MSc. Automotive Engineering

Car Body Design and Aerodynamics

Exercise 1 - Wheel Arches Definition

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Abstract

An attempt to define the wheel arches of any vehicle is presented in this work. The aim is to define the shape of the wheel arches and their corresponding volume to analyze the packaging of the vehicle. In the process, a MATLAB® GUI application has been developed to facilitate the process for the user and to generalize the developed model for any vehicle given its corresponding required data (check Appendix). The data used to test the model correspond to a BMW X5 xDrive40i. Eventually, the 3D CAD model was developed.

Contents

Motivation

Little to null importance is usually given for the size of the wheel arches by the end user of a vehicle. However, the size plays a huge role in packaging the vehicle, something that an engineer must always consider. The purpose behind this project is to test the proposal for designing the wheel arches suggested by the authors of reference[1] to evaluate the impact on the layout while packaging.

Objectives

To reason with the motivation behind this project, it's necessary to accomplish the following objectives:

1. Choose a vehicle and find the relevant data.
2. First-attempt definition of the front wheel arches from top view considering maximum steering angles of the front wheels.
3. First-attempt definition of the wheel arches from side view considering the maximum vertical displacement allowed by the suspension.
4. Final attempt definition of the wheel arches using a 3D CAD Software.

Methodology

1. Vehicle Choice

The vehicle chosen to fulfill the aim of this project is the BMW x5 xDrive40i shown in the Figure 1:

Figure 1: BMW X5 xDrive40i

The relevant data are represented in Table 1:

Wheelbase [mm]	2975
Track [mm]	1666
Tire Diameter [mm]	737
Tire Width [mm]	255
Steer Radius [mm]	6300
Vehicle Mass [kg]	2060
CG [mm]	1801
FR [mm]	1636
RR [mm]	2529
LUGGAGE [mm]	3511
N. Front Row [-]	2
N. Rear Row [-]	3
GC Front [mm]	180
GC Rear [mm]	200
Drive	AWD

Table 1: Vehicle Data

Some of the dimension represented in Table 1 are shown in Figure 2:

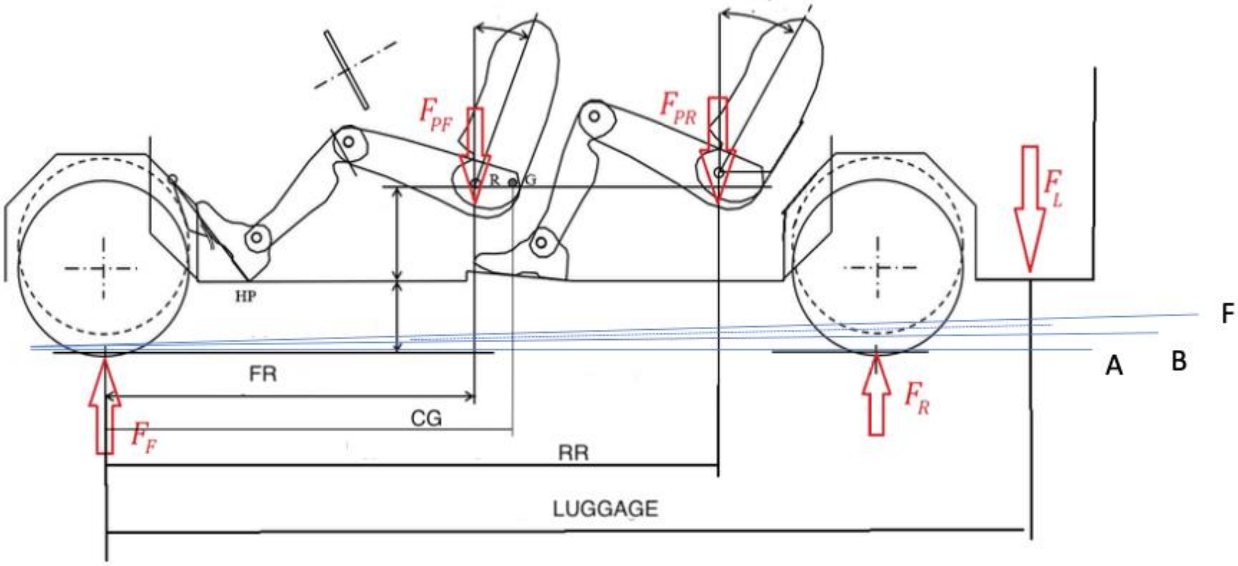

Figure 2: Dimensions

- N. Front Row: Maximum number of passengers, including driver, in the front row.
- N. Rear Row: Maximum number of passengers in the rear row.
- GC Front: Ground clearance measured from front of the vehicle in empty load.
- GC Rear: Ground clearance measured from rear of the vehicle in empty load.

2. Top View

The factors impacting the design of the wheel arches from top view are:

- The diameter of the tires.
- The width of the tires.
- The maximum steering angles in both directions.
- The location of the axis of steering with respect to the midplane of the tire.
- The thickness of the mud layer stuck on the tires.
- The driving axle(s) of the car to determine which wheels may have chains.
- The volume occupied by the suspension system.

2.1 Assumptions and Limitations

2.1.1 Ackermann Steering Kinematics

The maximum steering angles are obtained considering 100% Ackermann steering kinematics while taking a curve with a radius equal to the minimum steering radius of the vehicle. Recalling that the Ackermann steering kinematics is a valid model to analyze steering at low speeds, the assumption is thus adequate since the vehicle maneuver through a curve with a radius equal to its minimum steering radius is normally done at low speeds. As a result, this assumption doesn't impose any critical limitations on the model to be developed.

As shown in Figure 3, the Ackermann steering system considers that in a turning maneuver, all the lines drawn from the center of the tires and perpendicular to their plane intersect at one point. Therefore:

$$R_1 = \sqrt{R^2 - WB^2} - \frac{T}{2} \qquad \dots (1)$$

$$\delta_{11} = \tan^{-1}\left(\frac{WB}{R_1 - \frac{T}{2}}\right) \qquad \dots (2)$$

$$\delta_{12} = \tan^{-1}\left(\frac{WB}{R_1 + \frac{T}{2}}\right) \qquad \dots (3)$$

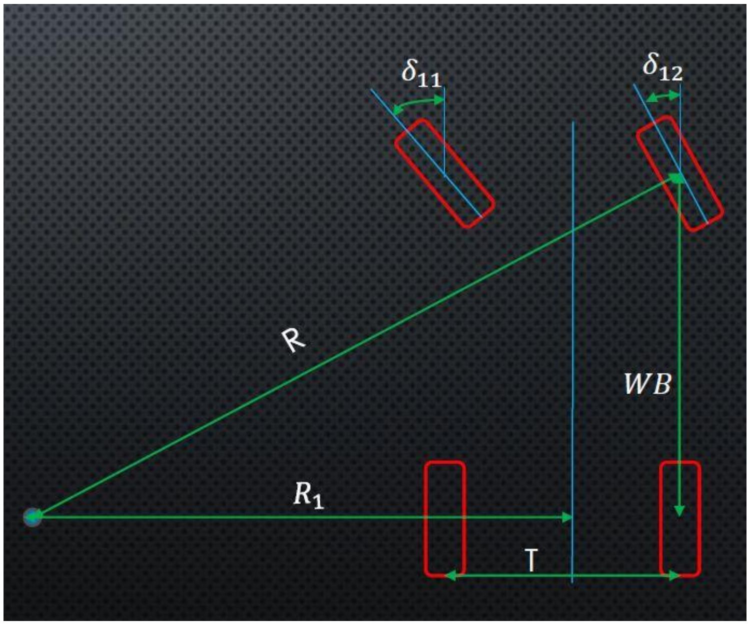

Figure 3: Ackermann Steering Kinematics

2.1.2 Steering Axis Location

The steering axis location is assumed to be at a distance from the midplane of the tire equal to one quarter of the tire width. This is just to simplify the model developed. If the offset is actually lower than the assumed one, then the model presented overestimates the size of the wheel arches and vice versa.

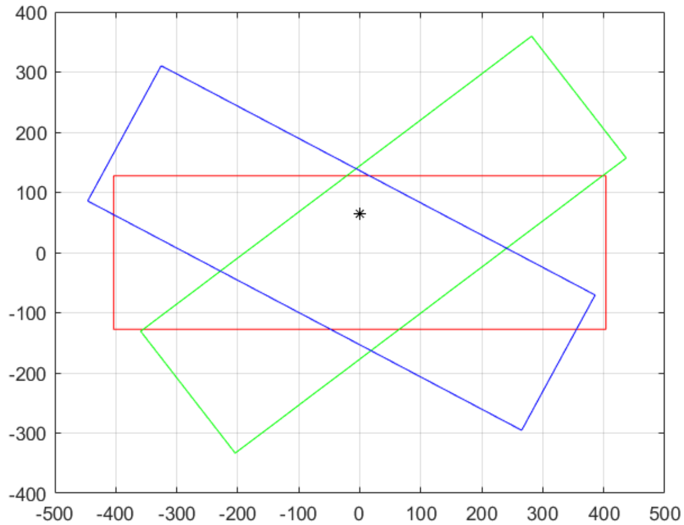

Figure 4: Front Left Tire Steering Positions

2.1.3 Volume Occupied by Suspension System

This model neglects the volume occupied by the suspensions. This is a huge simplification that impacts the results of the model as the volume occupied by the suspension system isn't negligible. However, we can consider that the volume obtained for the engine compartment after designing the 3D model includes the volume required by the suspension system. Moreover, in a later section, the stiffness of the springs is calculated; therefore, using basic Machine Design concepts and knowing the material of the springs, we can estimate the external diameter of the springs allowing us to estimate the volume required in case of a MacPherson Strut or a Trailing Arm suspension. In case of a Double Wishbone or a Multi-link suspension, a more rigorous investigation is required to obtain the required volume.

Note that this assumption is considered valid if the considered vehicle has a Leaf Spring suspension since the occupied volume by this type of suspension doesn't interfere with the volume of the wheel arches.

For the considered vehicle in this exercise, the front suspension is a Double Wishbone while the rear suspension is a Five-link suspension.

2.1.4 Miscellaneous

Other assumptions that have been considered do not limit the model but only affect the obtained results. These include the thickness of the mud layer (20 [mm]) and that of the chains (15 [mm]).

The considered vehicle is an AWD; therefore, the layer of chains is added to the front and the rear axle.

2.2 First-Attempt Definition

The first-attempt definition takes the assumptions and their corresponding results as input and, based on a graphical method, outputs a 2D drawing representing the wheel arches. For instance, using the data in Table 1 and substituting them in equations (1), (2), and (3), we obtain:

$$\boldsymbol{\delta_{11}} = \mathbf{37.42°}$$
$$\boldsymbol{\delta_{12}} = \mathbf{28.18°}$$

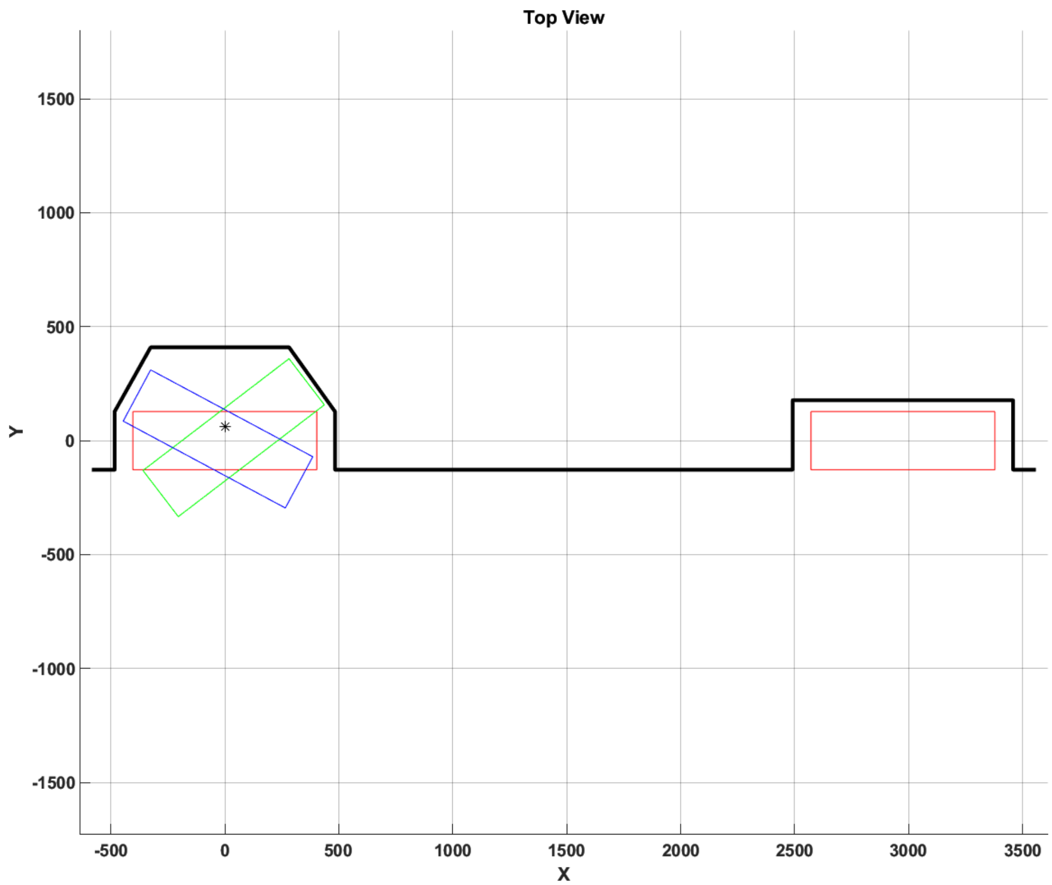

Figure 5: Top View - First Attempt Definition

As shown in Figure 5, the volume required for the suspension system isn't considered. Moreover, the model tries to obtain the minimum volume required.

Note that in the green position of the wheel, one might think that the tire gets in contact with the arch. However, due to the offset of the steering axis from the tire midplane, the tire also moves a bit forward as it is returning to its straight position.

3. Side View

The factors impacting the design of the wheel arches from side view are:

- The diameter of the tires.
- The thickness of the mud layer stuck on the tires.
- The driving axle(s) of the car to determine which wheels may have chains.
- The maximum stroke of the suspension system in compression.

The first factor is given from the data while the second and third factors have already been discussed in the previous section. Therefore, our attention shifts towards the maximum stroke of the suspension system.

3.1 Suspension Kinematics

The maximum vertical displacement allowed by the suspension suggested by reference[1] is in the range 70-90 [mm]. Therefore, a maximum vertical displacement in compression equal to 80 [mm] and a wheel travel equal to 170 [mm] has been considered in this work.

However, imposing a maximum vertical displacement without studying the behavior of the suspension is unrealistic; therefore, the stiffness of the springs must be calculated. For this purpose, the quarter car model was adopted in full load conditions. In other words, the total mass of the vehicle is the sum of its mass when empty, the mass of the 5 occupants, and the mass of their luggage. The mass of an occupant is considered according to the EU standard, the value of which is 70 [kg] and the luggage of each occupant is assumed a value of 10 [kg].

3.1.1 Quarter Car Model

This model considers the suspension system on one tire of the whole vehicle. Obviously, the mass must be calculated correctly. This means that it's necessary to calculate the mass distribution of the vehicle in full load conditions and, from that, obtain the equivalent mass acting on the front axle and the one acting on the rear axle.

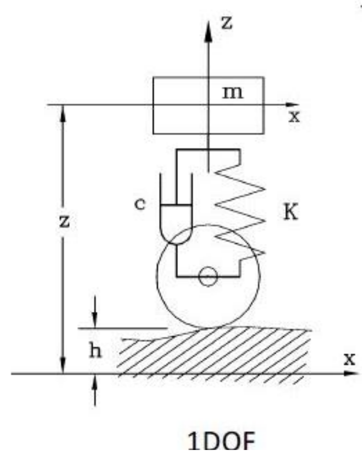

Figure 6: Quarter Car Model

Using the scheme of the loads acting on the vehicle in Figure 2, we can calculate the forces acting on the front and rear axles and then using the following equations:

$$\%m_f = \frac{F_f}{F_f + F_r} \ldots (4.1) \qquad ; \qquad \%m_r = \frac{F_r}{F_f + F_r} \ldots (4.2)$$

where $\mathbf{F_f}$ is the force acting on the front axle and $\mathbf{F_r}$ the one acting on the rear axle, we can calculate the equivalent masses on the front and rear axles.

To proceed with the evaluation of the stiffnesses, we rely on the natural frequency of the suspension. This is simply given by the following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \ldots (5)$$

The value to be chosen for the natural frequency follows the ISO 2631 standard shown in Figure 7:

The standard represents the acceleration of the vibration as a function of the frequency for certain comfort levels. In the range 1-1.5 [Hz], we have an acceptable level of comfort. Outside this range, the perceived comfort level by the passengers decreases.

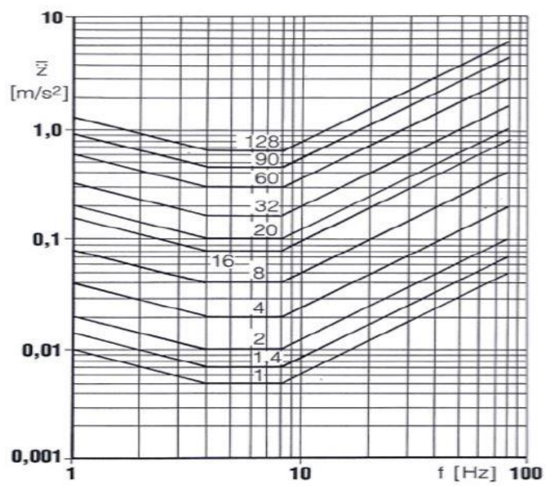

Figure 7: ISO 2631 - Vibration Comfort

In this work, a starting value of the natural frequency equal to 1.5 [Hz] has been chosen. Due to the non-linear behavior of the suspension beyond the bump stops, a negative value of the force has been obtained at maximum expansion of the rear suspension. This can be evidenced in Figure 8. As a result, it was required to decrease the stiffness of the spring. To decrease the stiffness, it was required to decrease the natural frequency of the spring ensuring an optimal value within the proposed range. Eventually, the chosen natural frequency was 1.28 [Hz] resulting in a characteristic curve of the suspension represented in Figure 9.

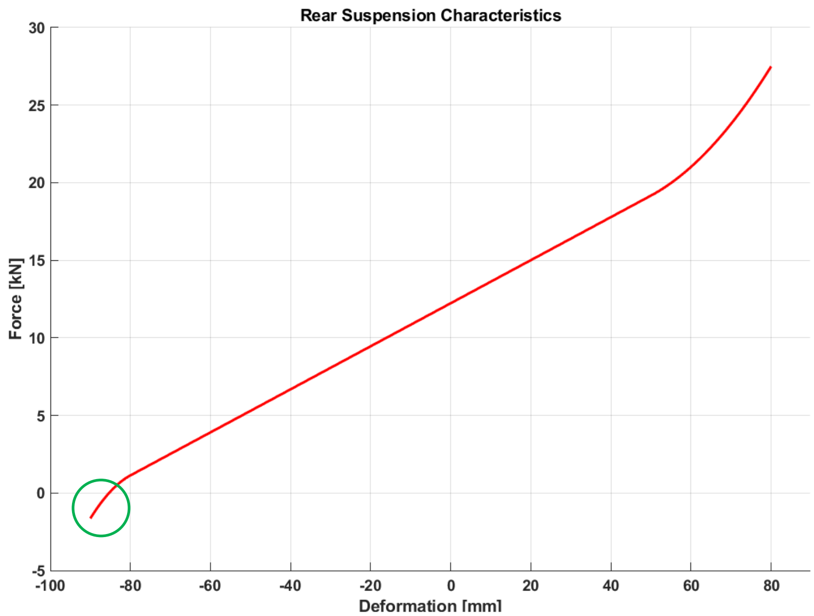

Figure 8: Rear Suspension Characteristics - f = 1.5 [Hz]

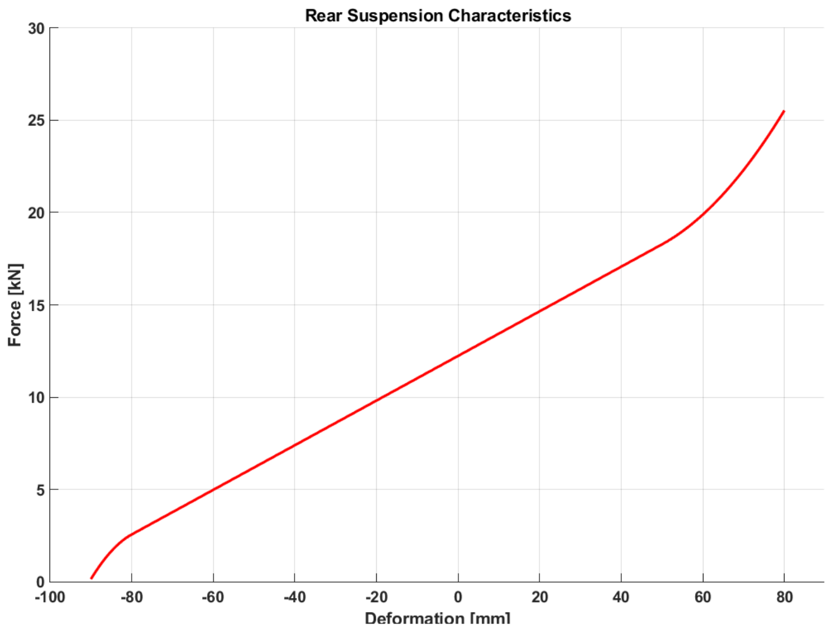

Figure 9: Rear Suspension Characteristics - f = 1.28 [Hz]

The corresponding values of the stiffnesses of the front and rear axles are:

$$\mathbf{k_f = 69.516\ [N/mm] \quad ; \quad k_r = 120.832\ [N/mm]}$$

3.1.2 *Load Cases*

To test the behavior of the suspensions when mounted on the vehicle, it's necessary to check the deflection in the front and the rear suspensions as a function of the number of passengers in the vehicle. This procedure allows us to evaluate the ground clearance and how much of the total vertical displacement is left at each load case. Moreover, with this procedure, we can calculate the extra force exerted by the springs at each load case.

The results of the analysis are summarized in Table 2:

Load Case	ΔF_f *[N]*	ΔF_r *[N]*	Δz_f *[mm]*	Δz_r *[mm]*	GC_f *[mm]*	GC_r *[mm]*
A	0	0	0	0	180	200
B	291	493	4.15	4	175.85	196
C	583	987	8.3	8.1	171.7	191.9
D	668	4686	9.5	13.8	170.5	186.2
E	753	2386	10.73	19.5	169.27	180.8
F	839	3085	12	25.3	168	174.7

Table 2: Load Cases – Results

A graphical representation of the deflections is shown in Figure 10:

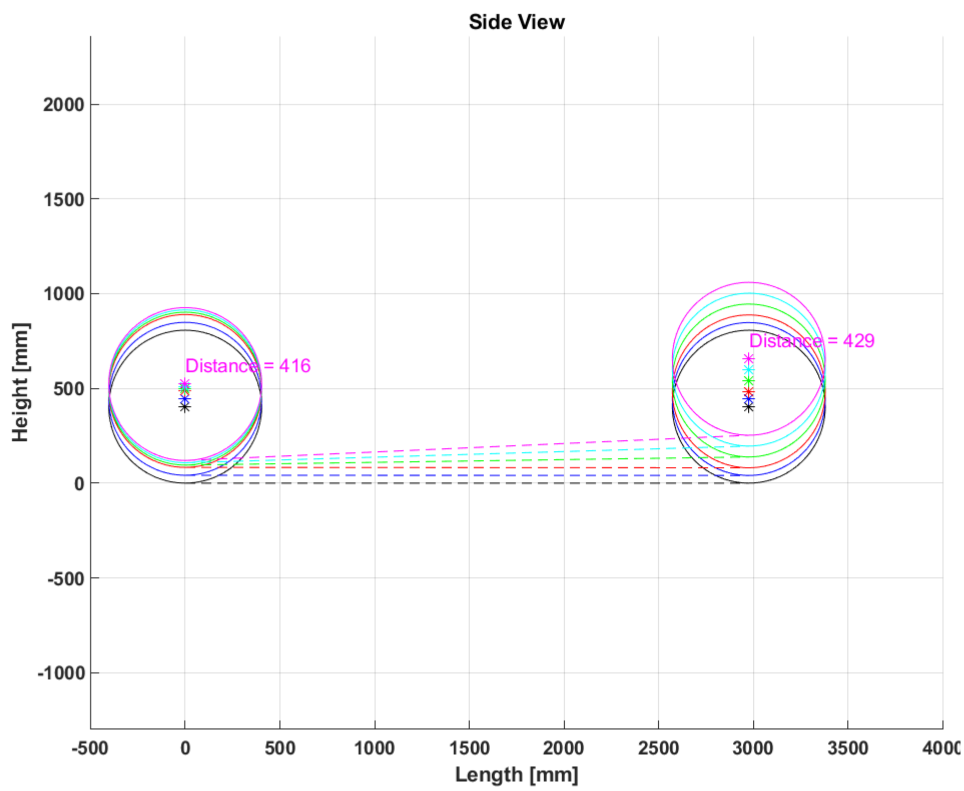

Figure 10: Δz [mm]

Note that everything in the previous figure is to scale except the deflection, it's multiplied by a scale 10:1 to enlarge the effect so it's clearer. In fact, since the diameter of the tire is 737 [mm], the mud layer thickness is 20 [mm], and the chains' thickness is 15 [mm], then with a maximum deflection of 25.3 [mm] on the rear axle, we must see the pink center at 429 [mm] from the ground. However, with a scale of 10:1 only for deflection, the pink center appears to be at 657 [mm] from the ground. That's why a label displaying the real distance from ground has been added.

3.2 First Attempt Definition

As mentioned in the previous section, a first attempt definition represents a proposed structure of the wheel arches in 2D. In this case, it is done by referring to the maximum vertical displacement value assumed for the suspension in the compression stroke after ensuring that the behavior of the suspension is acceptable. The first attempt definition of the wheel arches in the side view is shown in Figure 11:

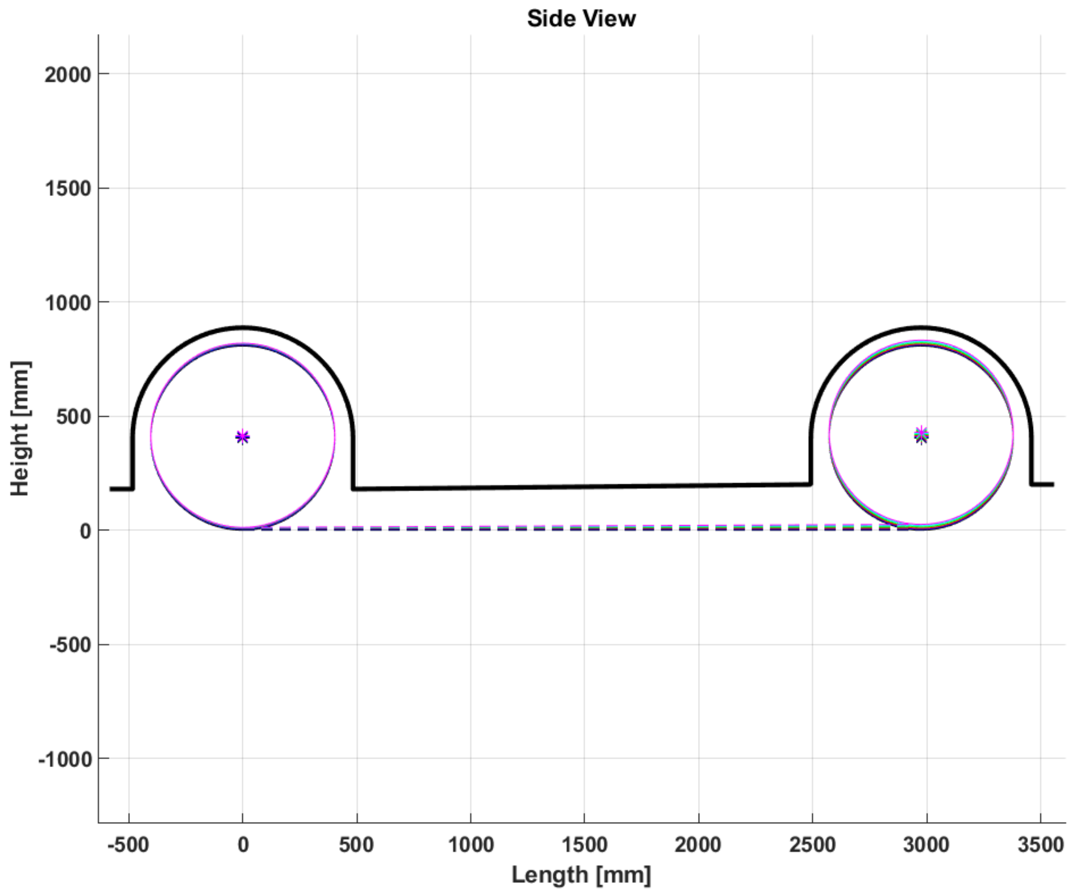

Figure 11: Side View - First Attempt Definition

Note that, in this figure, the deflection at each load case is shown to scale. Therefore, we can visualize how helpful it is to represent the deflections on a bigger scale. Moreover, we can also visualize how much displacement is left for the deflection of the springs beyond the deflection caused by the passengers when everything is to scale.

4. 3-D CAD Design

By combining the information obtained from the first attempt definition of the side view and the top view, it's possible to design, using a 3D CAD software (SolidWorks® in this case), the wheel arches to visualize their volume and to calculate the remaining volume for the engine. Moreover, it's also possible to locate the firewall which is essential for locating the pedals. Finally, after locating the pedals, we can use anthropometric data to package the vehicle. The design is shown in Figure 12, Figure 13, Figure 14.

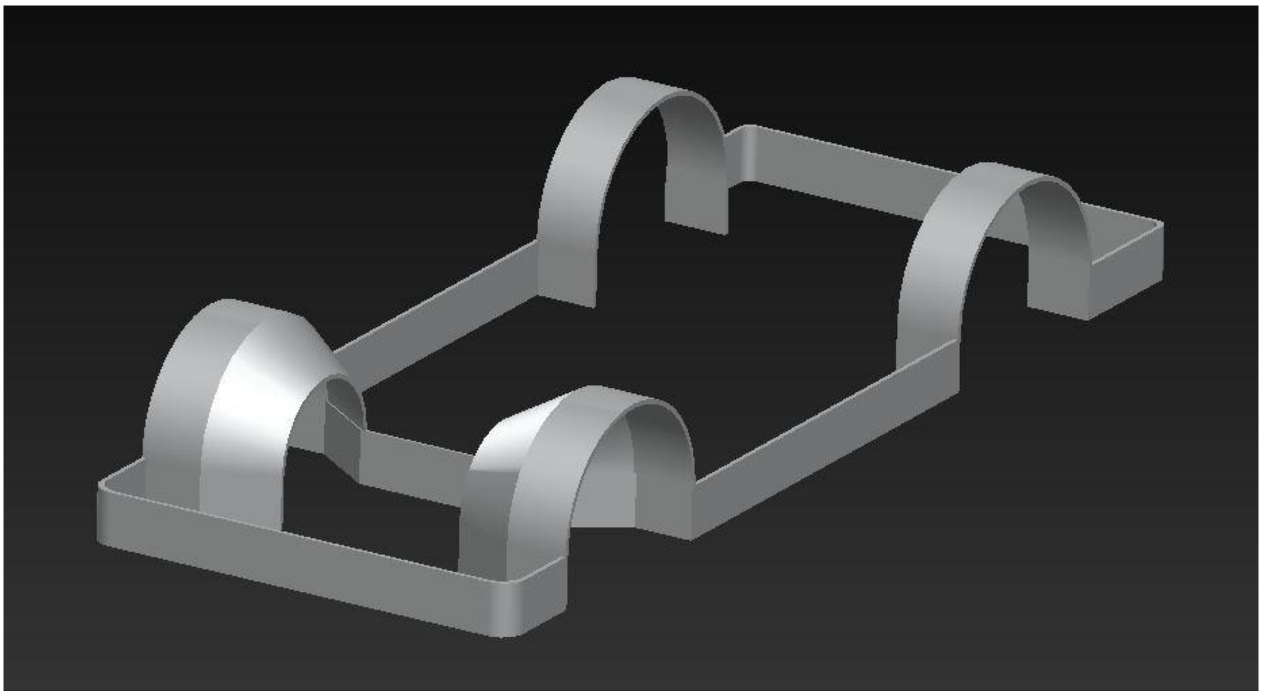

Figure 12: 3D CAD - Iso View

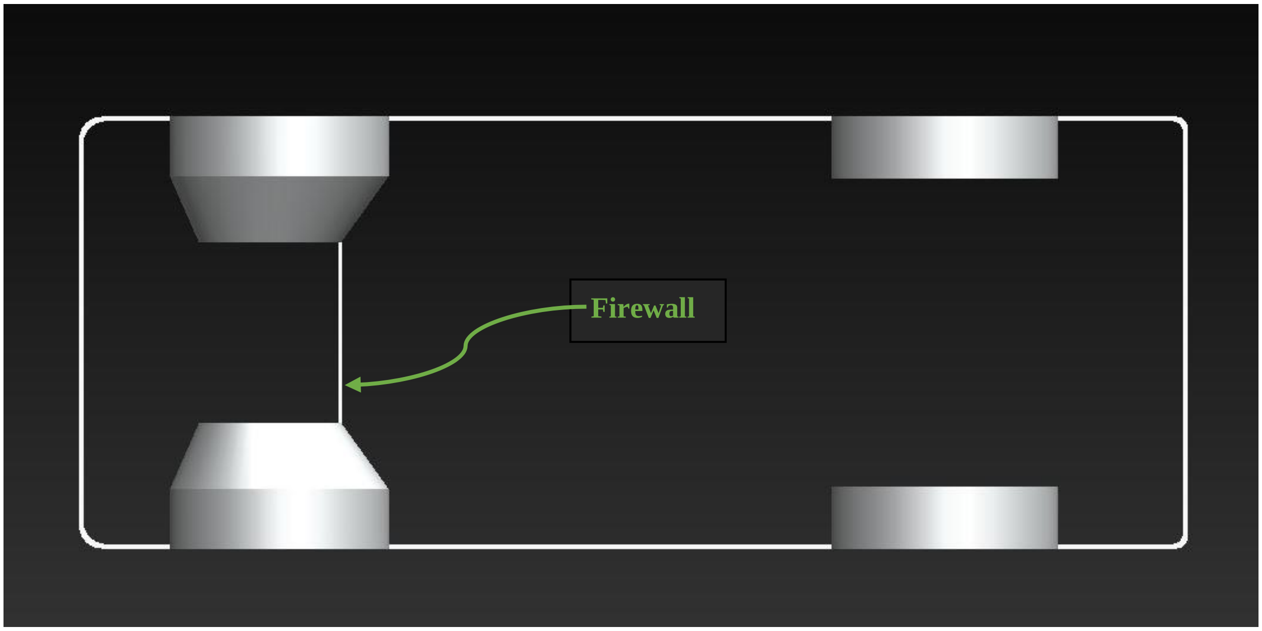

Figure 13: 3D CAD - Top View

Figure 14: 3D CAD - Side View

The thickness of the layer used to represent the wheel arches is equal to 20 [mm] which is in accordance with the suggested range by reference[1].

Results Analysis

First, the values of the maximum steering angles show that, according to Ackermann steering, the inner wheel steers more. However, both values must be considered in design to define the smallest wheel arches possible, saving the rest of the volume for the engine compartment and for packaging.

Second, although the wheel travel and maximum vertical displacement in compression stroke are defined by the designer, the study of the suspension kinematics and the behavior of the suspension when mounted on the vehicle are critical for simulating real-life scenarios. For instance, it can be clearly noticed that the rear suspension deflects more than the front suspension as a function of the load case. Moreover, the difference between the ground clearance in front and rear when the vehicle is empty is 20 [mm]; however, this difference decreases to 6.7 [mm] at full load. Recalling that ground clearance is an important factor affecting for the aerodynamic behavior of the vehicle, this signifies that this behavior changes with every load case.

Eventually, we can comment on the volume left inside the engine compartment of the vehicle. The studied vehicle features an engine mounted in longitudinal direction. By approximating the area in front of the firewall and assuming a height of 600 [mm], the volume obtained is at least 567 [L].

Conclusion

In this work, an attempt to define the wheel arches of a BMW X5 xDrive40i is presented. The aim is to study the factors impacting their volume to analyze the packaging of the vehicle. It has been shown that the maximum steering angles of the wheels and the maximum vertical displacement in compression stroke of the suspension are the main factors impacting the volume; yet, the mud layer thickness and the chain layer thickness mustn't be neglected during the analysis to avoid any contact with the wheel arches. Moreover, it has been shown that the study of the suspension kinematics and behavior is of utmost importance to simulate real-life scenarios and ensure that the chosen values aren't just arbitrary.

Finally, a MATLAB® GUI Application has been developed to ease the process and generalize it for any vehicle. For more information, kindly refer to the Appendix.

References

1. Morello, Lorenzo, Lorenzo Rosti Rossini, Giuseppe Pia, and Andrea Tonoli. *The Automotive Body Volume II: System Design.*
2. BMW Media Information "Technical Specification - The New BMW X5."

APPENDIX

In this section, a brief explanation of the developed application with MATLAB® is discussed. As shown in this work, all we need is the data of the vehicle and we can find a first attempt definition of the wheel arches in top view and side view.

The user interface is straightforward and is shown in Figure 15:

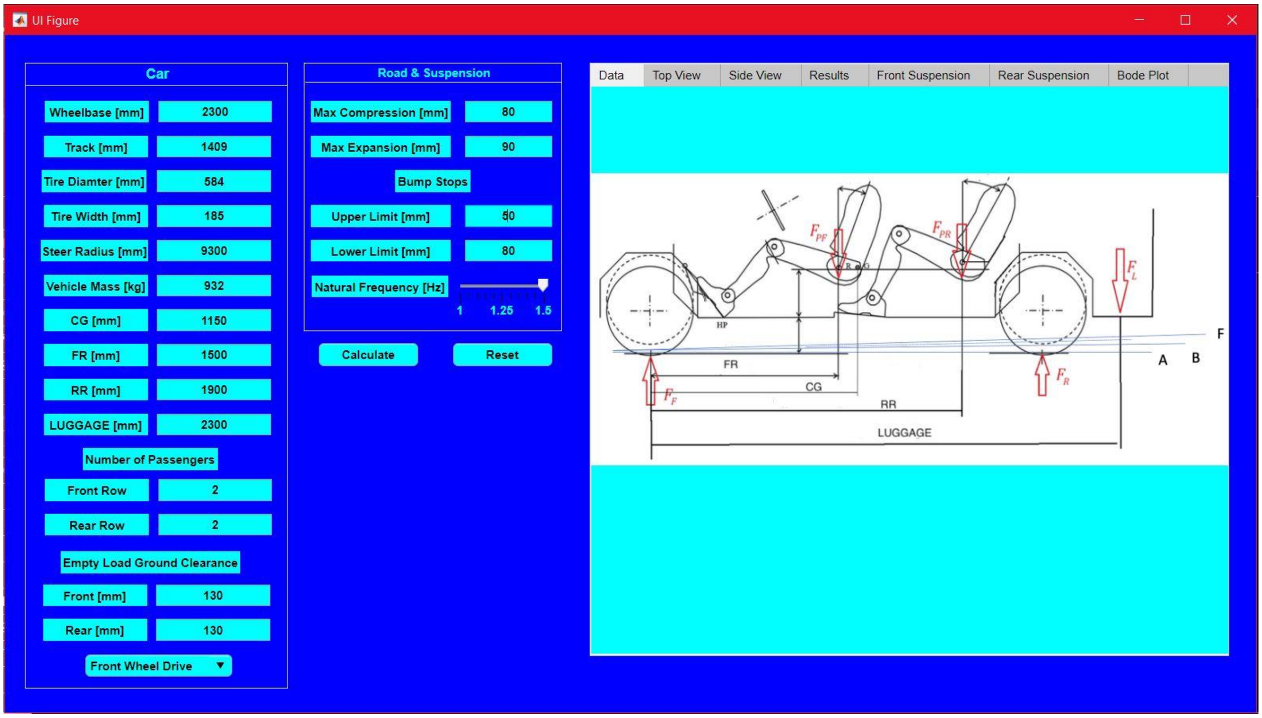

Figure 15: WheelArch App - Main Page

Note that the data shown in the figure belong to a FIAT 500. Also note that the natural frequency of the suspension can only be within the range 1-1.5 [Hz] to ensure the condition imposed by the ISO 2631 standard.

After entering all the relevant data, the user presses on the "Calculate" button. The code checks whether the data is sensible and then proceeds with the calculations. In case of ambiguity, the application shows an error message in the MATLAB® Command Window and seizes the process of calculation. In the positive case, the following figures are plotted and can be accessed by toggling between the tabs of the TabView.

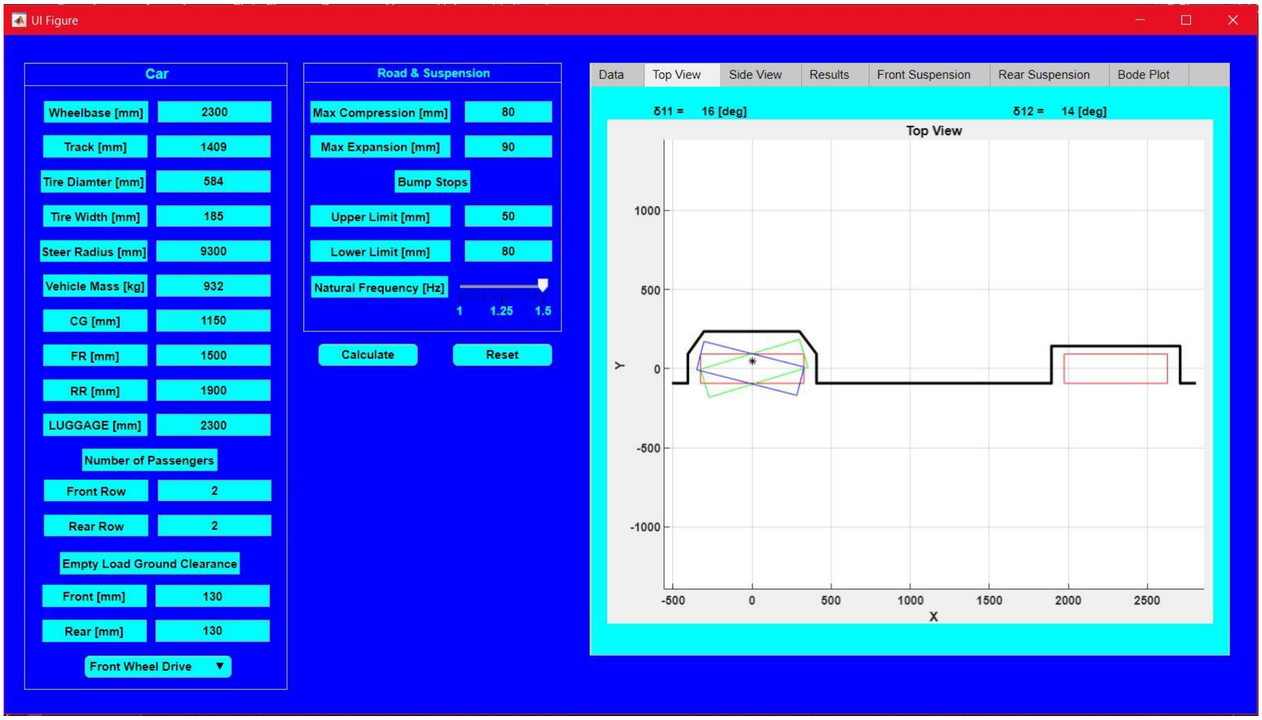

Figure 16: WheelArch App - First Attempt Definition: Top View

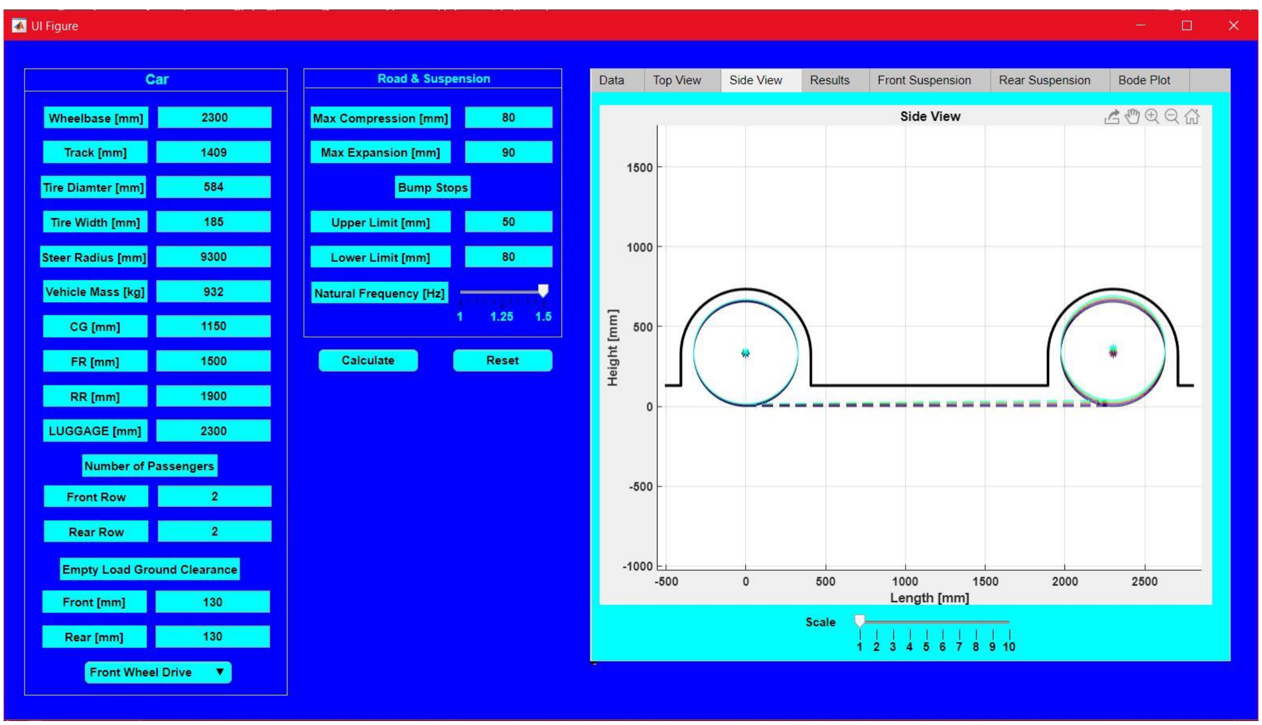

Figure 17: WheelArch App - First Attempt Definition: Side View 1:1

A slider has been added when viewing the side view that represents the scale of the deflection. When set to 1:1, the app also plots the first attempt definition in the side view. However, when the scale is changed, the plot is removed to avoid interference and confusion.

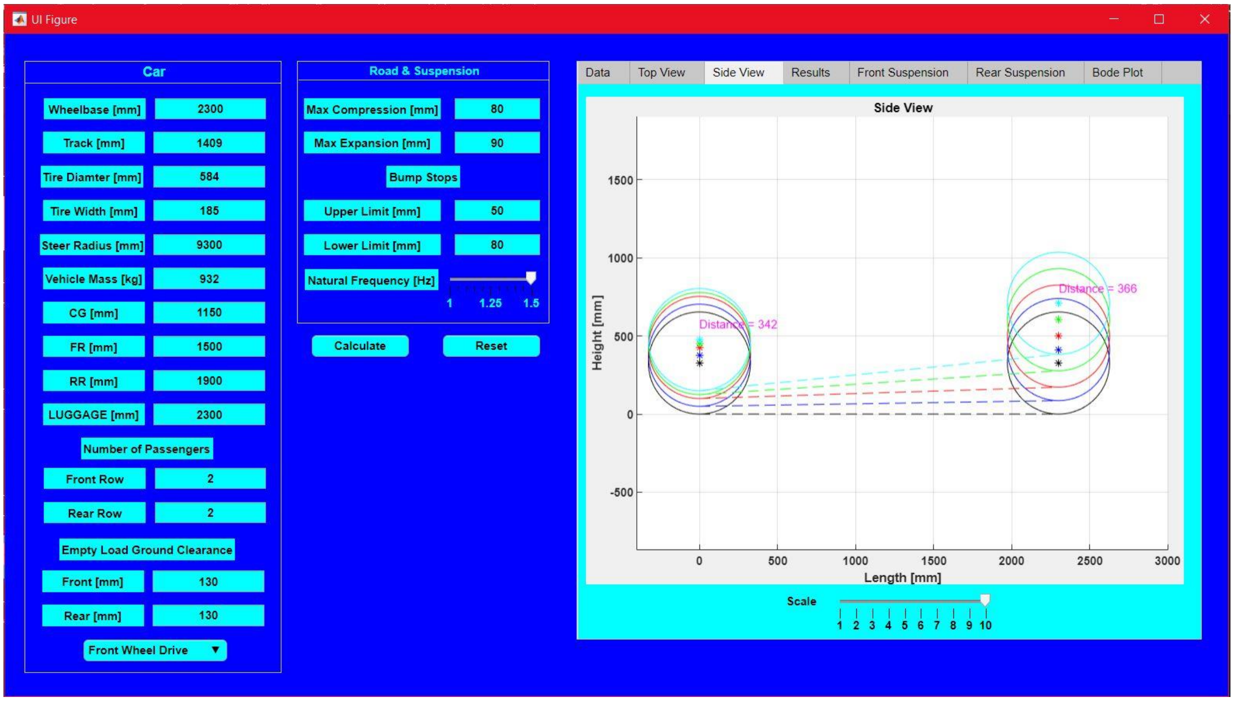

Figure 18: WheelArch App - Side View 10:1

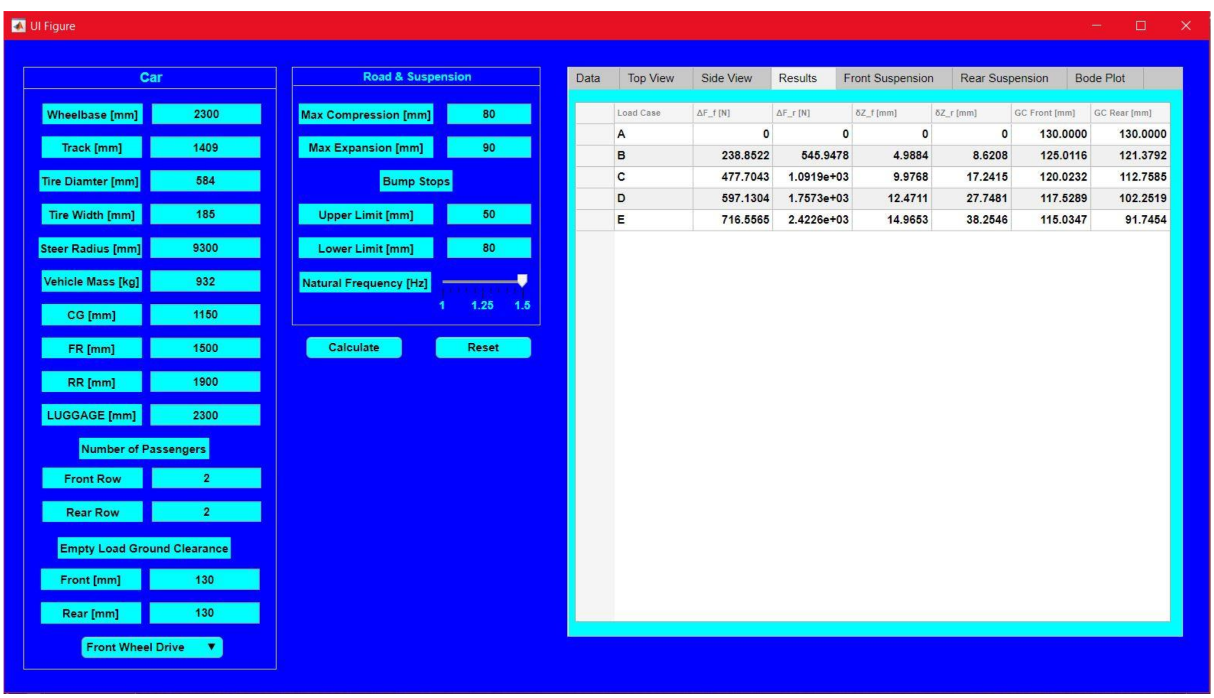

Figure 19: WheelArch App - Numerical Results

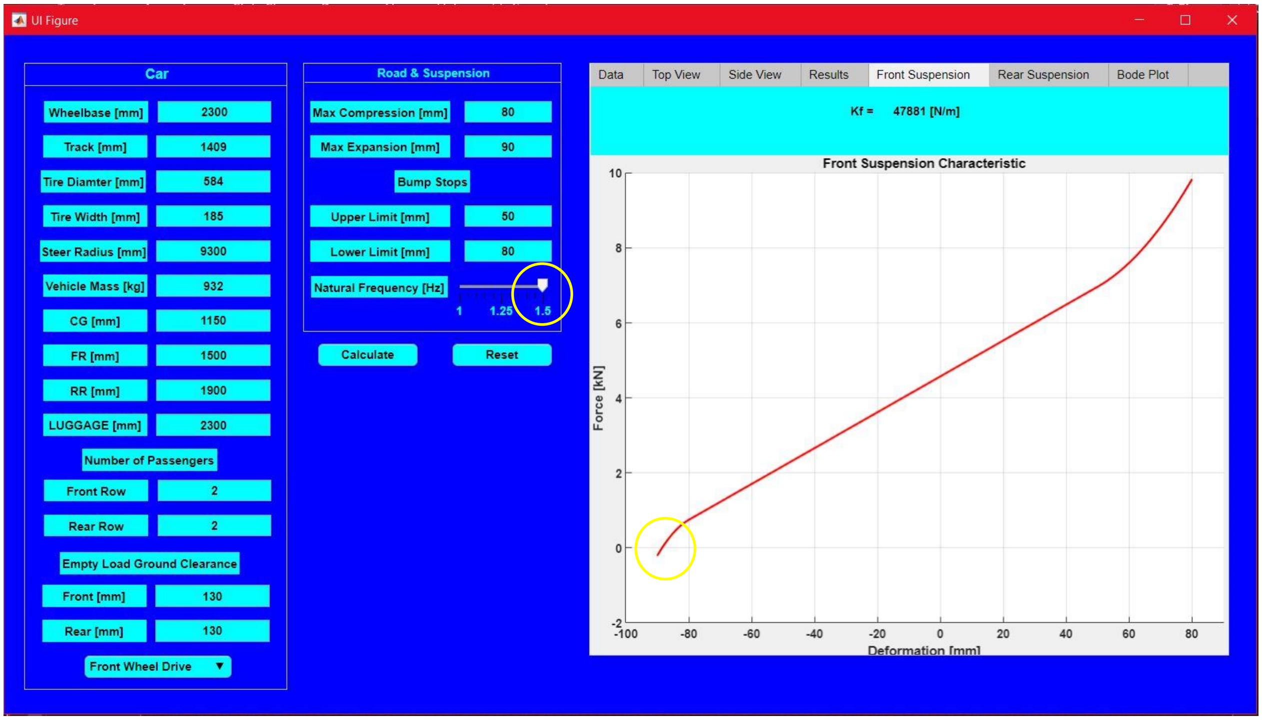

Figure 20: WheelArch App - Front Suspension Characteristic f = 1.5 [Hz]

From the figure above, we can see how it's helpful to have a slider for the frequency to change easily and obtain better results.

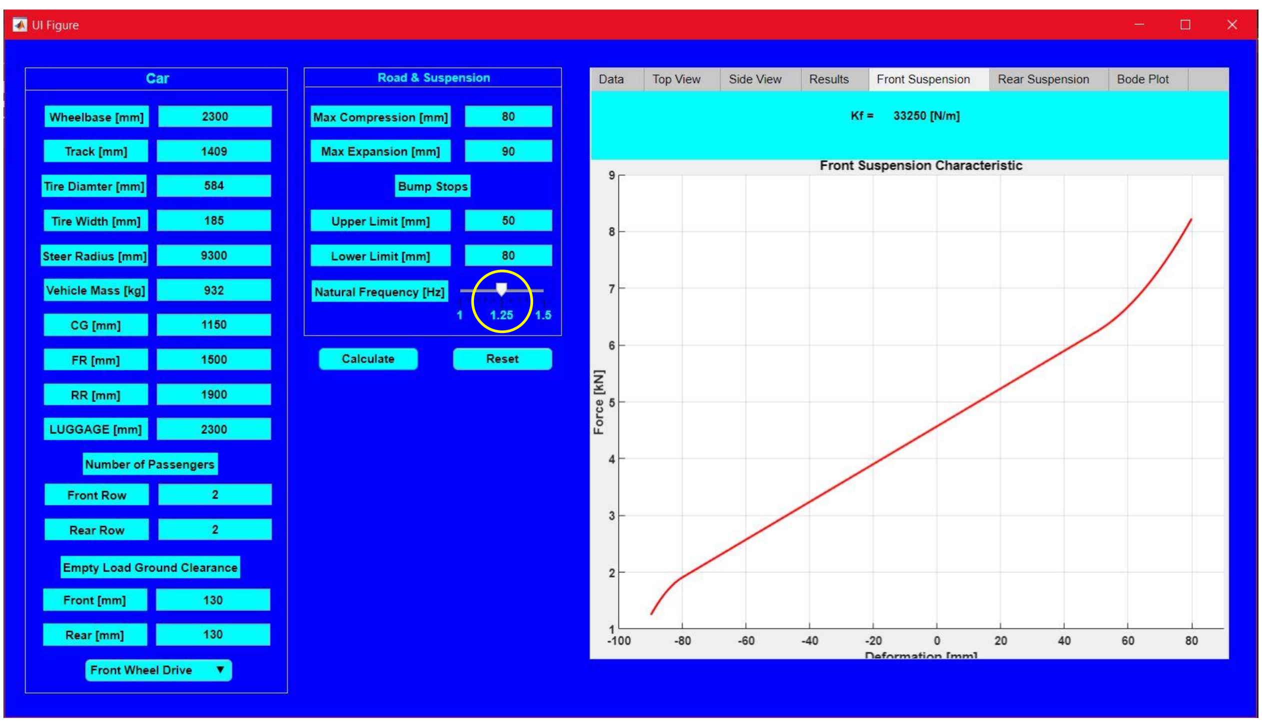

Figure 21: WheelArch App - Front Suspension Characteristic f = 1.25 [Hz]

The current version of the application still needs some verification from an expert in the matter. However, one could really see the benefit from having a user interface that is interactive and easy to manage.

Future versions can include the option to extract the data calculate into an excel spreadsheet. Moreover, it could write the coordinates of the first attempt definition into a file that can be read by a CAD software given a generic template of the wheel arch design and generate the design for the specific vehicle.