Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC03.20260123
Published: February 2, 2026

Internal Structure Design Optimization for the Truck Tanks to Minimize Slashing Effect

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Abstract

This research addresses the critical problem of fluid sloshing within tank trucks, a phenomenon that significantly compromises vehicle stability, safety, and braking performance during acceleration, deceleration, and cornering. Given the intensive transportation of liquid cargo, notably petroleum derivatives in oil-centric economies like Kuwait, effective mitigation of this internal wave formation is paramount for public safety and environmental protection. The unmitigated sloshing effect in a standard smoothbore tank poses a severe structural risk, as demonstrated by a preliminary Factor of Safety (FOS) of approximately 1.76 for a common 6 mm support thickness under static load. This low FOS suggests a high susceptibility to failure when subjected to the significant transient forces of sloshing.

The core objective of this paper is to optimize the internal baffle geometry of truck tanks to minimize this sloshing effect. This involved a case study using a benchmark elliptical tank design from local Kuwaiti manufacturers (ALMULLA industries), with the methodology built on rigorous Computational Fluid Dynamics (CFD) analysis. The CFD model was validated by successfully replicating an established academic study on liquid sloshing. The iterative optimization process led to the final, superior design: the Upper Welded Baffle with Three Cuts. This optimized configuration yielded substantial, quantifiable improvements compared to the initial smoothbore design: **Dynamic Pressure Reduction:** An 83.4 % reduction in the maximum dynamic pressure exerted on the tank walls, **Fluid Velocity Reduction:** A 73.9% reduction in the maximum average fluid velocity.

This paper successfully validates a CFD-based methodology for slosh mitigation and presents a practical, optimized baffle geometry for enhanced safety. The findings affirm that this structural optimization provides a highly effective means of stabilizing liquid cargo transport, offering clear justification for industry adoption by significantly increasing the safety and structural integrity of tanker trucks.

Keywords

Kuwait oil and gas industries, Fluid Sloshing, Design Optimization, Baffle Design, Tank Trucks.

1. Introduction

The State of Kuwait, a nation significantly vested in the hydrocarbon sector, relies extensively on the efficient and safe road transportation of large volumes of liquid cargo, including petroleum derivatives and vital water supplies for agricultural sectors (B. Klaus and P. Horn, 1986). Tanker trucks are indispensable to this critical logistical framework, but their operation is intrinsically susceptible to the dynamic forces induced by fluid sloshing the free movement of liquid within a partially filled tank which severely compromises vehicular safety and operational performance (Talal,2017).

Fluid sloshing is a nonlinear hydrodynamic phenomenon resulting from sudden changes in vehicle velocity, such as acceleration, braking, or cornering. This internal wave generation exerts substantial, transient forces on the tank walls, critically altering the vehicle's center of gravity and lengthening braking distances (Arab Times, 2020). The consequences of unmitigated sloshing are evident in several high-profile accidents in the region. For instance, a fuel tanker carrying 36,000 liters of diesel rolled over and ignited on Jahra Road in August 2020 (Sharaf AlKheder, 2022). Furthermore, a gasoline truck rollover occurred on King Fahad Road in March 2019 (KUNA, 2020) and fatal collisions involving water and fuel tankers have been reported in the past (Talal, 2019) and (Salem,2009). These incidents underscore the urgent need for effective slosh mitigation strategies to enhance public safety and protect the environment (Figure 1 and 2).

Figure 1: Tanker truck rolled over, reported at Jahra Road, Kuwait (Sharaf AlKheder, 2022).

Figure 2: Wrecked sedan and damaged tanker truck, reported at Wafra Road, Kuwait. (Arab Times,2025)

The foundational research on sloshing originated in the mid-20th century, primarily focusing on aerospace applications to assess internal wave effects on rocket stability (Salem, 2009). Subsequent studies expanded to ground transportation, examining the consequences of liquid motion in road tankers (Micheli, 2022). Most studies agree that the incorporation of internal structures, such as baffles and compartments, is the most practical passive mitigation method to reduce the effective base length of the fluid and thus dampen the slosh effect (White, F. M., 1981). Building on this historical and technical foundation, this study focuses specifically on minimizing longitudinal slosh the dominant force during acceleration and braking maneuvers through optimized baffle design, while acknowledging that lateral slosh remains a valid topic for future exploration.

Internal sloshing is an event that occurs due to movement of fluid that has free space in a bounded container after any change in speed (Talal, 2017). Kuwait and many countries depend on liquid transportation that encompasses hydrocarbons, water, chemicals and food products throughout the country. Such aspect is vital for Kuwait due to the dependence on fossil fuels and notably for water tankers to reach agricultural sectors for ground aggregation and ensure food security is maintained. Firstly, to provide background on the topic of sloshing, in the middle of the 20th century specifically in the 1950s and 1960, sloshing liquid inside nearly filled tankers was majorly studied towards aerospace **(**Micheli**,** 2022**).** This was achieved by experimenting with different tank vessel geometries to examine the effects of internal wave formation on overall stability (Salem, 2009). The studies evolved in the late 1970s, where researchers tried to determine the consequences of sloshing in nearly filled containers (Micheli, 2022). Hence, this paper will consider lowering the longitudinal slosh mainly due to current time constraints. However, lateral slosh can affect stability of the truck but is a future topic of research for this project.

1.1 Objectives

The primary objectives of this research are structured as follows:

- To establish and validate a robust Computational Fluid Dynamics (CFD) model capable of accurately simulating liquid sloshing dynamics in real-scale tanker trucks.
- To conduct a case study using an elliptical tank design benchmarked against specifications provided by local manufacturing sectors in Kuwait.
- To iteratively develop and analyze various

- internal baffle geometries to determine the optimal configuration for minimizing the dynamic pressure and velocity induced by fluid sloshing.
- To present a practically optimized baffle design that yields a quantifiable and significant reduction in internal sloshing forces, thereby enhancing the operational safety of liquid cargo transport in the region.

Figure 3: Fuel tanker accident on Kuwait's Jahra Road in 2020 (Siraye, 2020)

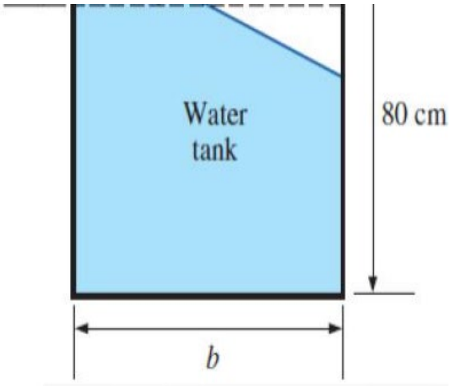


Figure 4: Illustrates how fluid rise occurs due to acceleration and is affected by base length.

2. Modeling and analysis

This section details the theoretical foundation, computational methodology, and critical validation steps used to simulate the fluid sloshing phenomena. The primary focus is the dynamic behavior of the liquid cargo during severe longitudinal deceleration, specifically emergency braking.

2.1 Theoretical Background of Slosh Dynamics

The dynamics of fluid sloshing are governed by fundamental principles of fluid mechanics and vehicle kinematics. During a braking event, the liquid surface inside the tank is subjected to a forward inertial force, causing the free surface to tilt. This tilt angle (θ) is crucial for calculating the resultant fluid rise (Y) and the forces exerted on the tank walls. The theoretical relationships used to quantify this effect are based on the acceleration imposed on the fluid body:

The deceleration (a_x) applied during an emergency stop is calculated as the change in velocity (ΔV) over the braking time (Δt). Based on the operational speed of 90 km/h (25 m/s) and an assumed braking time of 10 seconds, the average deceleration is:

$$Tan\theta = \frac{a_x}{g + a_z}, \rightarrow \quad \theta = ArcTan\left(\frac{25}{9.81}\right) = 14.3^o \tag{1}$$

On an ideal flat road, the free surface angle (θ) resulting from this acceleration is determined by the balance of inertial and gravitational forces, where a_z (vertical acceleration) is approximately zero:

$$0.5 * \left(Base * Tan\left(\frac{14.3Pi}{180}\right)\right) = Liquid\ Rise. \tag{2}$$

The total rise in the liquid level (Δh) is a critical parameter for safety analysis. Assuming the base length of the container is L, the maximum liquid rise on one side of the tank is proportional to the base length and the tilt angle. The incorporation of internal baffles and compartments effectively reduces the fluid's free surface base length (L), which is predicted to minimize the liquid rise and the resultant impact forces on the tank wall (White, A., 2020). This geometrical modification provides a gentler mass shift and reduced turbulent forces internally. This concept is illustrated in Figures 4 and 5.

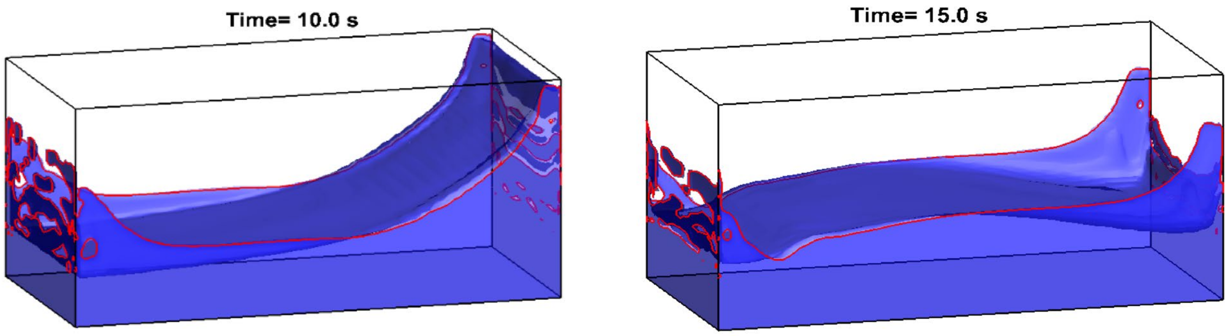


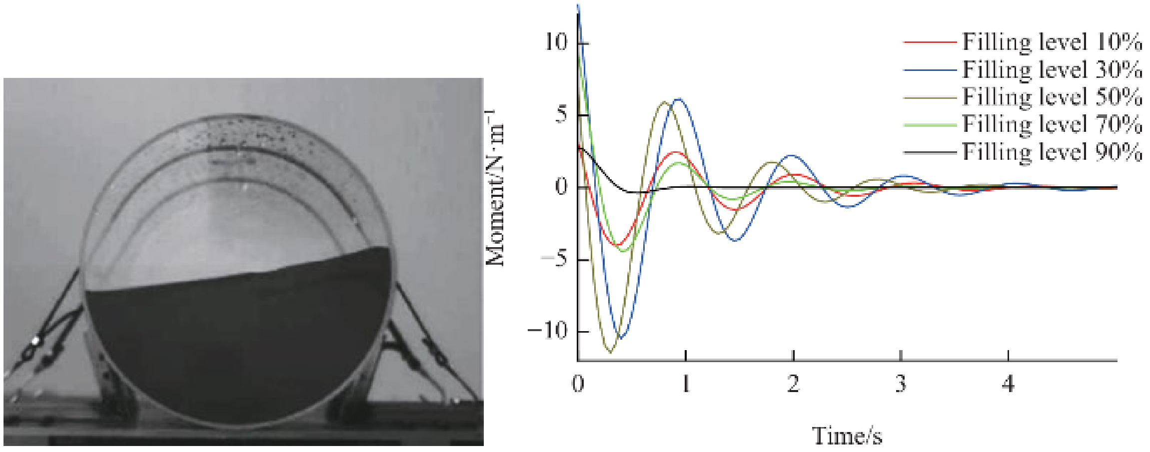
Figure 5: Illustrates how increasing time of acceleration can reduce the sloshing impacts (Rohit Kumar, 2001)

2.2 CFD Model Validation

Prior to simulating the complex elliptical tank geometry, the Computational Fluid Dynamics (CFD) methodology employed in SolidWorks Flow Simulation was validated against published experimental and numerical results. This step is essential to confirm the accuracy and reliability of the numerical solver and its ability to capture nonlinear sloshing dynamics. The validation effort replicated the study by (Lu et al., 2024). Which investigated lateral sloshing and mass variation in a cylindrical tank. The key parameters used for replication were:

- **Tank Geometry:** Cylindrical tank with a radius of 0.3 m and a length of 1 m.
- **Fluid:** Water, filled to 50% capacity.
- **Excitation:** A lateral acceleration pulse of 5 m/s2 for 0.1 s.
- **Duration:** Total simulation time of 5 seconds.

The replication successfully matched both the visual flow patterns (Figure 6, left) at the time snapshot of 0.3 s and the trend observed in the time-varying torque graph (Figure 6, right) reported by (Lu et al.,2024). The successful concordance between the simulated output and the established academic data confirmed that the SolidWorks Flow Simulation setup is appropriate for proceeding with the optimization study of the elliptical tanker truck.



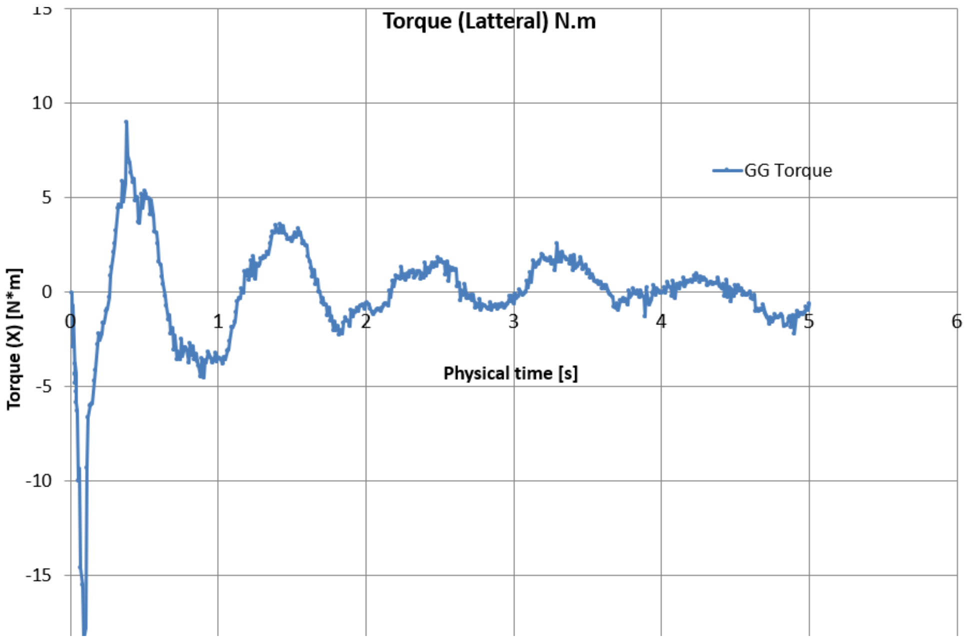


Figure 6: Physical test by (Lu et al, 2024) at 0.3s, & torque graph (Right blue graph) Output obtained.

2.3 Benchmark Tank Design and Dimensions

The benchmark case study was established in collaboration with Mula Industries Kuwait, a key local manufacturer of tanker trucks. The objective of the visit was to obtain realistic, industry-relevant specifications for the simulation model (Figure 7 and Figure 8). The dimensions for the elliptical tank design were set as follows:

- **Tank Cross-Section:** Ellipse (D1=2.4 m, D2=1.8 m).
- **Tank Length (L):** 10.7 m.
- **Tank Volume:** 36,000 liters (for full capacity).
- **Material Thickness (Tank):** 4 mm.
- **Material Thickness (Supports):** 8 mm (studied based on discussion with Mula engineers).

The simulations utilize a 50% fill volume, equating to 18,000 liters, to represent the maximum sloshing scenario. Preliminary analysis of the 8 mm supports under the static load of the 50% filled smoothbore design resulted in a Factor of Safety (FOS) of 2.53. This suggests that the unmitigated slosh forces could potentially reduce this FOS to unsafe levels, justifying the need for internal mitigation structures.

Figure 7: the oil tanker benchmark with built in baffles, Mula company Kuwait.

Figure 8: Manufacturing process for the oil tanks, The Mula company in Kuwait

2.4 CFD Setup and Boundary Conditions

The sloshing dynamics were simulated using the Volume of Fluid (VOF) model within SolidWorks Flow Simulation, which is appropriate for capturing the free surface interface between two immiscible fluids. The specific boundary conditions applied across the seven designed scenarios (Figure 9) are summarized in Table 1, where the dynamic velocity profile, designed to mimic a realistic full-cycle driving scenario (acceleration and severe braking), is depicted graphically in Figure 10. The simulation output focused on two key global goals for quantitative analysis: dynamic pressure exerted on the tank walls and the average fluid surface velocity during the braking phase, as these directly correlate with vehicle stability and structural integrity.

Table 1: Boundary conditions used in SolidWorks 2024 Flow

Parameter	**Value**
Time Step (Δt)	0.01 seconds
Total Simulation Time	60 seconds
Internal Fluids	Propane + Air (50%/50% Volume Fraction)
Overall Temperature	40°C
Fill Volume (50%)	18,000 liters
Velocity Profile (X-axis, Longitudinal)	0 to 100 km/h in 20 s (Acceleration), 100 to 0 km/h in 17 s (Braking)
Baffle Configuration	0 (Smoothbore) or 5 (Baffled Designs)

3. Simulation Model

This section details the design configurations for the internal structures and the parameters used for the iterative optimization study.

3.1 Design Optimization Strategy (11pt Bold, Left Justification)

The primary goal of the optimization phase was to identify an internal baffle geometry that maximizes the reduction in dynamic pressure and average fluid velocity during emergency braking, compared to the smoothbore benchmark. The design iteration process involved testing seven distinct configurations, as visually represented in Figure 9. These designs varied based on three key parameters:

1. **Baffle Position:** Middle-welded versus upper-welded.
2. **Number of Cuts/Holes**: Zero, one (1x), or three (3x) cuts.
3. **Gap Height:** The distance between the baffle's lower edge and the tank bottom (designed at 20 cm in the final model for fluid movement and cleaning access).

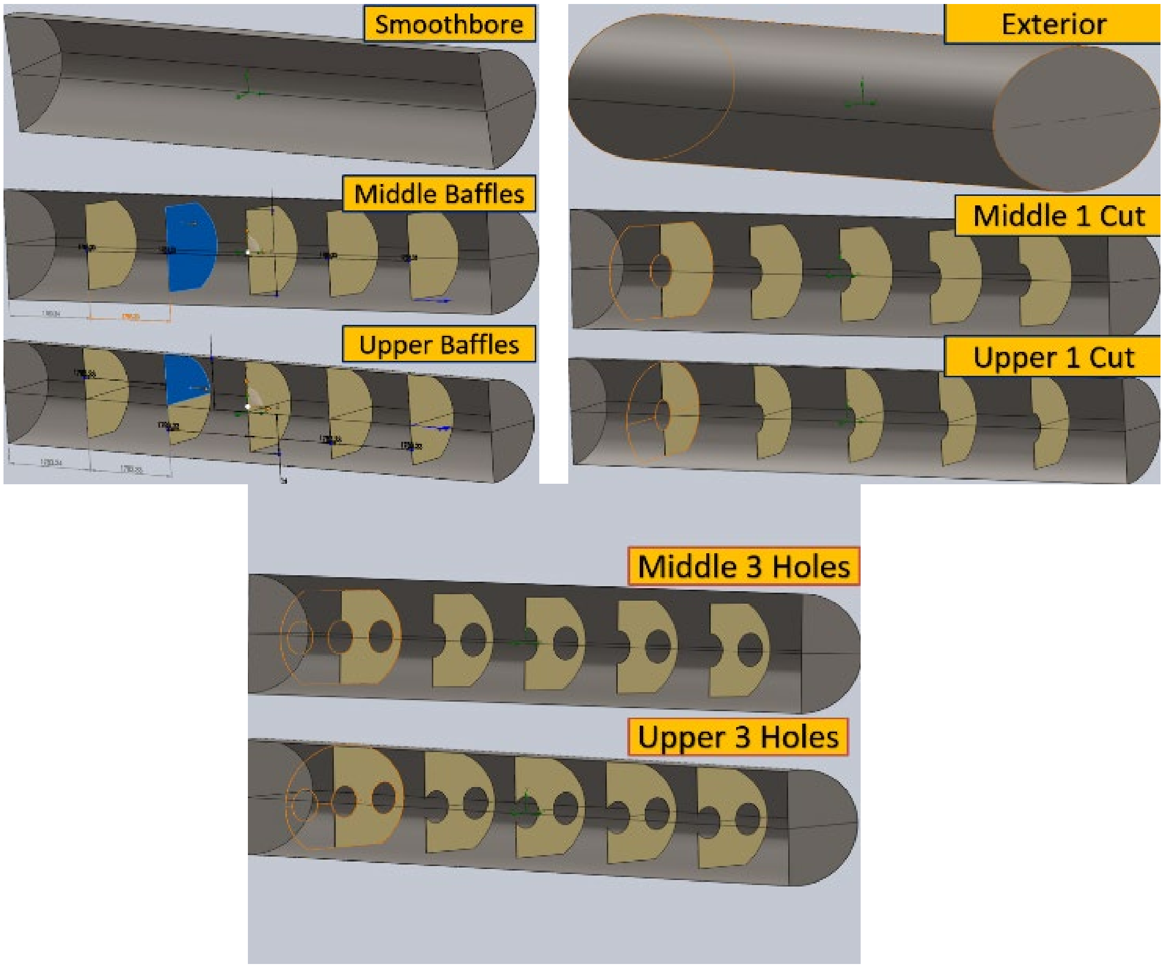


Figure 9: All 7 designs simulated for this research project with the variable being internal baffle design

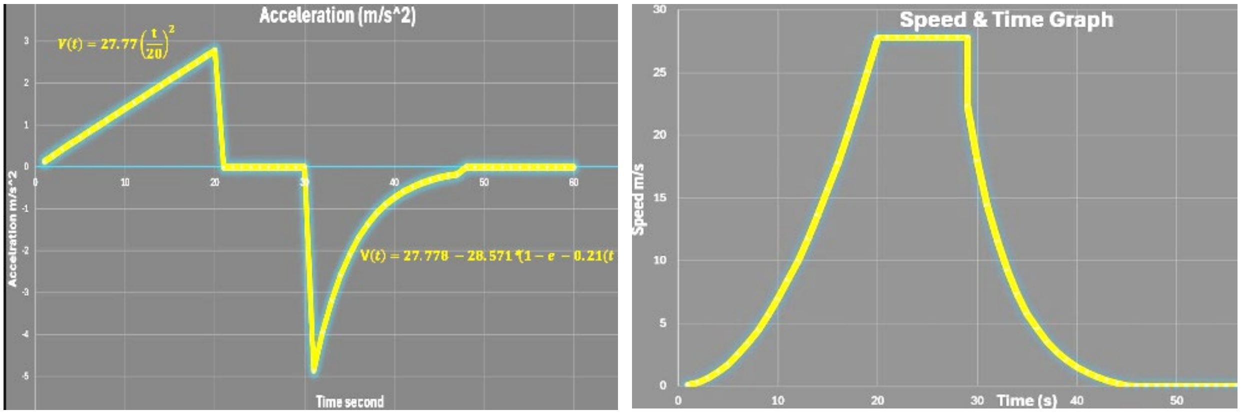


Figure 10: Acceleration and speed graphs used for this 60s simulation

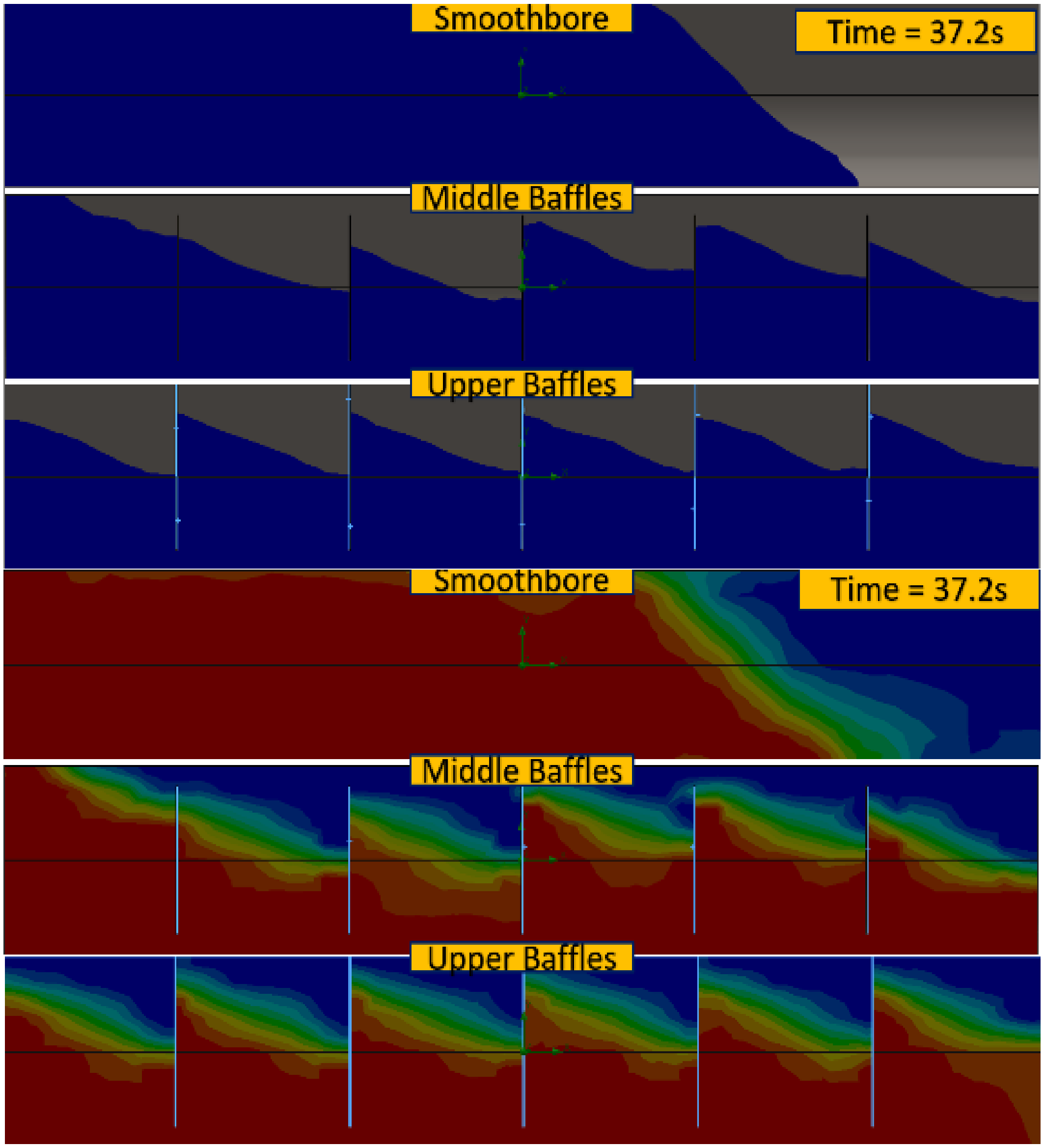


Figure 11: Fluid motion during braking at (37.2s) with heat map of propane volume fraction (Red = 100% propane, Blue = 100% Air), For the first 3 designs (Smoothbore, Middle Baffles & Upper baffles)

The final optimized design, referred to as the "upper welded baffles with three cuts," aimed to prevent fluid flow over the baffle while allowing crucial fluid passage below, retaining a 20 cm gap (Figure 13).

3.2 Smoothbore Benchmark Analysis

The smoothbore (no baffle) design served as the baseline for evaluating performance improvements. Under the 50% fill scenario, an initial structural analysis of the 8 mm thick support beams based on static load assumptions resulted in a Factor of Safety (FOS) of 2.53. Further simulations using a lower, yet common, support thickness of 6 mm yielded a substantially reduced FOS of approximately 1.76.

Such a low FOS indicates a high susceptibility to failure when subjected to the additional, significant transient forces induced by unmitigated sloshing during dynamic operations. This preliminary finding highlights the critical necessity of internal structures, not only for controlling fluid motion but also for indirectly protecting the vehicle's structural integrity, especially its chassis attachments and supports.

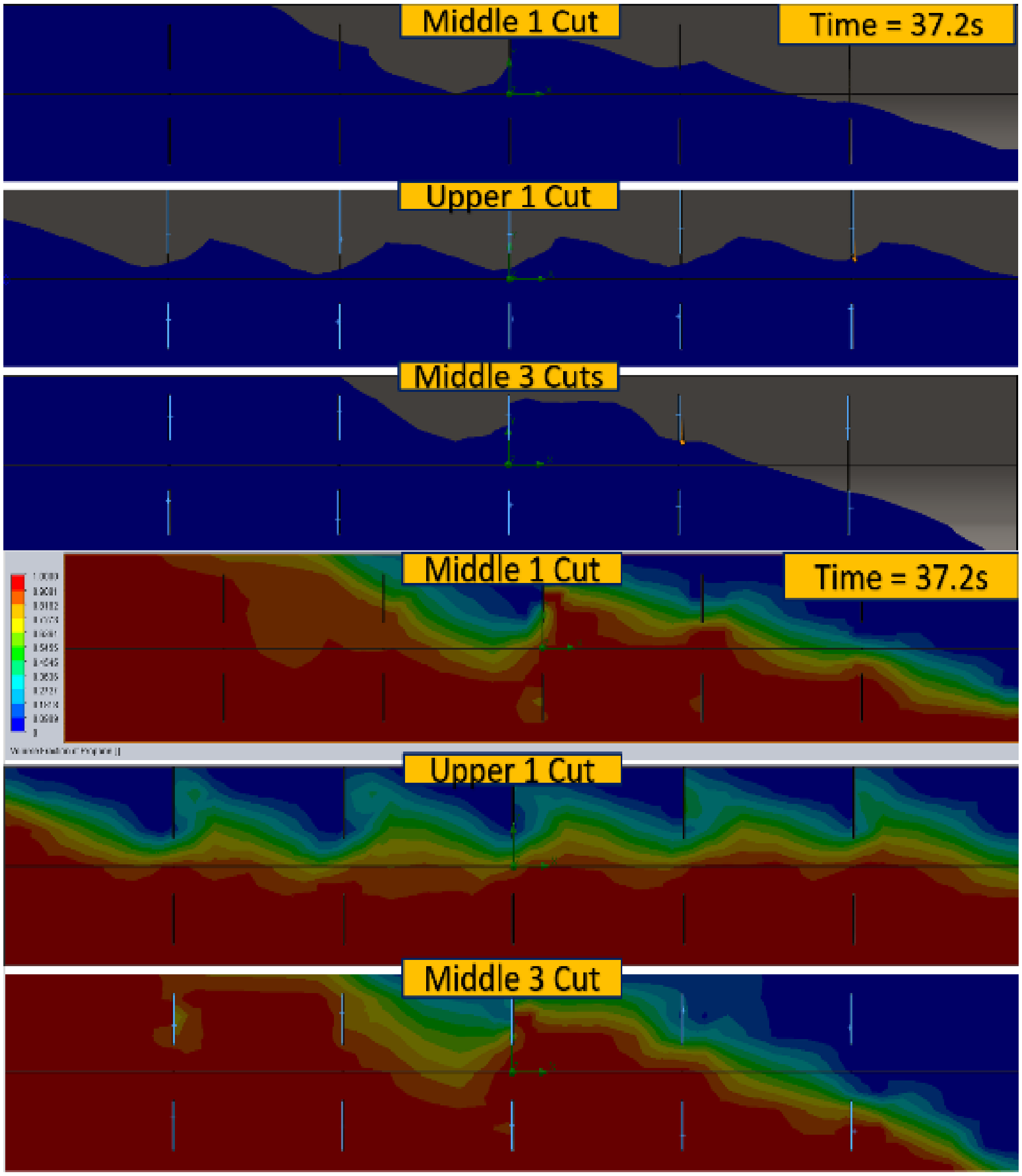


Figure 12: Fluid motion during braking at (37.2s) with propane volume fraction (Red = 100% propane, Blue = 100% Air), For the second 3 designs (Middle baffles 1x Cut, Upper Baffles 1x Cut & Middle baffles 3x Cuts).

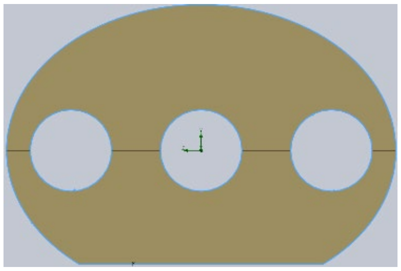


Figure 13: Baffle design of the upper 3 cuts. (20cm gap below to allow easy filling) (3x cuts, R = 25cm)

4. Results and Discussion

This section presents the comparative analysis of dynamic pressure and fluid velocity across the seven tested tank configurations, highlighting the performance improvements achieved through optimized baffle geometry.

4.1 Dynamic Pressure Analysis

The dynamic pressure exerted on the tank walls is the most critical metric for evaluating the risk of structural fatigue and instability. Table 2 summarizes the maximum pressure recorded for the smoothbore (benchmark) and the six baffled designs during the simulated emergency braking event.

Table 2: Dynamic Pressure Comparison Across Design Scenarios

Design Configuration	Maximum Dynamic Pressure (Pa)
1. Smoothbore (Benchmark)	26,000
2. Upper Welded Baffle (No Cuts)	16,000
3. Middle Welded Baffle (No Cuts)	17,000
4. Middle Welded Baffle (1x Cut)	11,000
5. Middle Welded Baffle (3x Cuts)	8,000
6. Upper Welded Baffle (1x Cut)	6,000
7. Upper Welded Baffle (3x Cuts) (Optimized)	4,300

The results clearly indicate that the presence of baffles consistently reduces the dynamic pressure by significantly disrupting the flow coherence. The most notable observation is the superior performance of the Upper Welded Baffle (3x Cuts) design, which recorded a maximum dynamic pressure of only 4,300 Pa. This represents a substantial 83.4% reduction in dynamic pressure compared to the 26,000 Pa measured in the smoothbore benchmark (Figure 11).

This performance advantage is attributed to two key factors: the upper welding position, which is crucial for intercepting the large-amplitude waves generated at the fluid surface, and the three small cuts, which manage the pressure differential while maintaining structural damping capability. Conversely, the Middle-Welded Baffle (No Cuts) configuration provided a less effective reduction, demonstrating the importance of baffle placement relative to the maximum liquid displacement during longitudinal sloshing.

Table 3: Maximum Fluid Velocity Comparison Across Design Scenarios

Design Configuration	Average Velocity (m/s)
1. Smoothbore (Benchmark)	2.3
2. Upper Welded Baffle (No Cuts)	1.7
3. Middle Welded Baffle (No Cuts)	1.8
4. Middle Welded Baffle (1x Cut)	1.2
5. Middle Welded Baffle (3x Cuts)	0.9
6. Upper Welded Baffle (1x Cut)	0.8
7. Upper Welded Baffle (3x Cuts) (Optimized)	0.6

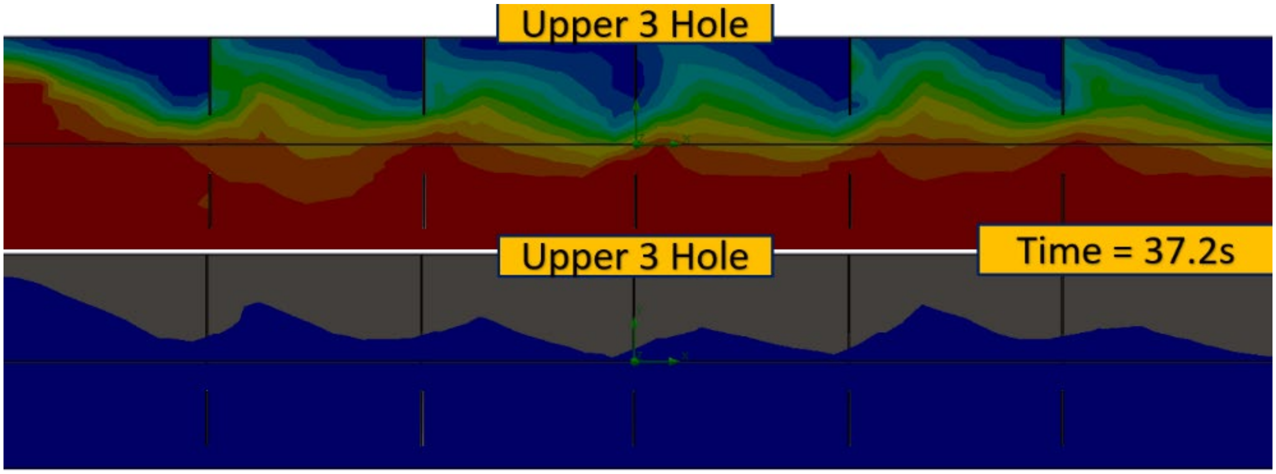


Figure 14: Simulation results for upper 3 cuts and heat map for propane volume fraction vs air (Red = 100 propane, blue = 100 Air).

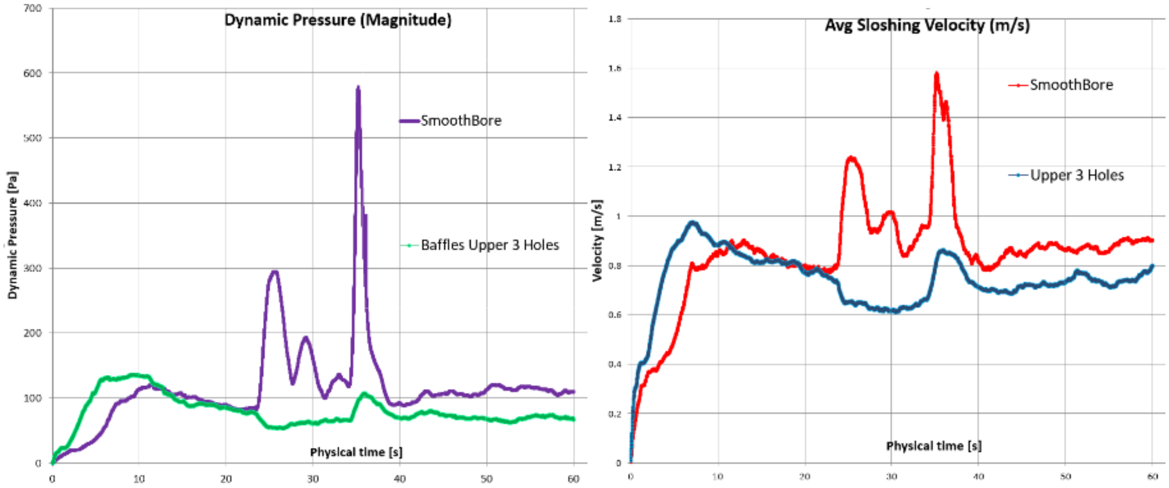


Figure 15: Dynamic pressure and Avg sloshing velocity comparison between smoothbore and final design

4.2 Fluid Velocity Reduction Analysis

The average fluid surface velocity is a direct indicator of the kinetic energy within the liquid and its potential to cause instability. The comparison of the maximum average velocity across all designs further supports the findings from the pressure analysis, as shown in Table 3.

The optimized Upper Welded Baffle (3x Cuts) design achieved the lowest maximum average fluid velocity at only 0.6 m/s. This translates to a 73.9% reduction compared to the 2.3 m/s recorded in the smoothbore tank. This significant velocity damping is essential for minimizing the impact forces and the corresponding destabilizing moments acting on the truck chassis. Figure 12 visually compares the velocity reduction across all tested scenarios.

4.3 Discussion on Optimal Baffle Design

The optimization study confirms the literature finding that internal structures are highly effective for slosh mitigation. The primary mechanism of action involves reducing the effective free surface area of the liquid, thereby limiting the wave amplitude and dissipating kinetic energy through turbulence around the baffle edges.

The superior performance of the Upper Welded Baffle with Three Cuts (Figure 13) is discussed in terms of its configuration:

Location: Positioning the baffle near the upper portion of the liquid (at 50% fill) allows it to immediately intercept and dampen the largest amplitude waves generated during braking, preventing them from propagating further. This placement is supported by the significant difference in performance between upper and middle-welded configurations.

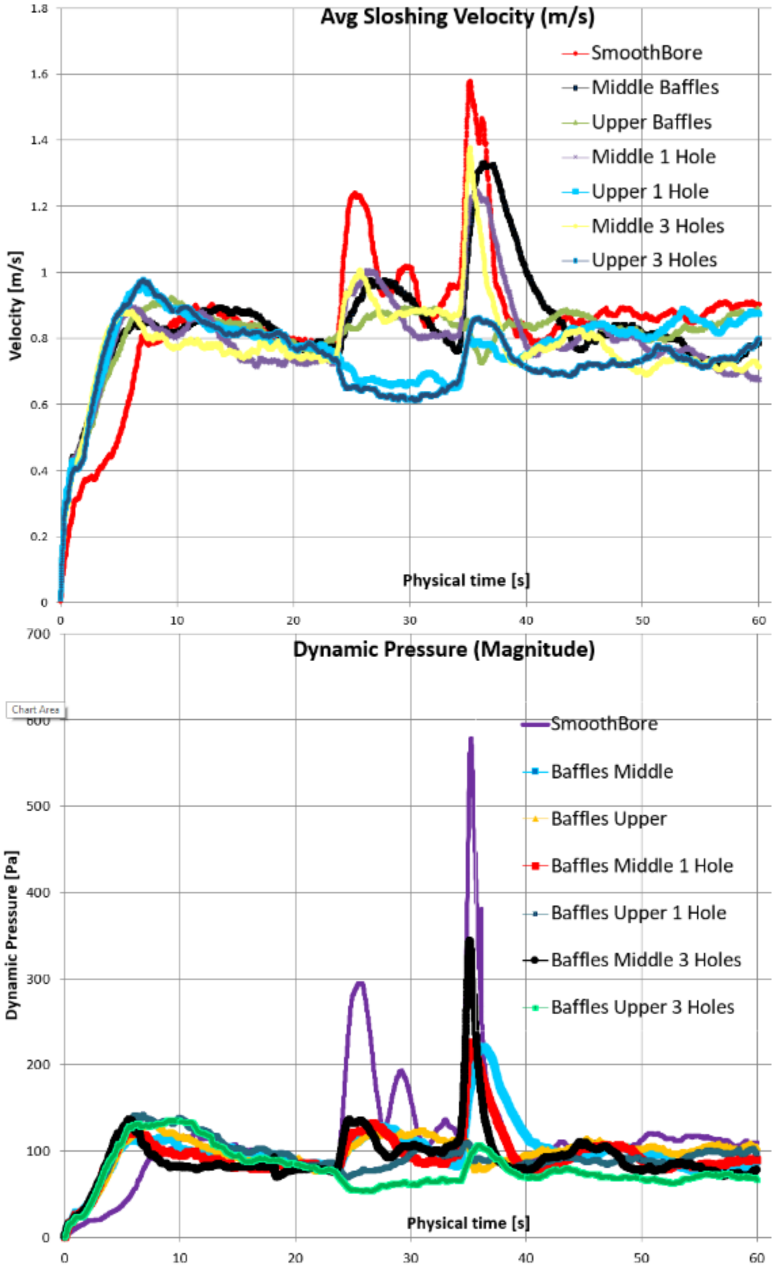


Figure 16: Average velocity & Dynamic pressure data graphs overlayed for all 7 designs

Apertures: The incorporation of three cuts, rather than a single large cut, proves more effective. The multiple smaller openings increase the turbulence generation per unit area, maximizing the dissipation of fluid kinetic energy through localized flow resistance without completely inhibiting the necessary fluid flow underneath the baffle for uniform pressure distribution and structural cleaning. The final optimized design is not only highly efficient in damping sloshing forces but is also practically viable for manufacturing and maintenance, as it retains the 20 cm gap required for periodic tank cleaning and inspection.

5. Conclusion

This study successfully investigated and optimized the internal structure design of elliptical tanker trucks to mitigate the critical issue of fluid **sloshing**, which poses a significant threat to vehicle stability and safety, particularly within Kuwait's liquid cargo transportation sector. Utilizing a validated Computational Fluid Dynamics (CFD) methodology, the research benchmarked a smoothbore tank design and iteratively tested various baffle configurations during a simulated emergency braking event. The primary finding validates that internal baffles are highly effective damping mechanisms. The optimization process yielded a superior design: the Upper Welded Baffle with Three Cuts. This configuration demonstrated exceptional performance in controlling fluid dynamics, achieving a substantial 83.4% reduction in maximum dynamic pressure (from 26,000 Pa to 4,300 Pa) and a 73.9% reduction in average fluid velocity (from 2.3 m/s to 0.6 m/s), compared to the smoothbore benchmark.

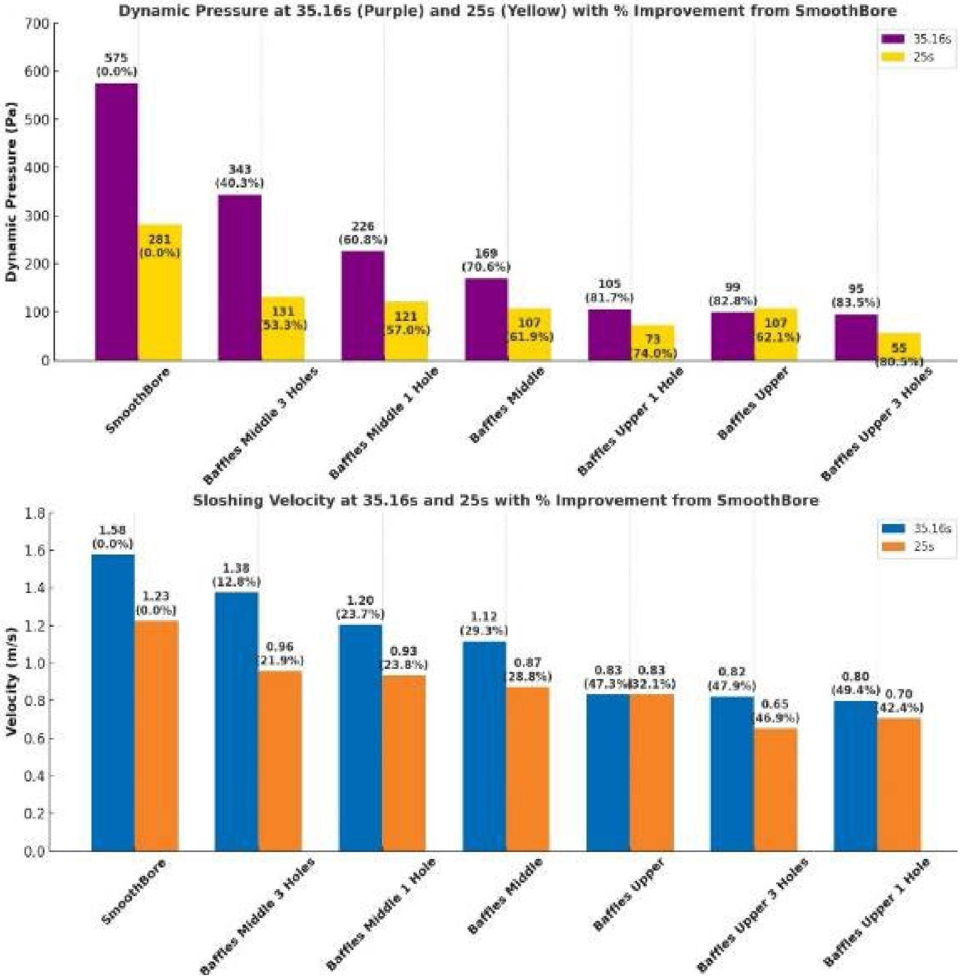


Figure 17: Dynamic pressure & Average velocity data as bar chart with percentage reduction compared to smoothbore tank

The key contribution of this work is the development and validation of a practically viable and highly efficient baffle geometry that can be directly implemented by local manufacturers. This design offers enhanced safety margins for drivers and cargo, leading to reduced accident risks and extended vehicle structural life. Future research should focus on extending this analysis to include lateral sloshing dynamics during high-speed cornering and exploring the effect of integrating multiple compartments within the tank geometry to further minimize the unconstrained free surface area.

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