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Computational Simulation of Fuel Tank Sloshing for a FSAE car using CFD Techniques

Anirudh Ganesh Sriraam, Manav Badamwala, Sagnik Deb, Bibin John

Abstract— Sloshing refers to the highly random motion of any fluid inside an object where the dynamic forces of the liquid can interact with the object to alter the overall system dynamics. This work summarises the process of designing and simulating the 3-D geometry of a fuel tank using CFD and the volume of fluid (VOF) method considering multi-phase fluid flow predicting fuel slosh movement at a specific capacity within a definite fixed volume.[13-16] As the performance of the engine heavily depends on a constant supply of fuel, the splashing of gasoline inside the partially filled fuel tank can severely affect the performance when subjected to sudden left and right turns during a Slalom in FSAE tracks. This scenario can be modelled, analysed and effectively controlled by reducing pressure intensities inside the tank walls using a set of strategically placed Baffles. Therefore, this study attempts to reduce the sloshing behaviour by considering multiple types of geometries and shows the final geometry chosen using computational simulations inside the fuel tank considering 1.5 litres of fuel and remaining with air inside a 7.3 litres fuel tank, thus predicting the effect of sloshing forces and moments inside the tank structure considering lateral and longitudinal acceleration fields. The model is discussed and results are presented.

In addition, this paper can be referred to as a detailed tutorial on how to simulate and take in consideration of all the factors which will be useful in deciding vehicle fuel requirements and optimum design.

Index terms: Computational Fluid Dynamics, Sloshing, Fuel tank, multi-phase fluid flow.

I. INTRODUCTION

Every automobile uses a fuel tank as a reservoir for its fuel. Most fuel tank assemblies include a tank shell having baffles inside them which act as support as well as sloshing reduction agents [1]. A racecar's primary objective is to be as light as possible. So, the use of plastics in the manufacture of a fuel tank became widely popular in the automotive industry. Many studies have been done in this field to assess the life cycle and feasibility of plastic based fuel tanks [2].

However, the use of such fuel tanks restricts design abilities since it only allows only partial height baffles to be integrated into the tank design [3].

Liquid sloshing is the movement of liquid free-surface inside a partially filled container due to external disturbances or forces [4]. This has severe implications in the performance of a vehicle. In most cases the sloshing of fuel causes unusual noises and vibrations [5]. In race cars, the effect of sloshing magnifies to situations wherein the fuel shifts to a side of the tank, away from the engine supply point, thus starving the engine of fuel.

Draining and Fuel starvation prediction is of critical importance in the design of a fuel tank. It is critical for a high-performance car to have a reliable fuel tank capable of feeding fuel to the engine at all times involving complex trajectories with varied acceleration profiles [6]. Fuel starvation in an engine leads to loss of pressure in the combustion chamber, which subsequently leads to a loss of power. In a competition where, a time interval of 1 second implies a rank loss of 10, every instance of avoiding power loss counts towards obtaining a better result. Fuel starvation in an engine leads to a low-pressure injection of fuel in the combustion chamber. This leads to a poor combustion phase as there is a longer mixing time, along with a distorted air fuel combination inside the combustion chamber [7].

It has been observed that the effect of sloshing varies with respect to the fill amount. Since sloshing refers to the free flow of fluid, the forces have different effects at different fill percentages [8]. A race car is subjected to high lateral and longitudinal forces. Thus, the design process involves analysing the flow of fluid under varying magnitudes of steady lateral, longitudinal and combination of lateral and longitudinal accelerations [9].

One of the most widely used ways to reduce the amplitude of sloshing is the construction of baffles inside the fuel tank. The study of transient fluid slosh analysis using Computational Fluid Dynamics (CFD) methods based on Navier-Stokes solver along with Volume-of-Fluid VOF technique has validated the effect of baffles to reduce sloshing effects [10]. The location of these baffles or partition walls play a major role in the free flow of the fluid. In the past studies were performed to analyse the sloshing motion to obtain a relation between the acceleration, location of partition walls, and the fill percentage [11]. The size of holes/orifice in the baffles has a major influence on the magnitude of sloshing. Increase in the size of orifice beyond the standard size has little or no major effect on the sloshing properties [12].

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A. Pravega Racing FSAE Vehicle

The comparison for improvement was done on 2017 PRV16 and 2019 PRV19 Vellore Institute of Technology vehicles to determine its effects on the performance of the vehicles. These vehicles were very similar in their performance aspects.

This was due to the implementation of the same CBR 600RR engine in both vehicles. The data analysis of the car during a slalom was taken and spikes in Air Fuel Ratio were found indicating sloshing phenomenon. This problem is due to the free sloshing of the fuel that temporarily provides less power to the engine. The target to achieve hence was to optimize the fuel tank volume and to reduce sloshing phenomenon of PRV16 fuel tank.

Fig. 1: 2019 Pravega Racing PRV18

Fig. 2: 2017 Pravega Racing PRV16

2018	**Values**
Engine	CBR 600RR
Volume of Fuel Tank	8.2L
Weight of Vehicle	245 Kg
2019	Values
Engine	CBR 600RR
Volume of Fuel Tank	7.3L
Weight OF Vehicle	235 Kg

Table 1 Performance Comparison between PRV16 and PRV18

II. OBJECTIVE

From the literature review we have inferred that sloshing is an important phenomenon which has to be minimal in order to get the best performance in a race car. As our car is subjected to high longitudinal and lateral forces reducing sloshing to get the maximum power was of at most importance. So, our objective was to design a fuel tank which provides constant fuel supply to the engine and there is no power loss experienced.

III. METHODOLOGY

The following research and experiments were performed for and on the 2018 prototype of Pravega Racing named as PRV 18. The vehicle is a formula student prototype car built for the Formula SAE competition series. Formula SAE is a student design competition organized by SAE International annually in various locations globally. The team of Pravega Racing designed, manufactures and competed in Formula Student Germany 2019 in the combustion class.

PRV18 is a formula student prototype vehicle, powered by the Honda CBR 600RR engine housed in a spaceframe chassis with pushrod type suspension, along with front and rear aero packages. The car is capable of accelerating to a speed of 100kmph from a standing start in under 5 seconds. One of the events in the competition involves completing an endurance run which involves driving the car for a timed distance of 22km while maintaining complete mechanical and functional integrity at the end of the run. The fuel tank is designed keeping in mind the volume requirements as well as the increased effects of sloshing as the fill level approaches 0%. Multiple iterations and analysis were performed to reach an optimum value of 7litres, which would ensure sufficient fuel for endurance without compromising on the vehicle performance throughout the run. Mock endurance runs performed in testing sessions concluded in the car retaining 1lt of fuel at the end of the run without any significant sloshing.

The initial designs were modelled in CAD software keeping in mind the geometric constraint and volumetric limitations. The designs were narrowed down to a few designs which satisfied all conditions while being lightweight. The next step involved executing simulations and optimising the designs based on the results. Initial simulations were performed using mono directional forces followed by a combination of mono directional forces.

After optimisations, the designs were simulated with forces measured on the car in real time using a data acquisition system integrated with the car. The fuel tank had to be designed such that there would be no fuel starvation at lateral accelerations of 1.6G (15.68m/s2). Since the competition involves fixed rules regarding the track layout, a similar track was recreated in the testing grounds in accordance with those norms. Extensive testing was carried out to inspect for fuel starvation due to sloshing at the high-speed corners where the lateral acceleration forces would reach magnitudes of 2G(19.6m/s2).

Further tests were conducted to estimate the fill percentage at which sloshing would occur. This was done by a novel method of measurement of fuel consumption by using data collected from the data acquisition system which involves the throttle input, engine RPM, fuel table/map input for the Electronic Control Unit (ECU). The data acquired from the tests were then compared to simulated results and further optimisation were made to the design.

IV. CALCULATION

A. Fuel Consumption Calculations

The car employs an electronically controlled fuel injection system, wherein a PE3 ECU, by Performance Electronics is used. The ECU refers to a fuel table which consists of a specific value of injector open time for a given throttle position/load and a given RPM. The fuel table is unique for the car's engine and its respective intake manifold.

The first objective is to estimate optimum volume consumption of the Vehicle during a standard endurance (21 Km) event in FSAE.

TPS/ RPM	**0**	**521**	**1042**	**1562**	**2083**	**2604**
100	3.84	3.91	4.00	4.25	04.31	4.56
96	3.84	3.91	4.00	4.25	04.31	4.53
92	3.88	3.94	4.00	4.22	04.28	4.50
88	3.88	3.94	4.00	4.22	14.28	4.50
84	3.88	3.94	4.00	4.22	04.28	4.47
80	3.91	3.94	4.00	4.22	04.25	4.44
76	3.91	3.97	4.03	4.19	04.25	4.41
72	3.91	3.97	4.03	4.19	04.22	4.41
68	3.94	3.97	4.03	4.19	04.22	4.38

Table 2 Fuel map

TPS/RPM	**0**	**521**	**1042**	**1562**	**2083**	**2604**
100	47524	32	136	4472	13119	34212
96	176	0	0	44	1256	6802
92	56	0	24	32	1351	8372
88	28	12	32	100	380	8620
84	32	4	108	304	764	8271
80	32	0	8	68	116	3828
76	56	16	28	108	24	2044
72	48	0	48	120	60	1404
68	64	0	0	84	156	996

Table 3 Number of times the car reached a specific RPM/TPS

TPS/ RPM	**0**	**521**	**1042**	**1562**	**2083**	**2604**
100	0.46335	0.000312	0.00131	0.04320	0.13027	0.33664
96	0.00173	0.000000	0.00000	0.00043	0.01273	0.06815
92	0.00068	0.000000	0.00029	0.00039	0.01645	0.10121
88	0.00034	0.000147	0.00039	0.00121	0.00462	0.10499
84	0.00039	4.87E-05	0.00131	0.00370	0.00937	0.10074
80	0.00030	0.000000	9.74E-05	0.00083	0.00142	0.04697
76	0.00067	0.000195	0.00034	0.00132	0.00029	0.02532
72	0.00058	0.000000	0.00058	0.00147	0.00074	0.01752
68	0.00077	0.000000	0.00000	0.00104	0.00193	0.01243

Table 4 Fuel Consumed

The average fuel consumption required for the vehicle was calculated as follows: -

1. The Fuel Map (Table 2) provides us with the time the injector was switched on (in ms) at various throttle positions vs the various RPM values.
2. Table 3 provides us with the number of times that the fuel injector is activated at a particular RPM and throttle position during an Endurance event for FSAE.
3. Both of these values are multiplied and the corresponding matrix is multiplied with the volume fuel rate the injector is capable of producing. (3ml/sec).

$$Total\ Volume = On\ Time \times No.Of\ Time\ switched\ On \times Rate\ Of\ Fuel\ Injected$$

After Adding all of the matrix values, the capacity of fuel was found out to be 7.3L. The entire fuel table and number of actuations are mentioned in the Appendix (Table A and Table B).

B. Vehicle Acceleration Data

It was observed that the engine suffered from fuel starvation in areas where the car had to negotiate high speed turns. To understand the problem, a 3-axis accelerometer was mounted inside the car close to its centre of gravity, and the transverse forces measured in a data logger. It was then observed that the sloshing had a prominent effect at lateral accelerations of 1.1G's (10.791m/s2). The data collected for this study was taken from the following testing scenarios: -

a. Slalom tracks

The slalom part of track (Fig 3) was taken and the data captured (Table 5) was analysed to detect the issue

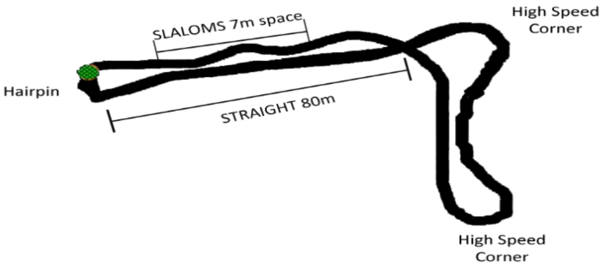

Fig. 3 Track Setup as per GPS

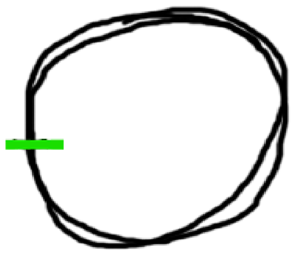

Fig. 4 Skidpad Track Setup as per GPS

Time	accel_x_g	accel_y_g	X	Y
0	-1.1	-0.1169	-10.791	-1.14679
0.005	-1.1	-0.1169	-10.791	-1.14679
0.01	-1.2	-0.334	-11.772	-3.27654
0.015	-1.2	-0.334	-11.772	-3.27654
0.02	-1.2	-0.334	-11.772	-3.27654
0.025	-1.2	-0.334	-11.772	-3.27654
0.03	-1.2	-0.334	-11.772	-3.27654
0.035	-1.2	-0.334	-11.772	-3.27654
0.04	-1.2	-0.334	-11.772	-3.27654
0.045	-1.2	-0.334	-11.772	-3.27654
0.05	-1.3	-0.2338	-12.753	-2.29358
0.055	-1.3	-0.2338	-12.753	-2.29358
0.06	-1.3	-0.2338	-12.753	-2.29358
0.065	-1.3	-0.2338	-12.753	-2.29358
0.07	-1.3	-0.2338	-12.753	-2.29358
0.075	-1.3	-0.2338	-12.753	-2.29358
0.08	-1.3	-0.2338	-12.753	-2.29358

Table 5 Slalom Acceleration Data

b. Skidpad Cornering

To obtain a uniform lateral acceleration situation, the car was driven in a circular track of fixed radius at a capped speed. The track map (in Fig 4) was taken and the data captured (Table 6) was used for the analysis. This test was performed so that we could obtain a near-constant velocity, along with a high lateral force value.

H	accel_x_g	accel_y_g	X (m/s^2)	Y(m/s^2)
0.005	-1.0354	-0.1503	-10.1573	-1.47444
0.01	-1.0354	-0.1503	-10.1573	-1.47444
0.015	-1.0354	-0.1503	-10.1573	-1.47444
0.02	-1.169	-0.9686	-11.4679	-9.50197
0.025	-1.169	-0.9686	-11.4679	-9.50197
0.03	-1.169	-0.9686	-11.4679	-9.50197
0.035	-1.169	-0.9686	-11.4679	-9.50197
0.04	-1.4195	-1.0855	-13.9253	-10.6488
0.045	-1.4195	-1.0855	-13.9253	-10.6488
0.05	-1.4195	-1.0855	-13.9253	-10.6488
0.055	-1.4195	-1.0855	-13.9253	-10.6488
0.06	-1.4863	-0.8517	-14.5806	-8.35518
0.065	-1.4863	-0.8517	-14.5806	-8.35518
0.07	-1.4863	-0.8517	-14.5806	-8.35518
0.075	-1.4863	-0.8517	-14.5806	-8.35518
0.08	-1.169	-0.9185	-11.4679	-9.01049

Table 6: Slalom Acceleration Data

c. Geometry Decision

The design of CAD was done on SolidWorks. The design had 5 iterations as mentioned in table 7. All the tanks were designed based on packaging on the vehicle chassis. The restrictions included the height to be at most 190mm and the width shouldn't exceed 500mm.

These restrictions were decided based on the chassis design and the seat placement

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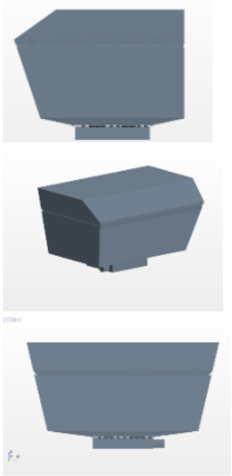
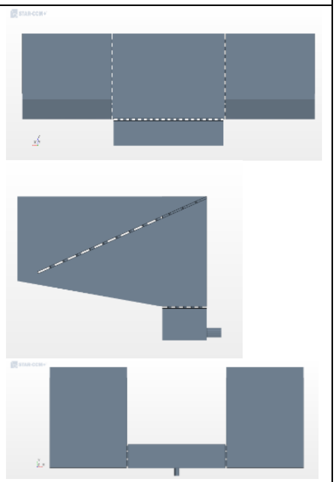
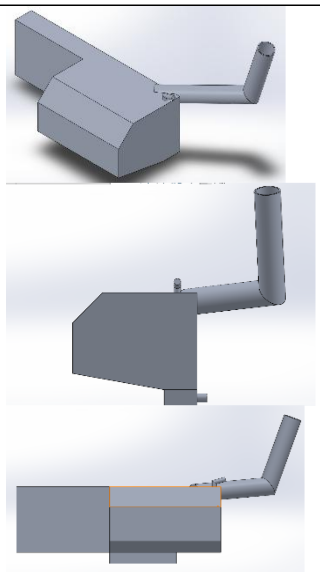
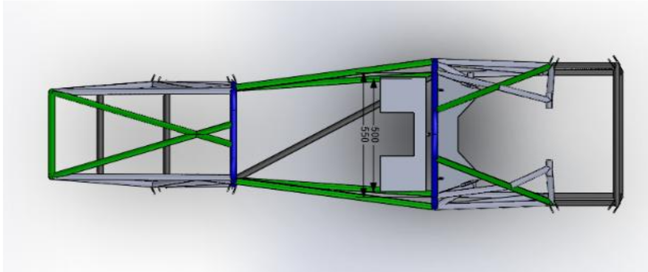
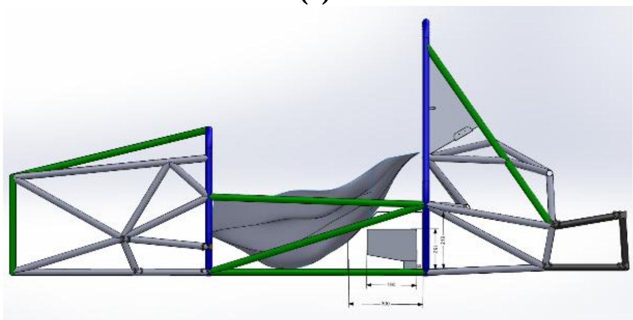
Design Type	CAD Views
Single Piece (PRV 16) With Volume changed to 7.4L	
U shaped	
L Shaped	

Table 7 Geometries Iterated

The U-shaped Fuel tank was chosen by making a relationship matrix of different factors:



(a)



(b)

Fig. 5 Geometry Visualization of Fuel Tank

A. Lesser Height:

The height of the fuel tank is a very important aspect for the packaging of the entire vehicle. According to the rules of the competition the driver's helmet should be under 2 inches from the line connecting the front hoop and the main hoop of the vehicle. Hence Height of the fuel played a crucial role in order to satisfy the rules and regulations. Fig 5 shows the maximum possible height of the fuel tank. The limits were set as 500mm in width,212mm in height and 230 mm in length. The tank should be designed according to these limits in order to satisfy the rules of the competition.

B. Symmetricity

The symmetricity of the fuel tank ensures that similar phenomenon is observed in both sides of the fuel tank. Hence, when the sloshing is observed in one direction, it can be easily assumed that the same would be occurring in the other side. This reduces simulation time as the sloshing only has to be observed in one direction rather than both.

C. Lesser material Used

As the fuel tank is being designed for is a race car. Weight plays a crucial role in the vehicle performance. Hence the lesser the material was used more will be the performance of the vehicle.

D. Complexity

Higher complexity leads to increased sources of leaks in the fuel tank. As the fuel tank will be joined together by the process of welding the complexity of the tank had to be kept in mind for manufacturability.

E. Inherent Anti-Sloshing Property

This factor was one of the most crucial factors. The better a fuel tank resisted sloshing without the baffle the easier it will be to control the flow of the fuel by adding baffles.

Hence the inherent anti-sloshing property provides a comprehensive idea about whether to proceed with further iterations with baffles or not.

Decision Criteria

	Lesser Height	Symmetricity	Lesser Material Used	Lesser Complexity	Inherent Anti-Sloshing Property	Total
Weight	3	2	2	3	4	
Single Piece	3	3	9	9	1	64
U Shaped	**9**	**3**	**3**	**1**	**9**	**78**
L Shaped	3	1	3	3	3	38
Cuboidal	9	3	3	9	1	70
Hemishperical	1	9	9	1	3	54

Fig.6 Decision Criteria Matrix

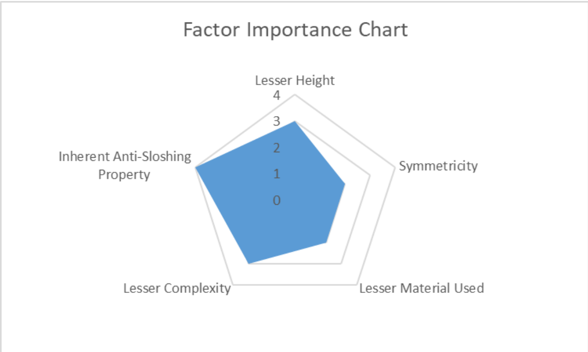


Fig. 7 Factor Importance Chart

Top Three Totals	
1	78
2	70
3	64

Criteria Weights Menu	Project Weights Menu	Criterion
1	0	None
2	1	Low
3	3	Mid
4	9	High

Fig. 8 Criterion Final values

V. MODELLING

The fluid flowing inside a partially filled fuel tank can be considered a mixture of two fluid flowing inside a fuel tank with lateral and longitudinal acceleration of the fluids given with a table taken via an IMU (Inertial Measurement Unit). The motion can be modelled using momentum and mass conservation equation.

The continuity equation (for a phase i) is given as:

$$\frac{\partial}{\partial t}\left(\alpha_i \rho_i \mathbf{v}_i\right) + \nabla\left(\alpha_i \rho_i \mathbf{v}_i \mathbf{v}_i\right) = \bar{s}_i^{\alpha}$$

And the momentum equation is given as

$$\frac{\partial}{\partial t}\left(\alpha_i \rho_i\right) + \nabla\left(\alpha_i \rho_i \mathbf{v}_i\right) = s_i^{\alpha}$$

There were two options to choose for the multiphase model: -:

1. Dispersed Multiphase (DMP)
2. Eulerian Multiphase (EMP)

The Dispersed Multiphase (DMP) model simulates dispersed phases in a Eulerian manner. The Dispersed Multiphase model combines aspects of both the Lagrangian Multiphase (LMP) model and the Segregated (Eulerian) Multiphase (EMP) models.

By default, DMP uses one-way coupling: the continuous phase influences the dispersed phase particles through terms such as drag in the momentum equation and heat transfer in the energy equation, but there is no reverse effect. When the optional Two-Way Coupling model is activated in DMP, the reverse effect is accounted for, and dispersed phase source terms appear in continuous phase equations.

In the Eulerian Multiphase Mixture model, mass, momentum, and energy are treated as mixture quantities rather than phase quantities. STAR-CCM+ solves transport equations for the mixture as a whole, and not for each phase separately [2]. The model is computationally more efficient than models that simulate each phase separately. Hence, for just figuring out the phases interaction we don't require heat transfer coefficient. This reduces our computational burden.

VI. SIMULATION DOMAIN

Creating an appropriate domain is necessary to avoid any interaction of its walls and baffles, which can result in inaccurate results. Hence a negative volume body was made in solid works that insects the walls of the fuel tank and baffles. This leads to sealing of the corners of the baffles.

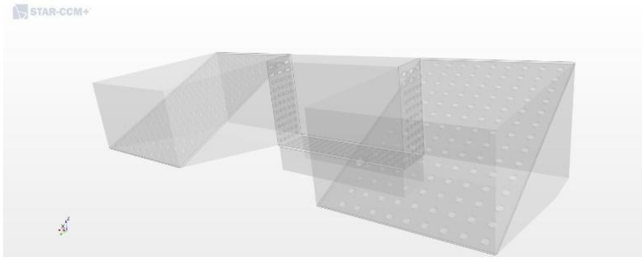


Fig. 9 CAD Geometry of Tank

Generating a good quality mesh is the answer to accuracy and the stability of the numerical computations. For volume mesh model, polyhedral mesh is used. Fig. 10 shows the polyhedral mesh formed on the tank. The mesh has 1063879 cells, 7203744 faces, 6372536 vertices. The next most important part of setting up the simulation is assigning boundary conditions. The first step is setting up the physics model for the simulation. Table 8 specifies the physics continuum used for doing the computational analysis and defining the boundary conditions for the same.

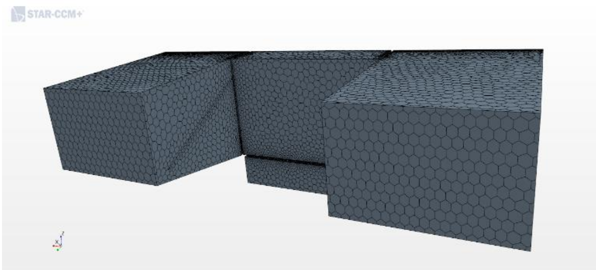


Fig. 10 Polyhedral mesh formed on the Tank

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PHYSICS CONTINUUM
MODELS
All y+ Wall Treatment
Volume of Fluid
Eularian Multiphase
Gradient
K-Epsilon Turbulence
Reynolds Average Navier Stokes
Segregated Flow
Realizable K-Epsilon Two-Layer
Implicit Unsteady Steady
Three Dimensional
Turbulent
Segregated Fluid Isothermal

Table 8: Physics Continuum

VII. SIMULATION SETTINGS

A. Time Step

The time step was decided based on the Courant number. Selecting time step size will depend on Courant-Friedrichs-Lewy condition (CFL number) that is: -

$$C = \frac{U \ \Delta t}{\Delta x} \leq C_{max}$$

For the simulation to be accurate it is important that the CFL number is less than the Max Courant Number (taken as unity). The minimum length (Δx) to be observed was set to be the outlet diameter that is approximately m. The free stream velocity (U) was set to be equal to the velocity at 10m/s.

$$\frac{U \ \Delta t}{\Delta x} \leq C_{max} \ \rightarrow \Delta t = \frac{\Delta x}{U} = \frac{0.07[m]}{0.5 \ \times 10 \ \left[\frac{m}{s}\right]} = 0.018s$$

B. Amount of Fuel

Fuel Table used in the ECU is extracted from the ECU via the bundled software. The fuel table can then be exported to a .csv file compatible with most spreadsheet softwares. The fuel map (Table 9) that was used to determine the volume of fuel tank is used again.

TPS/RPM	0	521	1042	1562	2083	2604
100	3.84	3.91	4.00	4.25	04.31	4.56
96	3.84	3.91	4.00	4.25	04.31	4.53
92	3.88	3.94	4.00	4.22	04.28	4.50
88	3.88	3.94	4.00	4.22	14.28	4.50
84	3.88	3.94	4.00	4.22	04.28	4.47
80	3.91	3.94	4.00	4.22	04.25	4.44
76	3.91	3.97	4.03	4.19	04.25	4.41
72	3.91	3.97	4.03	4.19	04.22	4.41
68	3.94	3.97	4.03	4.19	04.22	4.38

Table 9 Fuel map

Followed by fuel map data from the data logging system is extracted. The Table 10 below contains RPM and Throttle Position Sensor data extracted from various sensors used in the vehicle.

TPS/RPM	0	521	1042	1562	2083	2604
100	0	0	0	0	0	0
96	0	0	0	0	0	0
92	0	0	0	0	0	0
88	0	0	0	0	0	0
84	0	0	0	0	0	0
80	0	0	0	0	0	0
76	0	0	0	0	0	0
72	0	0	0	0	0	0
68	0	0	0	0	0	0

Table 10 Number of times the car reached a specific RPM/TPS

The RPM and throttle values are extracted and a matrix for the injector open count matrix is prepared. This involves counting the number of times a certain RPM and corresponding throttle value occurs in regular operation.

TPS/RPM	0	521	1042	1562	2083	2604
100	0.46335	0.000312	0.00131	0.04320	0.13027	0.33664
96	0.00173	0.000000	0.00000	0.00043	0.01273	0.06815
92	0.00068	0.000000	0.00029	0.00039	0.01645	0.10121
88	0.00034	0.000147	0.00039	0.00121	0.00462	0.10499
84	0.00039	4.87E-05	0.00131	0.00370	0.00937	0.10074
80	0.00030	0.000000	9.74E-05	0.00083	0.00142	0.04697
76	0.00067	0.000195	0.00034	0.00132	0.00029	0.02532
72	0.00058	0.000000	0.00058	0.00147	0.00074	0.01752
68	0.00077	0.000000	0.00000	0.00104	0.00193	0.01243

Table 4 Fuel consumed

$$\text{Total Volume} = \text{On Time} \times \text{No. Of Time switched On} \times \text{Rate Of Fuel Injected}$$

$$\text{Fuel Remaining} = \text{Fuel poured into fuel tank} - \text{Total Fuel Consumed}$$

The fuel quantity inside fuel was set by adjusting the height that the fuel covers. This was mainly due to the fact that the geometry of the fuel tank was complex and would generally lead to errors if volume where to be specified to the software.

The height was decided to be kept at 210mm which equals to 1.54L. A field function was used to set the volume of fluid in the tank. The minimum value was derived by measuring the fuel consumed till the drop-in performance is observed. The difference in the Volumes would give us the minimum value after which fuel sloshing occurs.

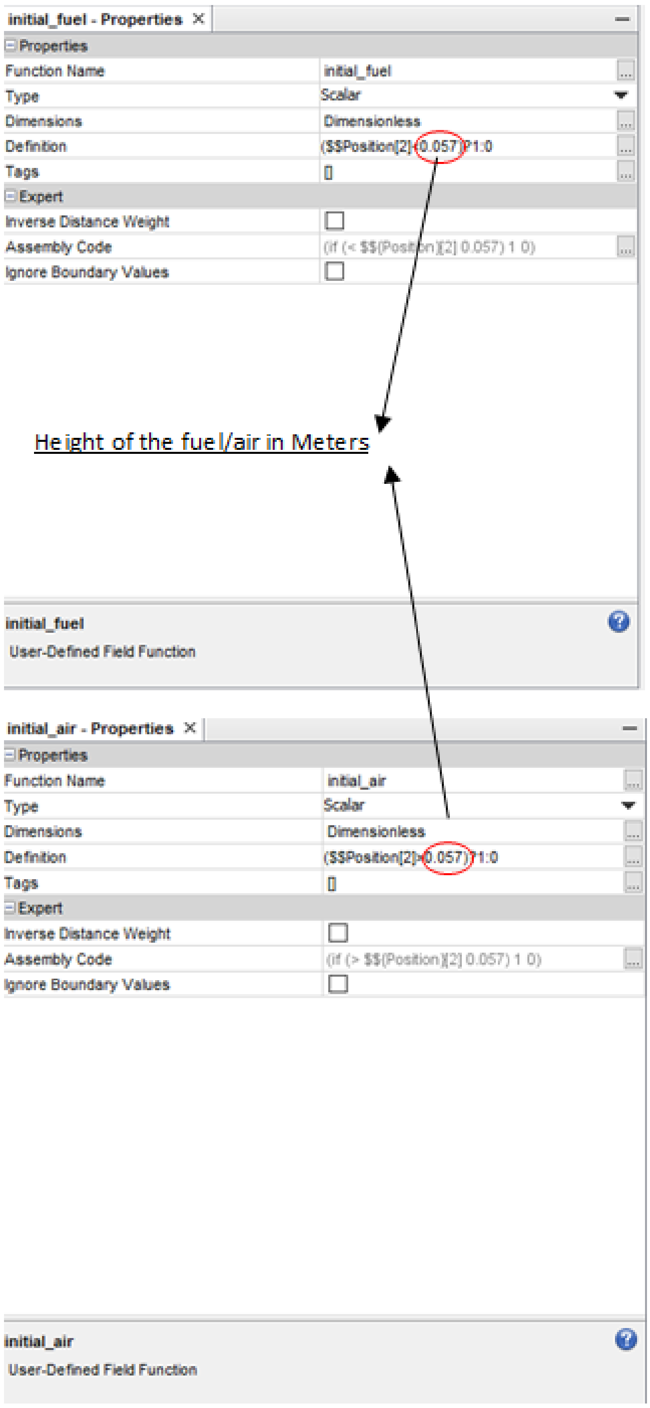

Fig. 11 Field Function for (a) Initial Fuel Fraction (b) Initial Air Fraction

VIII. RESULTS

A. Simulation Visualisation

The results obtained were visualized by using a threshold value for the "volume fraction of fuel" ranging from 0.5 to 1. This provides an accurate display of how the fluid sloshes in the tank. Fig 11-12 below shows the sloshing in the fuel tank with volume fraction of fuel being measured on the outlet of the tank surface.

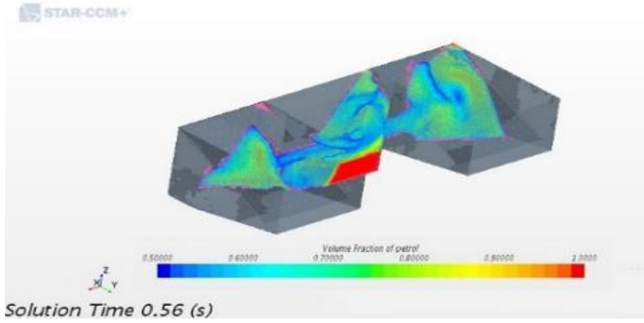

Fig. 12 Threshold Visualisation Of the "U-Shaped" Fuel Tank

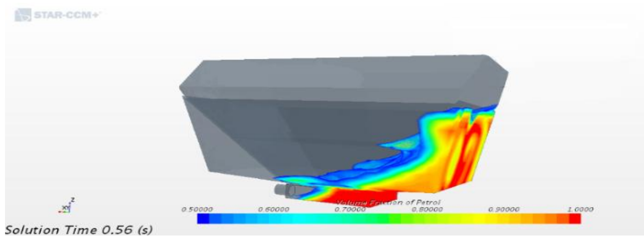

Fig. 13 Threshold Visualisation Of "Single" Fuel Tank

Initially the fuel tanks were iterated without the presence of the baffle to check for their inherent anti-sloshing behaviour. The best iteration was then chosen to be iterated with baffles to further reduce the sloshing.

The visualization of the threshold proves to provide good information about placement of the baffles to restrict the flow.

The screenshots of the fuel sloshing were used to place baffles at the places where the flow could be controlled. These mainly included: -

a. Bottom Tank
b. Minor Tank Connection
c. Major Tank Reservoir

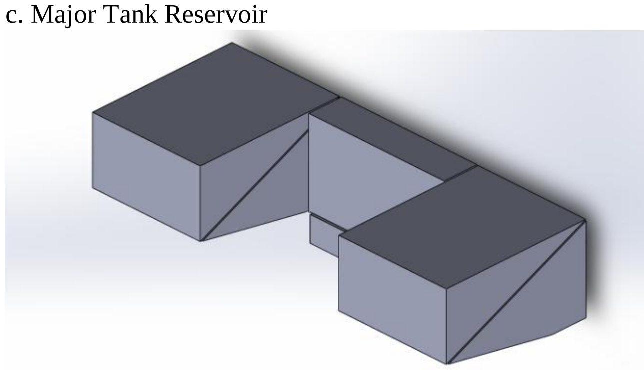

Fig 14 U-Shaped specifying regions of fuel tank

Fig 15 Comparison of Sloshing in Baffles included tanks
Different baffles where iterated at different locations.

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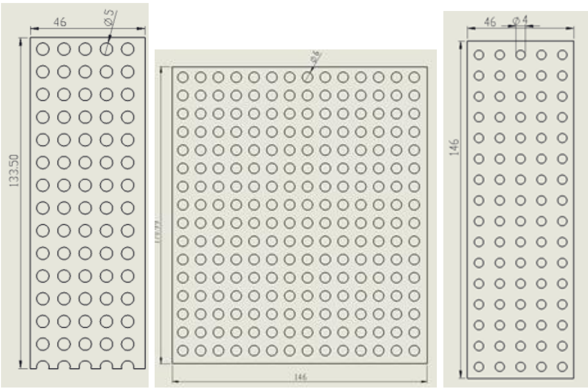
It was found that the baffles performed best when the holes where circular and of the diameter 4mm to 6mm. The larger hole baffles (diameter of 6mm)- "Slant Baffles"-allow more seamless flow of fuel and where hence placed in the major tank reservoir for sloshing prevention inside the major tank due to braking and acceleration. The Minor Tank Connection where installed with the moderate baffles (5mm diameter)- "Parallel Baffles". This provided further restriction to the flow of fuel and didn't allow transfer of fuel from minor major occur easily. This ensures that the amount of fuel that was between the two major reservoirs remained confined. Lastly, the Bottom tank was installed with the smallest hole baffles- "Bottom Baffle". This was done to ensure that maximum amount of flow restriction occurs. This ensures that the fuel that was once full in the bottom tank doesn't leave the volume as quickly.

The baffles were of different types as mentioned as follows: -



(a) (b) (c)

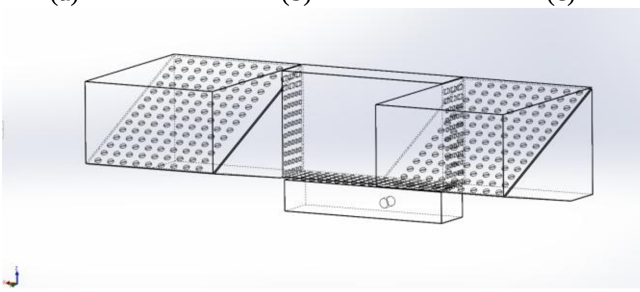


Fig. 16 U-Shape Fuel Tank (a) Parallel Baffles (b) Bottom Baffles (c) Slant Baffles (d) Placement of Baffles

The improvement due to reduction in sloshing was measured by measuring the amount of fuel present in the outlet at every moment of the sloshing. The Fig. 16 and Fig. 17 show the variation of the level of outlet fuel fraction with respect to time for the initial (PRV16) and final iteration (PRV18).

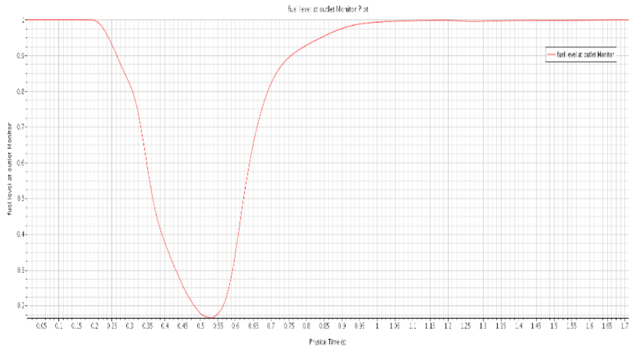


Fig. 17 Volume fraction Variation with time for PRV16

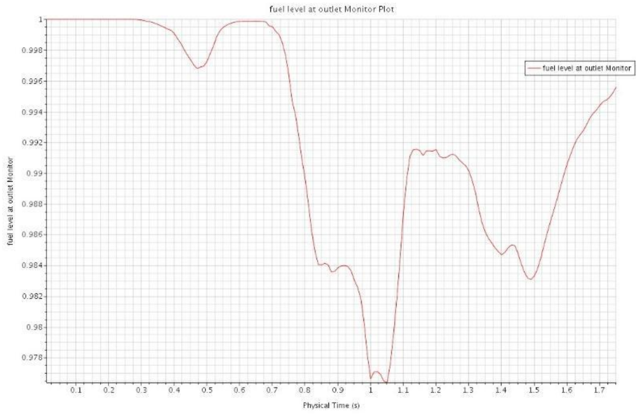
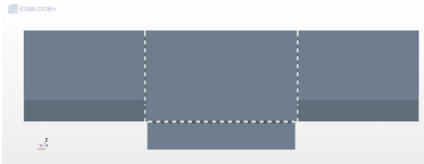
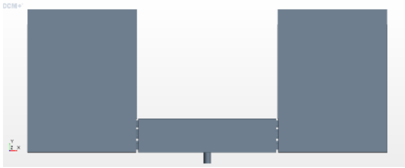


Fig.18 Volume fraction Variation with time for "U-Shaped" PRV18 Fuel Tank

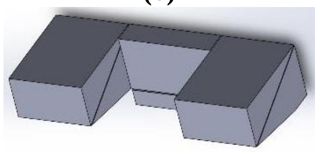
It is observed that the fuel fraction for the modified fuel tank dropped to a volume fraction of 0.978 only compared to the 0.2 of the original fuel tanks. Also, the drop was delayed by a twice the time from 0.55s to 1.05s.



(a)



(b)



(c)

Fig. 19 Final Fuel Tank Geometries (a)Front View (b)Top View (d)Isometric View

B. Testing and Validation

One of the major effects of sloshing is visible loss of power. This loss of power occurs due to the absence of fuel in the cylinder during combustion, which in turn increases the Air-to-Fuel ratio (AFR). This absence of fuel occurs due to the absence of fuel at the fuel outlet of the tank. This absence of fuel is what is referred to as sloshing. The fuel inside a fuel tank gets displaced continuously due to the various forces acting on the vehicle in the course of its motion. The displacement of the fuel in the lateral direction, away from the outlet point, leads to fuel starvation. The fuel tank was designed to ensure sufficient fuel quantity at lateral forces of 1.1G. Data Acquisition and logging system in the FSAE car was used to identify the points of power loss, using AFR spikes in correspondence to the increase in lateral acceleration. The data was also used to validate the design of the tank.

The FSAE car in context used a wide band Bosch LSU 4.2 lambda sensor coupled with a Performance Electronics signal conditioner, for noise filtration, to measure the AFR value. A 3-axis accelerometer (ADXL 335) was used to measure the forces acting on the vehicle in real time. A Little fuse Hall Effect Sensor was used to measure the vehicle speed. The sensor data was logged in a Race Capture Pro MK2 data logger. The data analysis was performed in GEMS Data Analysis software. The data is then imported into the GEMS Data Analysis software, wherein the data of the AFR, Lateral Acceleration and Vehicle Speed are plotted against time to inspect and find out points of power loss. The data given below (Fig. 16) shows the spikes in AFR corresponding with the increase in lateral acceleration on the skidpan. These are the points of sloshing and subsequent power loss, which was further verified with the driver feedback.

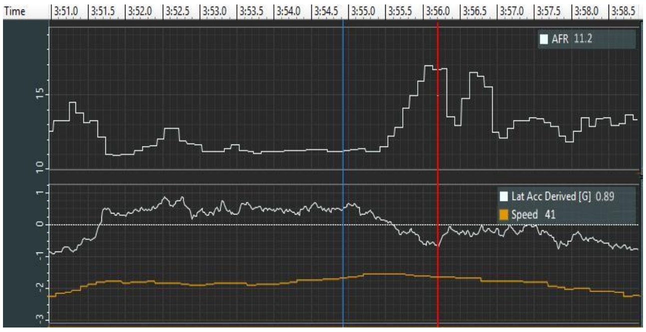


Fig. 20 AFR and Lateral Acceleration Data For "Single Piece" fuel (PRV16)

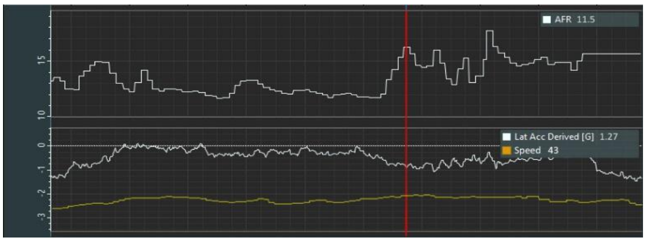


Fig. 21 AFR and Lateral Acceleration Data For "U-Shaped" fuel (PRV18)

The following graphs correspond to the data recorded in the skidpad run of the car. Fig 17 refers to the data logged with the car running on the older fuel tank. Fig 18 refers to the data logged with the car running with the newly designed tank.

It can be observed from the figure 16, there is a peak in the AFR value at a lateral acceleration of 0.8G's, thus indicating the onset of sloshing at lower lateral acceleration.

However, the second fig is from the same test carried out with the new tank, under the same conditions and test track, with the same amount of initial fuel. It can be observed that sloshing begins at a lateral acceleration of 1.2G's. This design is thus validated as the peak lateral acceleration reached by the vehicle is 1.3G's as indicated in the data used for the design and analysis of the fuel tank.

The same slalom test was carried out after the new fuel tank was installed, with the ambient conditions (ambient temperature, pressure, humidity) almost similar to the initial test. There was significant improvement, due to reduced sloshing occurrence. This is shown in the data given below (Fig 18), where it was observed that the AFR value corresponds to the expected AFR value. The spikes in AFR value were under high lateral accelerations of 0.9 G thus validating the design of the new fuel tank.

IX. CONCLUSION

The final result that was obtained was a fuel tank that had achieved a superior stability of the fluid it carried inside it. This was achieved by incorporating baffles which the smaller the holes of the baffles leading to higher restriction of flow. Holes of the range 4-6mm allowed the fluid to flow as well as provide enough restriction to sloshing.

From the above study, it is observed that analysis of fuel tank and the type geometry used to make the tank have a positive effect on the vehicle's performance. Symmetricity of the tank provided the best solution to tackle sloshing.

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