V is velocity of tanker truck, and R is critical radius of curvature.

Table 1: The coded name of baffles.

Full name	Coded name
Transverse baffles	TB
Bottom-mounted longitudinal baffle	BMLB
Upper-mounted longitudinal baffle	UMLB
Curved-longitudinal baffle	CLB
Longitudinal baffle with two holes (inline)	2HLB
Longitudinal baffle with two holes with varying hole position (staggered)	2VHLB
Longitudinal baffle with four holes (inline)	4HLB
Longitudinal baffle with four holes with varying hole position (staggered)	4VHLB

Table 2: Properties of fluid material.

Fluids	Density (kg/m^3)	Viscosity (kg/m-s)
Diesel	846	0.0029
Air	1.225	$1.7894e-5$

Table 3: Boundary conditions.

Conditions	Values
Wall motion	Stationary wall
Shear boundary condition	No slip

In the operating conditions panel, the following conditions are considered:

(i) Operating pressure: −101325 Pa

(ii) Lateral acceleration: $X = 2.65\ \mathrm{m/s^2}$

(iii) Gravitational acceleration: $Y = -9.81\ \mathrm{m/s^2}$

(iv) Tangential acceleration: $Z = 0\ \mathrm{m/s^2}$

Operating density: the software package's operational density option is utilized, and the operating density is set to have minimum density, which is the density of the lighter phase of air, which is $1.225\ \mathrm{kg/m^3}$ [22].

Noniterative time advancement is enabled for transient formulation to make computation less CPU intensive. Green–Gauss node-based spatial discretization scheme is used for more accurate or computationally intensive and minimizes false diffusion, recommended for unstructured meshes [23].

2.9. Geometry Modeling of Tanker Truck. Figure 14 depicts a 3-dimensional tanker truck that has been modelled in CATIA V5. The model truck is thought to be attached with one tanker body with six axles, and the tanker is attached to the tanker truck. The measurements and characteristics utilized for geometry creation are based on the standard data originating from outside the country. On this analysis, a reliable model is not taken into account. Only surface models are accepted by the software. Geometry that has been developed is then loaded in STEP format to ANSYS workbench. Finally, the findings of the CFD were imported into ANSYS LS-DYNA for a dynamic analysis to investigate the stability of tanker trucks under lateral forces.

2.10. Mesh Generation on Tanker Truck. Tanker truck parts are divided into critical and noncritical components. The truck's crucial structural elements, which have an impact on the dynamic analysis of the truck's stability, include some critical components. The tanker body, bulkhead, baffles, and chassis frame are just a few examples of crucial components. Noncritical truck parts do not affect the tanker truck's dynamic analysis. Examples of noncritical parts are valves, hose and clamps, and ladders. Due to their complexity, such noncritical sections are therefore removed from models, as seen in Figure 15. Additionally, modeling such components will aggravate model instability rather than increased model accuracy [24]. After geometry building, mesh production is completed in a meshing tool.

This enhances the precision of momentum balancing by excluding the development of hydrostatic pressure within the lighter phase [22]. Initial volume proportion of diesel is patched in the bottom half of the tank and at 80% of fill level after the proper boundary conditions are applied. The volume fraction of diesel at 50% and 80% fill levels when tanker truck is at initial stage ($t = 0$ sec) is shown in Figure 16. The contour plots of the volume fraction of diesel at 50% and 80% when the tanker truck is in a moving condition ($t = 0.5$ sec) are shown in Figure 17.

It is more practical to patch a diesel volume fraction of one where liquid is than to patch an air volume fraction of one in the remaining tank space. The initial volume fraction of diesel is patched in the bottom with 50% and 80% fill level as shown in Figure 18.

2.11. Stability Test Using LS-DYNA. In this research work, to perform stability of the tanker truck with existing and the new design of baffle, ANSYS LS-DYNA software is selected. It can be used to examine the effects of the lateral sloshing on the stability of truck.

2.12. LS-DYNA Boundary Conditions. The boundary conditions used in ANSYS LS-DYNA are listed as follows.

3. Results and Discussion

3.1. The Volume Fraction of Diesel in Tanker. The volume fraction is the proportion of fluid volume to all other fluid volume. The volume fraction is a measure of the phase

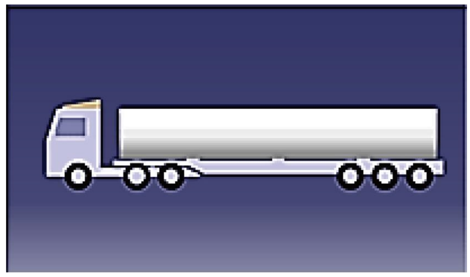


Figure 14: Geometry of creation in CATIA.

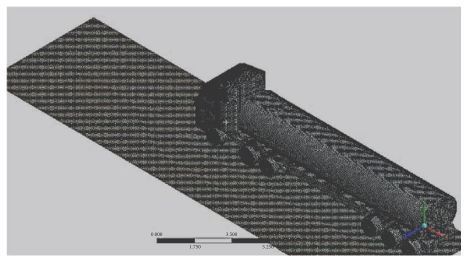
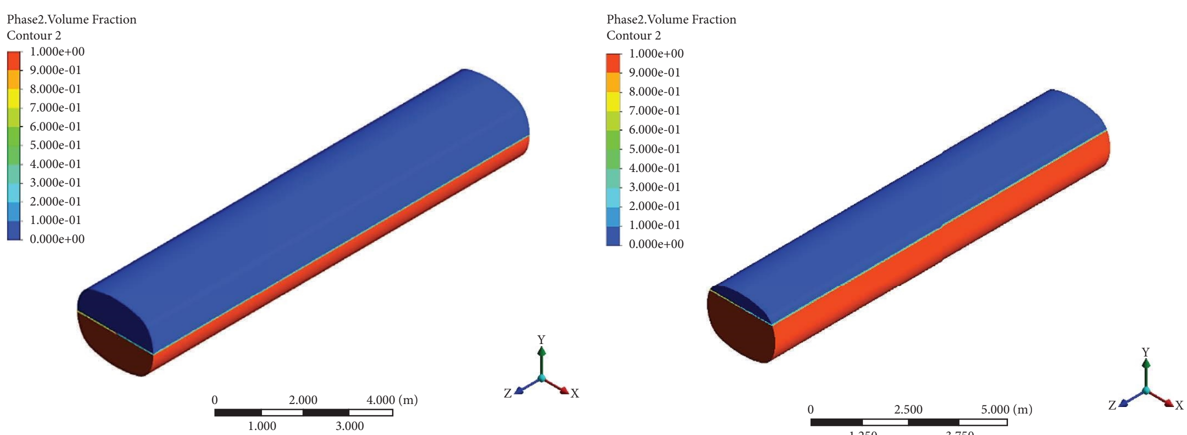
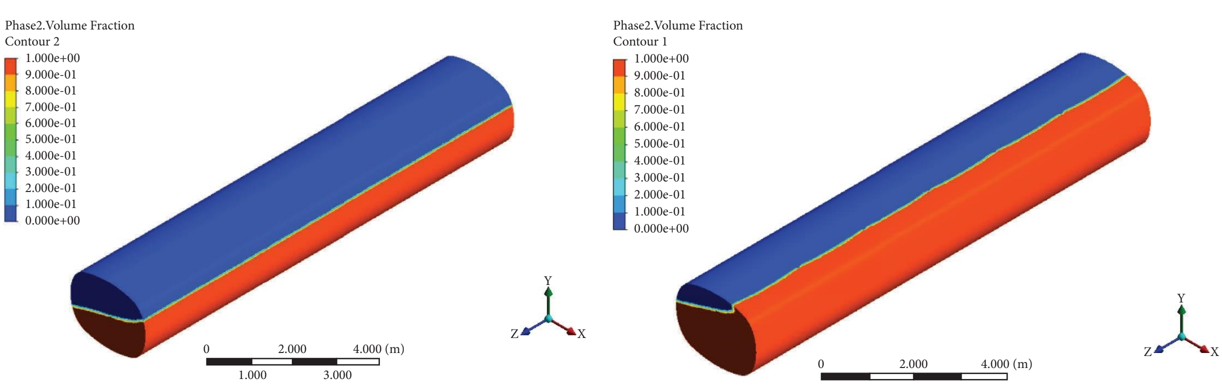


Figure 15: Mesh generated on tanker truck.



(a) (b)

Figure 16: The volume fraction of diesel at (a) 50% and (b) 80% fill levels when tanker truck is at initial stage ($t = 0$ sec).



(a) (b)

Figure 17: The contour plots of the volume fraction of diesel at (a) 50% and (b) 80% when the tanker truck is in a moving condition ($t = 0.5$ sec).

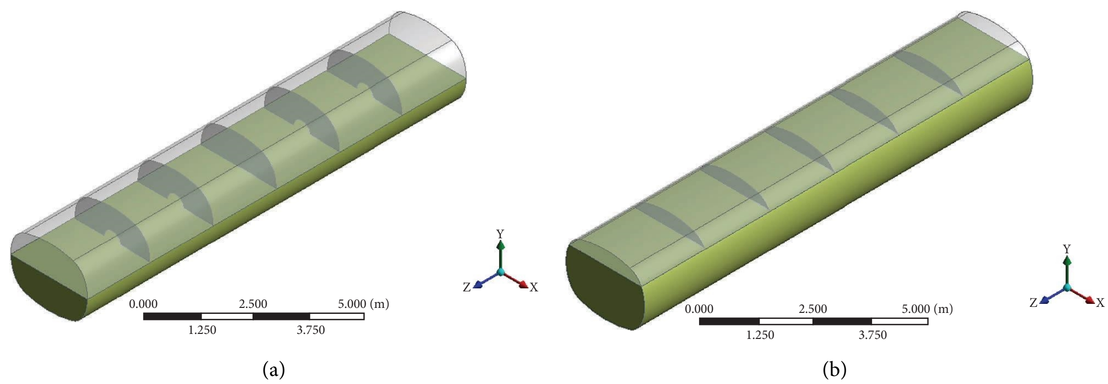


Figure 18: The initial volume fraction of diesel is patched in the bottom with (a) 50% and (b) 80% fill level.

present in the tanker, where 1 represents only diesel, represented by red color, while 0 represents only air, represented by blue color. Values between 0 and 1 represent the proportion of diesel to the total volume. The volume fraction of diesel at 50% and 80% fill levels when tanker truck is at initial stage ($t = 0$ sec) is shown in Figure 19. The contour plots of the volume fraction of diesel at 50% and 80% when the tanker truck is in a moving condition ($t = 0.5$ sec) are shown in Figure 20.

3.2. Pressure Contour. The high pressure is increased as the fuel is moved to the side wall of the tanker. As the time step increases the pressure in 50% fill level increases as the space available for free movement is high (Figure 21). The bulk of fuel doesnt swirl much with fill level of 80% (Figure 22). The colors on the pressure contour indicate the intensity of the pressure. The red color indicates the maximum pressure, and the blue color shows the minimum pressure. The value for each color map is also given on the left of the contour.

3.3. Percentage Comparison between TB, BMLB, UMLB, CLB, 2HLB, 2VHLB, 4HLB, and 4VHLB at 50% and 80% Fill Conditions. Figures 23–28 show the graph between lateral forces, vertical forces, and roll moment vs. time with various baffles at 50% and 80% at $a = 2.65\,\text{m/s}^2$ when tank is subjected to lateral acceleration.

3.3.1. Comparison in Terms of Lateral Forces with Eight Baffle Designs at Both Fill Levels. The chart below shows the percentages reduction of lateral sloshing in terms of lateral forces using various designed baffle systems.

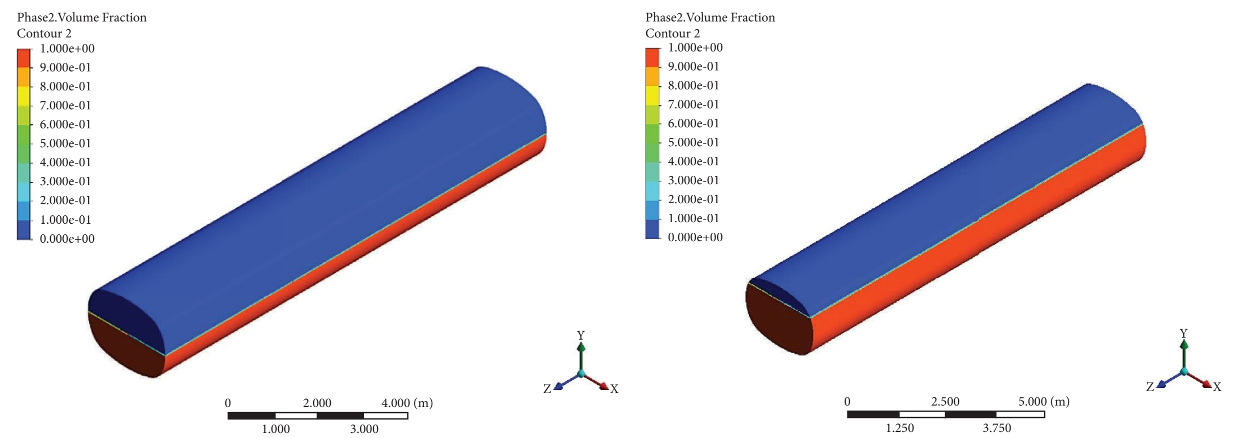
The four-hole longitudinal baffle with the same hole line arrangement and different hole location arrangements, as seen from the comparison of baffles, offers the highest lateral force reduction at 50% fill levels. The four-hole, hole-varying position (staggered) baffle between these two baffles exhibits the highest reduction in lateral forces. Additionally, a four-hole longitudinal baffle with variable hole positions and a curved longitudinal baffle exhibits a significant reduction in lateral forces at fill levels of 80%. Although the curved longitudinal baffle from the two baffles exhibits the highest force reduction, the truck's stability is eventually impacted by a rapid spike in lateral forces. Therefore, for 80% fill levels, a four-hole longitudinal with staggered hole position layout is best.

When the tank is filled to both fill levels and then subjected to lateral acceleration, Figures 24 and 25 show a graph comparison of lateral forces using various baffle systems. Using transverse baffles either results in no reduction since they provide less resistance to the lateral motion of fuel or ineffectiveness due to their placement. The truck's rolling motion is affected by these lateral forces, which also make steering difficult. The most significant reduction in sloshing pressures from other baffles was seen in transverse with four-hole longitudinal baffles with various (staggered) hole location arrangements.

The results demonstrate that peak force immediately reduces because this baffle arrangement is the optimum method for quickly dissipating energy when fuel contacts the side wall because of the small diameter and numerous holes. In general, it is found that as the number of holes increases, lateral force decreases by a certain amount.

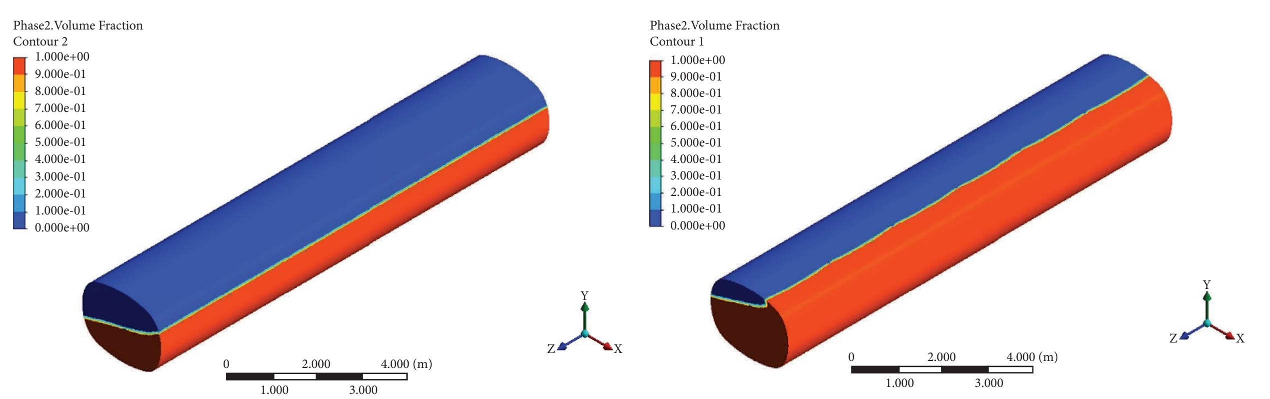
3.3.2. Comparison in Terms of Vertical Forces with Eight Baffle Designs at Both Fill Levels. Figures 26 and 27 show the comparison of vertical forces using four types of baffle designs at both 50% and 80% fill levels. As a result, the finding shows that transverse baffles offered some variation in vertical forces, but not excessively so. Other baffles are almost the same reduction amount at both fill levels. Therefore, the sloshing effect on vertical forces is less or negligible especially for higher fill levels.

3.3.3. Comparison in Terms of Roll Moment with Eight Baffle Designs at Both Fill Levels. The comparison of several baffle designs in terms of roll moment is shown in Figure 28. Consequently, at 50% fill levels, a four-hole longitudinal baffle with a hole design that varies in position is particularly effective in reducing roll moments. The curved longitudinal baffle, however, offers the biggest reduction from the other baffles at 80% fill levels, and however, due to an unforeseen rise in moment, tanker truck stability is impacted. The ideal hole configuration is four holes with different hole positions.



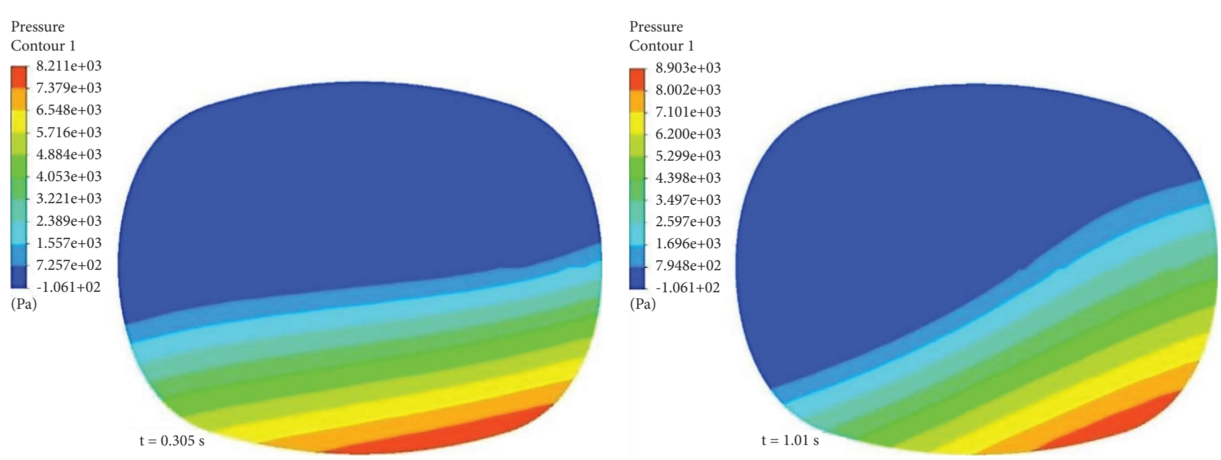
(a) (b)

Figure 19: The volume fraction of diesel at (a) 50% and (b) 80% fill levels when tanker truck is at initial stage ($t = 0$ sec).



(a) (b)

Figure 20: The contour plots of the volume fraction of diesel at (a) 50% and (b) 80% when the tanker truck is in a moving condition ($t = 0.5$ sec).



(a) (b)

Figure 21: Pressure contour of the tanker at 50% fill level with TB at various time steps.

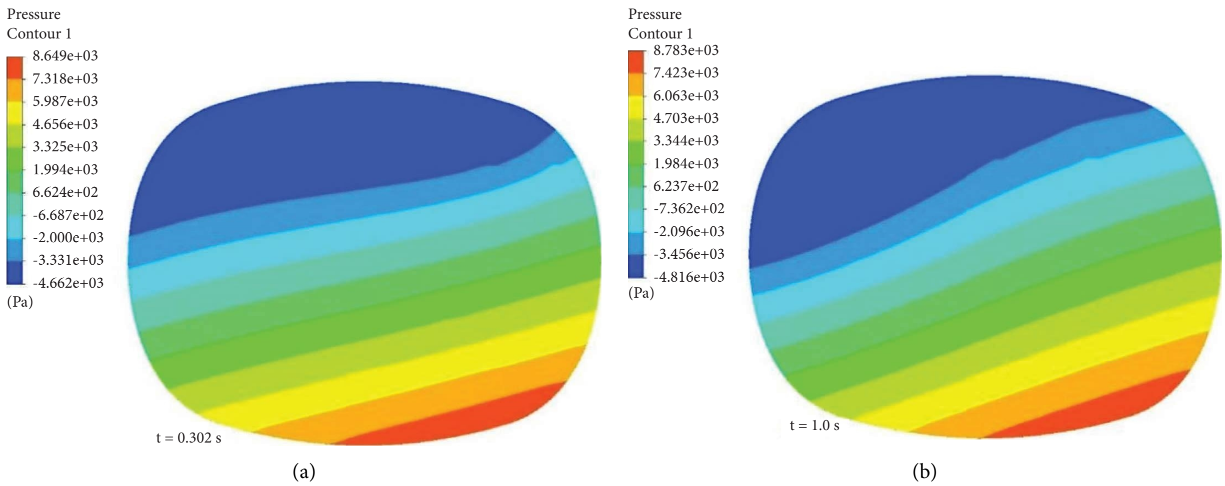


Figure 22: Pressure contour of the tanker at 80% fill level with TB at various time steps.

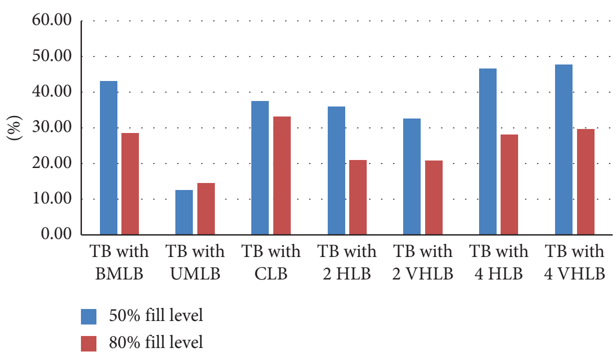


Figure 23: Percentage comparison in terms of lateral force.

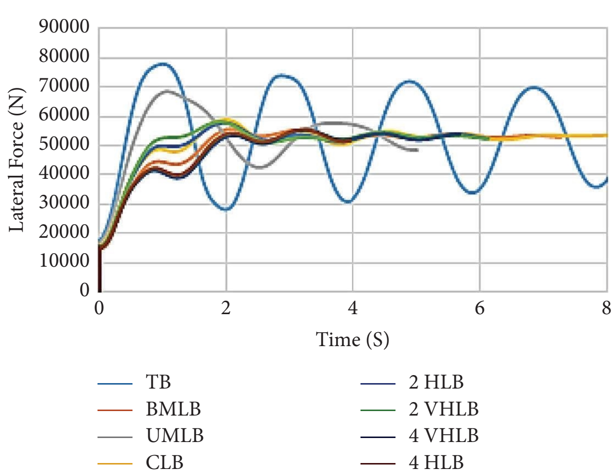


Figure 24: Lateral force at 50% fill with different baffle designs.

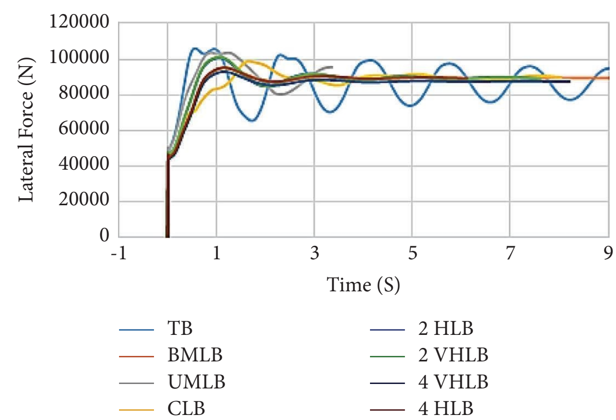


Figure 25: Lateral force at 80% fill with different baffle designs.

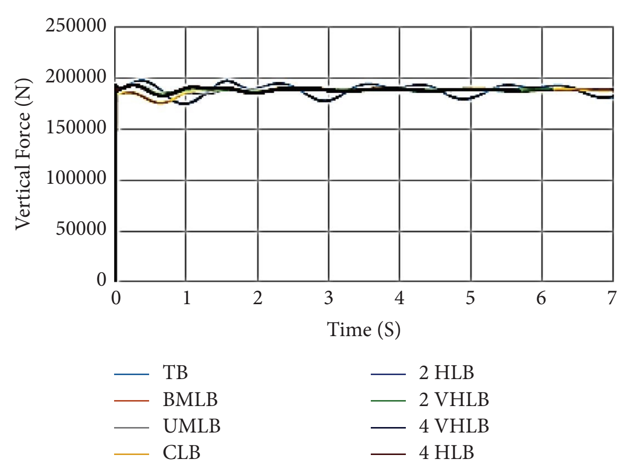


Figure 26: Vertical force at 50% fill with different baffle designs.

When the tank is filled to both fill levels and is exposed to lateral acceleration, the graph comparison of roll moments utilizing different baffle systems is displayed, as can be seen in Figures 29 and 30.

The variability of the roll moment is greater at 50% fill levels than at 80% fill levels. This shows that modified oval tanks are significantly impacted at lower fill levels. Moreover, transverse baffles in this situation provide less barrier to diesel flowing laterally. The study's findings indicate that, among all baffle designs, lateral baffles with four holes and longitudinal baffles with different hole position

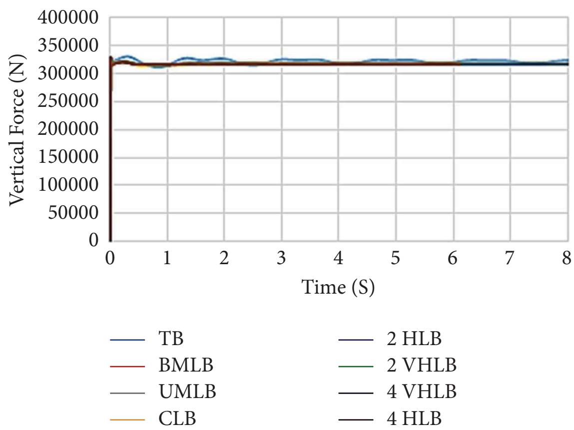


Figure 27: Vertical force at 80% fill with different baffle designs.

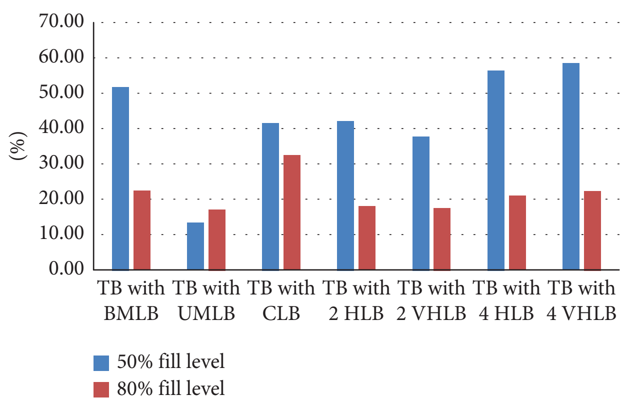


Figure 28: Percentage comparison in terms of roll moment.

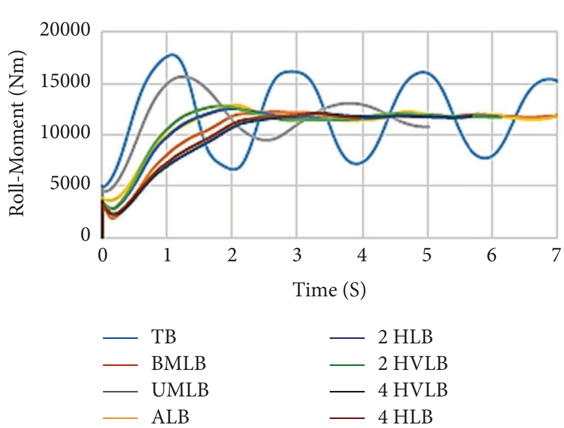


Figure 29: Roll moment at 50% fill with different baffle designs.

arrangements showed the highest reduction in roll moment as compared to other baffle arrangements. A longitudinal baffle of this type not only effectively dampens the fluid flow energy but also minimizes the effective sloshing. These baffle designs also greatly improve the roll stability of the modified oval tanker truck by successfully preventing lateral cargo movement.

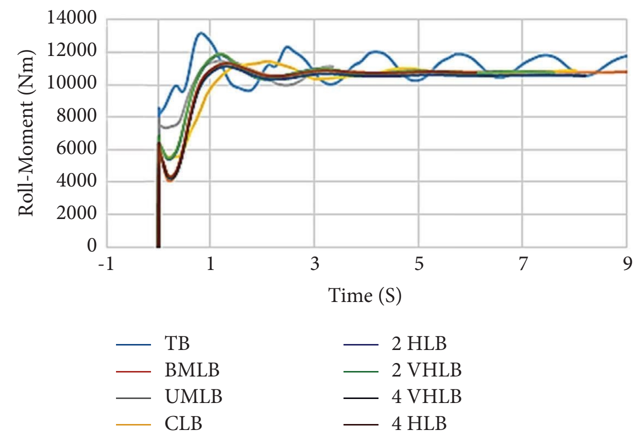


Figure 30: Roll moment at 80% fill with different baffle designs.

3.4. Verification. The validation of the CFD model using VOF is carried through merely referring to the suitability of the aforementioned viscous model for tanker slosh analysis. In numerous baffle design analysis, the VOF in multiphase model is utilized and has shown a very good correlation with the experimental findings [7, 10, 11, 25, 26]. The maximum reduction of peak moment in cylindrical tank was 34% that was obtained using horizontal baffles with the length ratio of 0.75 for 50% fill level and for 70% fill level 30% reduction of peak moment were offered by vertical forces with the length ratio of 0.75 [10]. The same strategy was utilized to address the effect of tanker truck sloshing using a modified oval form with vertical and horizontal baffles, and the outcomes were closely matched. The clean bore tank (B0) was evaluated with conventional baffles with a large central orifice (B1), obliquely placed conventional baffles (B2), partial baffles in an alternating pattern without an equalizer (B3), and semicircular orifice baffles of identical opening area (B4) at different fill level with cylindrical tank geometry [11]. The graphs obtained for the lateral forces and roll moments were comparable with present work. The time histories of lateral slosh force responses and roll moment reactions are given in Figures 31 and 32 [11].

Additionally, a validation case has been taken into account to analyze the mobility of the gasoline's free surface in a rectangular fuel tank that is only partially full [22]. Figures 33 and 34 demonstrate the free liquid surface of gasoline at various time intervals with and without baffle systems, respectively. It demonstrates that without baffle systems, fluid movement along the side of the wall increases as time steps increase, whereas with baffle systems, gasoline mobility decreases as time steps increase.

In order to address the tanker truck's sloshing impact, the same strategy has been applied. Finally, the results showed similar motion with this actual simulation.

The following Section 3.5 shows the result of motion of free surface of diesel fuel to validate the results with the existing transverse baffles and the best-chosen baffles which is four-hole longitudinal baffles with varying hole position.

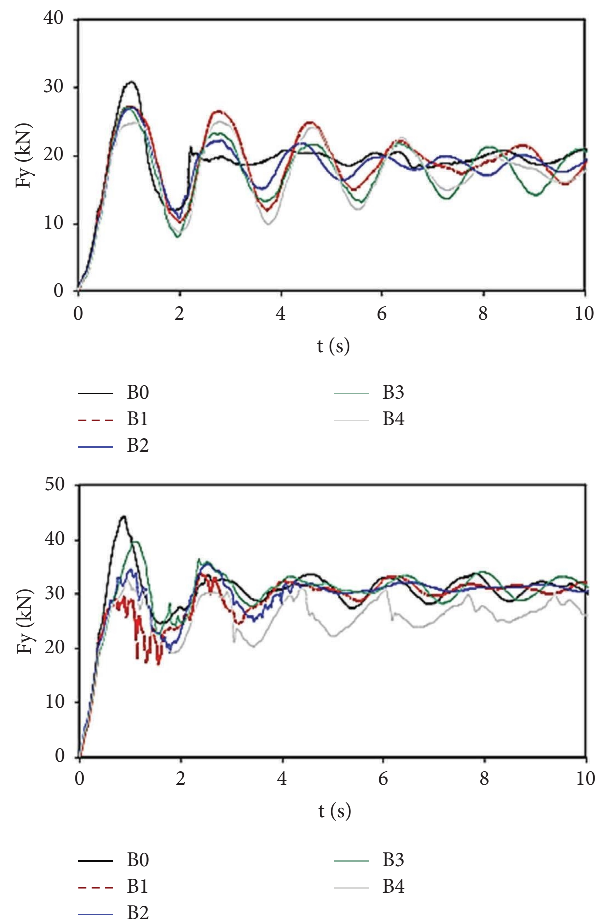


Figure 31: Time histories of lateral slosh force responses of various baffled tanks subject to $g_y = 0.25\,\mathrm{g}$.

3.5. The Diesel in the Tanker Truck's Free Liquid Surface Interface at 50% and 80% Fill Levels at Various Time Steps. Figure 35 depicts the movement of diesel within a tanker with transverse baffles at various times. It has been found that when a tanker has four transverse baffles inside, the fuel contacts the side wall of the tanker when turning, increasing the cornering moment because all of the fuel's motion is in that direction. Hence, as seen on Figure 35, the high fuel motion causes the roll moment to increase without rapidly decreasing up to 1.1 seconds. Due to this high surge, the vehicle may consequently topple.

Figure 36, which uses multihole longitudinal baffles in various positions to depict diesel motion inside a tank, is shown as follows. Because this baffle is passing the center longitudinally, the turning moment and lateral forces were further diminished, placing them within a safe range. The fluid motion simply demonstrates motion fuel returns to stable condition on a multihole longitudinal baffle tanker with varied hole position. For instance, when compared to the transverse mounted baffle seen in Figure 36, the fluid velocity rises up to 0.7 seconds before falling to its stable condition at 1.1 seconds. Hence, the side slosh of the fluid and, subsequently, the side trust on the tanker truck during cornering were greatly decreased by the multihole with variable hole position longitudinal baffle.

Using transverse baffles at 80% fill levels, Figure 37 depicts the motion of diesel fuel. In this instance, it is evident that fluid motion occurs at various times. Since transverse baffle placement is ineffective for dissipating the energy, the velocity of the fuel in this figure likewise rises at the side walls as previously indicated. Figure 37 makes this point very clear: due to the substantial amount of fuel, the motion rises up towards the walls for up to 0.9 seconds before significantly decreasing at 1.1 seconds in comparison to the 50% full level.

Figure 38, which uses bottom-mounted longitudinal baffles, depicts the movement of fuels at 80% fill levels over time. Since the longitudinal baffle arrangement greatly reduced the fuel side movement, the fluid motion is almost always less at the side walls, and therefore, there is hardly any side surge. It is discovered to be superior than the transverse baffle arrangement for lowering tanker truck rollover and guaranteeing stability.

3.6. Results of Dynamic Analysis. In this instance, the 50% fill level is analyzed utilizing both the optimal baffle system, four-hole longitudinal baffles with various (staggered) hole position arrangements, and the existing baffle systems, known as transverse baffles. According to CFD studies, while

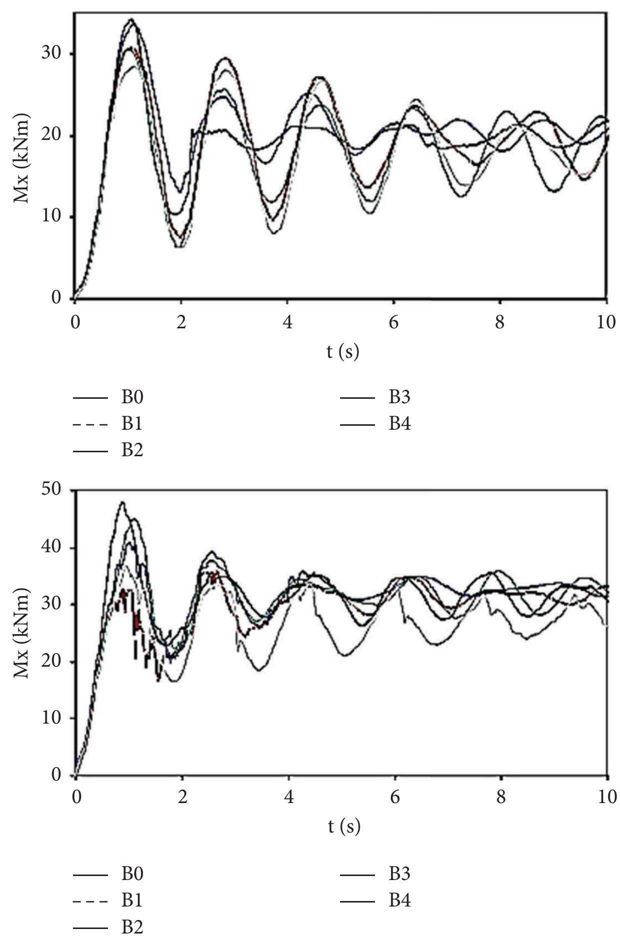


Figure 32: Time histories of various baffled tanks' roll moment reactions when subjected to $g_y = 0.25$ g.

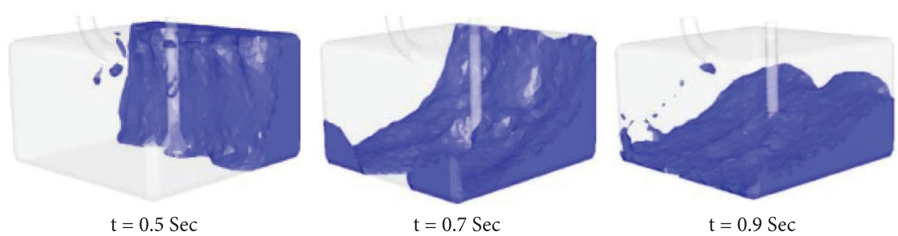


Figure 33: Tanker without baffle.

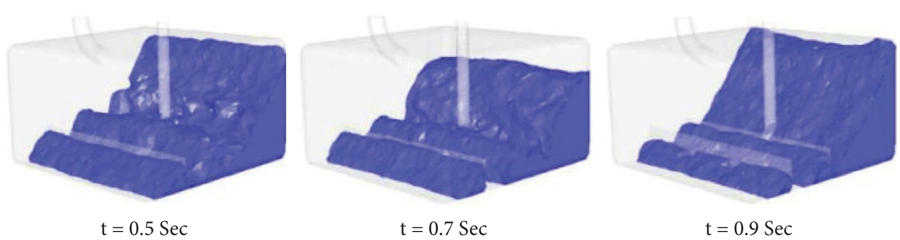


Figure 34: Tanker with baffle.

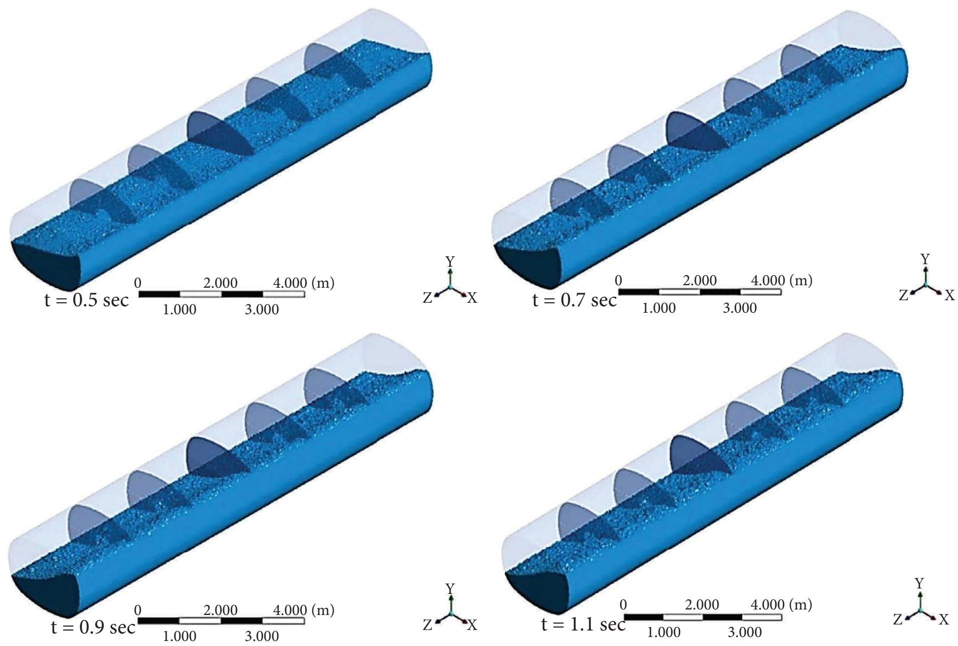


Figure 35: The free liquid surface of the diesel in tanker truck with transverse baffles at 50% fill condition.

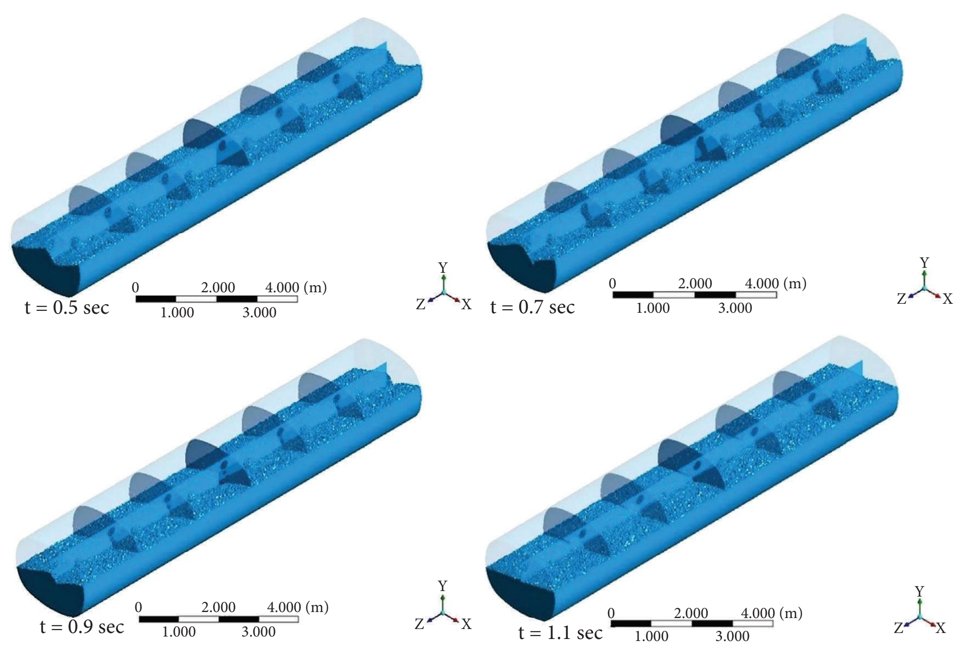


Figure 36: The free liquid surface of the diesel in tanker truck with transverse and multihole with staggered hole position longitudinal baffles at 50% fill condition.

the tanker truck is moving at a speed of 34 km/h, the lateral forces applied in this situation when using a transverse baffle and a four-hole longitudinal baffle with variable hole location arrangements are 77960 N and 40726.72 N, respectively.

3.6.1. Using Transverse Baffles. The analysis shows that a tanker truck will rollover when it is traveling on a straight route, applying lateral forces, and using a transverse baffle system. The tanker truck initially begins to lift off from the left side to the right side at 0.5 seconds. At 1 second, the tanker truck completely rolls over and hits the ground. This shows that the lateral sloshing effect cannot be completely eliminated by transverse baffles.

3.6.2. Using Four-Hole Longitudinal Baffle with Varying Hole Position Arrangements. The tanker truck is using four-hole longitudinal baffles with holes that vary in position at 50%

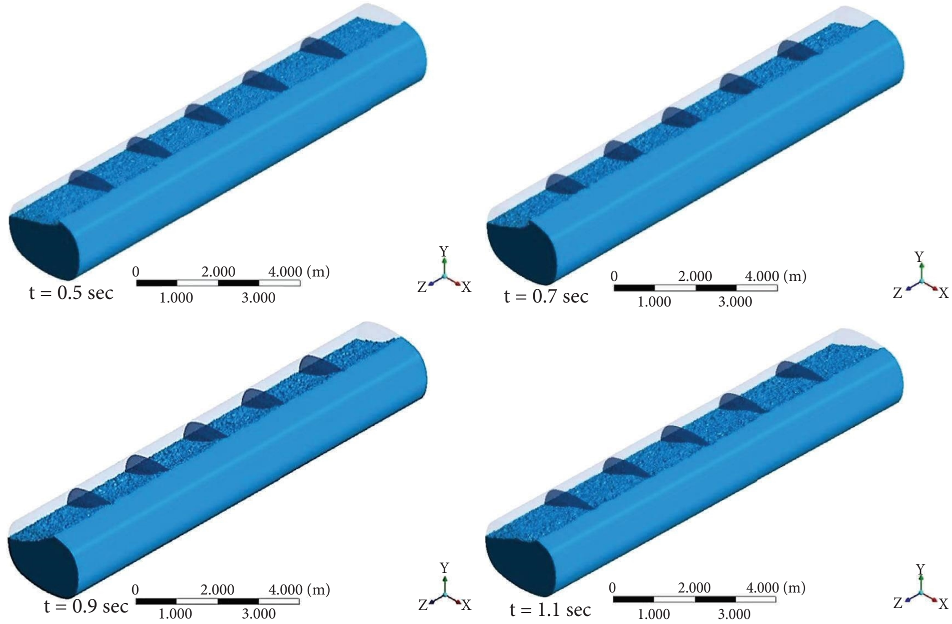


Figure 37: The free liquid surface of the diesel in tanker truck with transverse baffles at 80% fill condition.

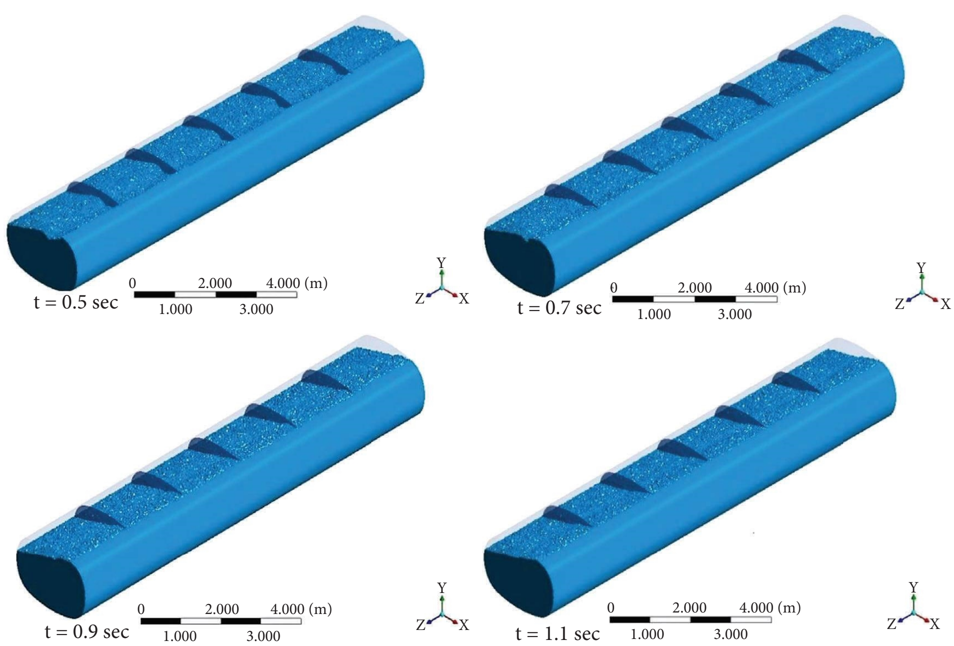


Figure 38: The free liquid surface of the diesel in tanker truck with transverse and multihole with varying hole position longitudinal baffles at 80% fill condition.

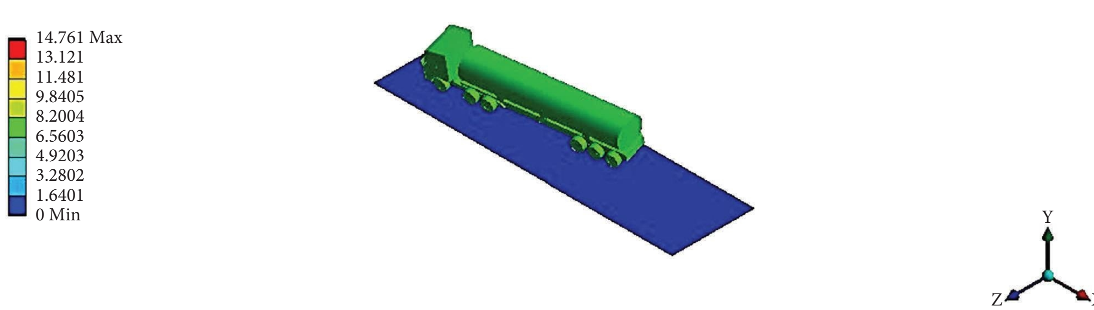


Figure 39: $t = 0.5$ sec.

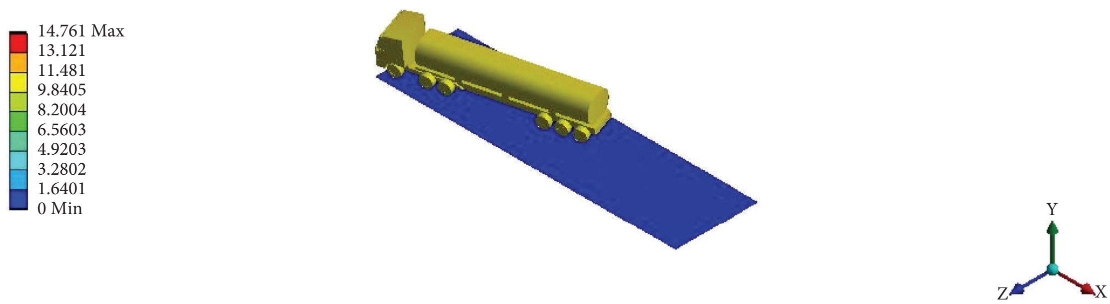


Figure 40: $t = 0.7$ sec.

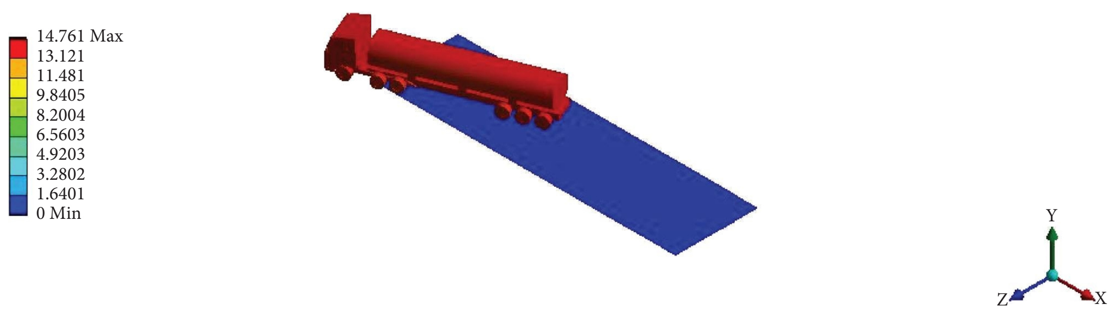


Figure 41: $t = 1$ sec.

fill levels at various time steps, as indicated in the aforementioned Figures 39–41. As a result, the tanker truck is safe from 0.05 seconds to one second, as shown above. As a result, the CFD result validated by LS-DYNA result matches because the optimum baffle system designs on both simulations are four-hole longitudinal baffles with hole variable position arrangements.

4. Conclusions

The aim of this study is to investigate the best baffle system designs and its arrangements in partial filled cargo tanker trucks at cornering conditions. The simulation of this study is carried out using volume of fluid (VOF) multiphase model in ANSYS Fluent in transient time state and also using ANSYS LS-DYNA for dynamic analysis to check the stability of tanker truck.

The main findings are summarized as follows:

(i) The existing baffle design systems known as transverse baffles were not effective in reduction of lateral sloshing effect due to its placement and hence prone to rollover the tanker.

(ii) The force and roll-moment fluctuation are more at 50% fill level.

(iii) When the fill level is higher (80% in this case), the fluid fluctuation is less; however, the magnitude of the forces is larger due to large mass of fuel.

(iv) Finally, comparing the best baffle system designs with different hole arrangements, it is concluded that multiholes' longitudinal baffles with staggered hole arrangement helps to a great extent in reduction of the sloshing effect by separating the mass of the fuel and flow of fuel to the side wall of tanker than inline hole arrangement. Its maximum lateral force and roll moment reduction are 47.76% and 58.66% when the fill level is 50%, and 29.69% and 22.52% when fill level is 80%, respectively. This type of baffle design greatly reduced the maximum peak moment and helps to improve the rollover stability of the truck and also minimize the accident which is caused by rollover.

Data Availability

The data supporting the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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