Geometry Optimization of Aerodynamic Add-on devices on Road Vehicles

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Abstract

The rising trend in fuel prices has led to growing concern about vehicle fuel economy, and viscous drag is one of the main factors. Improvement in fuel efficiency can be achieved at a relatively low cost by installing aerodynamic devices to streamline vehicles and reduce drag. We report here an efficient numerical technique to optimizing the geometry of such devices. The technique combines shape optimization, geometric modeling, and Finite element analysis (FEA). To assess the validity of our optimization algorithm, we compare our optimization results against known test cases similar to the configurations in hand. We use this method to examine how effective add-on devices are in reducing drag on a simple model of a commercial truck. To further back our simulation results we run experiments on a scaled model truck, with interchangeable add-on devices, inside a wind tunnel.

Introduction

In the history of aerodynamic research around bluff bodies it has always been observed that the shape of the body is one off the main obstacles to improving fuel economy. The air flow produces pressure unbalances between the fore and aft facing surfaces of vehicles. This pressure difference along with vortex shedding and skin friction cause drag. The drag coefficient (C_D) is a dimensionless quantity that is used to quantify the resistance of an object in a fluid. A lower drag coefficient indicates that the object will experience less aerodynamic drag.

$$C_D = \frac{F_D}{\frac{1}{2}\rho A v^2}$$

According to the US Department of Energy, aerodynamic drag accounts for 2.6% of the 12.6% of fuel energy being used to propel a mid-size car in urban driving and 11% of 20% available at highway speeds. Therefore improving vehicle aerodynamics plays an important role in getting better mileage and performance.

Deliverables

1. Implement and benchmark the optimization algorithm used for drag reduction.
2. Design, simulate and optimize several aerodynamics add-on devices on a scaled model of a commercial truck.
3. Complete experimental testing on constructed models to confirm and adjust the computational results

Aerodynamic add-ons: rear cabin flap

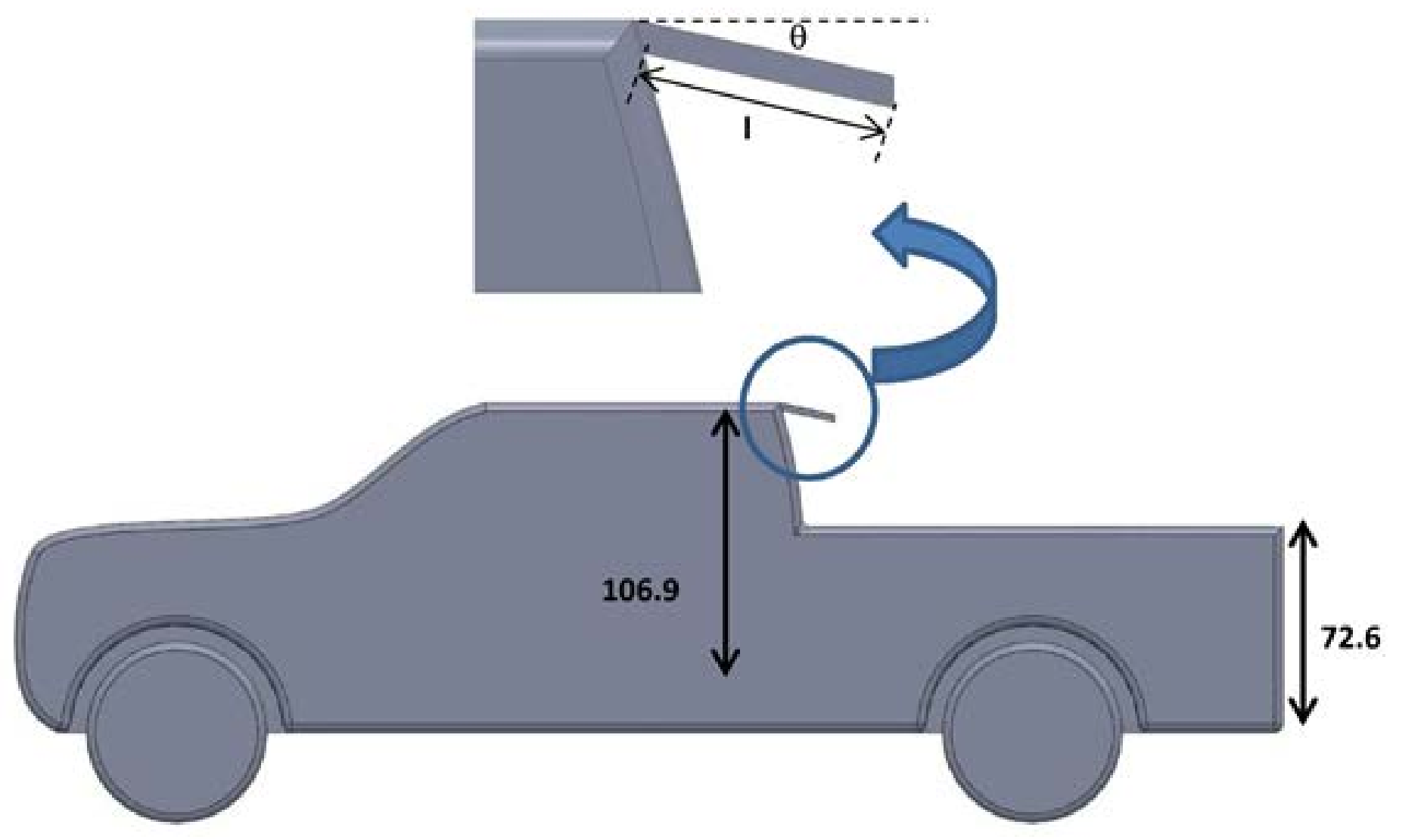

Fig. 1: Rear cabin flap

Optimization Technique

- We used a Globalized and Bounded Nelder-Mead (GBNM) algorithm to guide the optimization toward global minimum
- We automated the application programming interface (API) calls in SolidWorks
- We automated the Meshing, and Finite Element Analysis (FEA) in ANSYS Workbench.
- The Visual Basics for Application (VBA) interface controls the communication between SolidWorks, ANSYS Workbench and The GBNM algorithm.

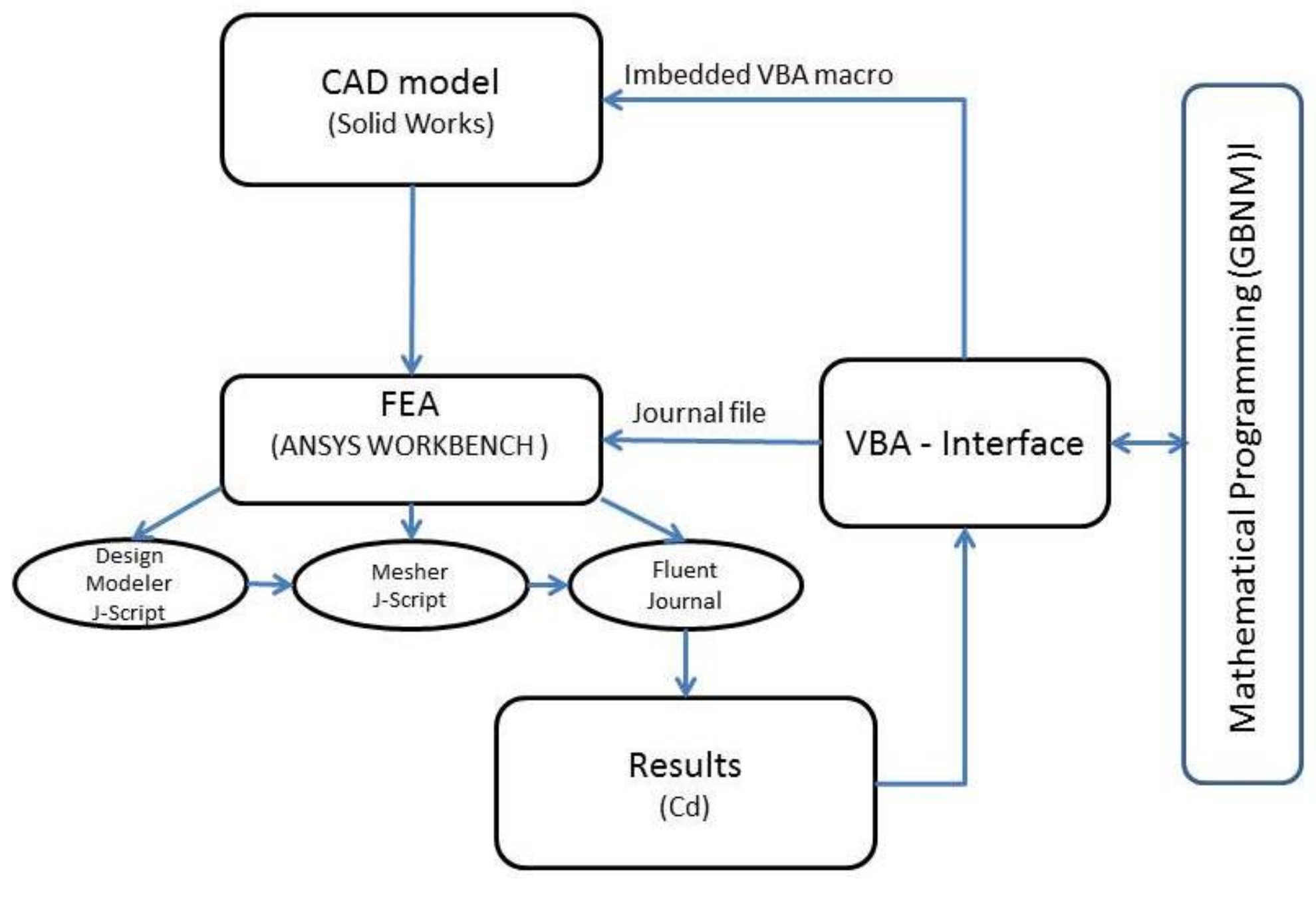

Fig. 2: Optimization technique

Simulation Box

The simulation domain extended around three times the vehicle length to the front and five times to the rear. The width and height of the control volume were set so that the cross section of the vehicle did not exceed 1.5% of the domain area. A box was created around the vehicle and in the wake region to control the mesh size during the meshing process. The box extended about half a car length in front, to the sides and to the top, and about a car length in the wake.

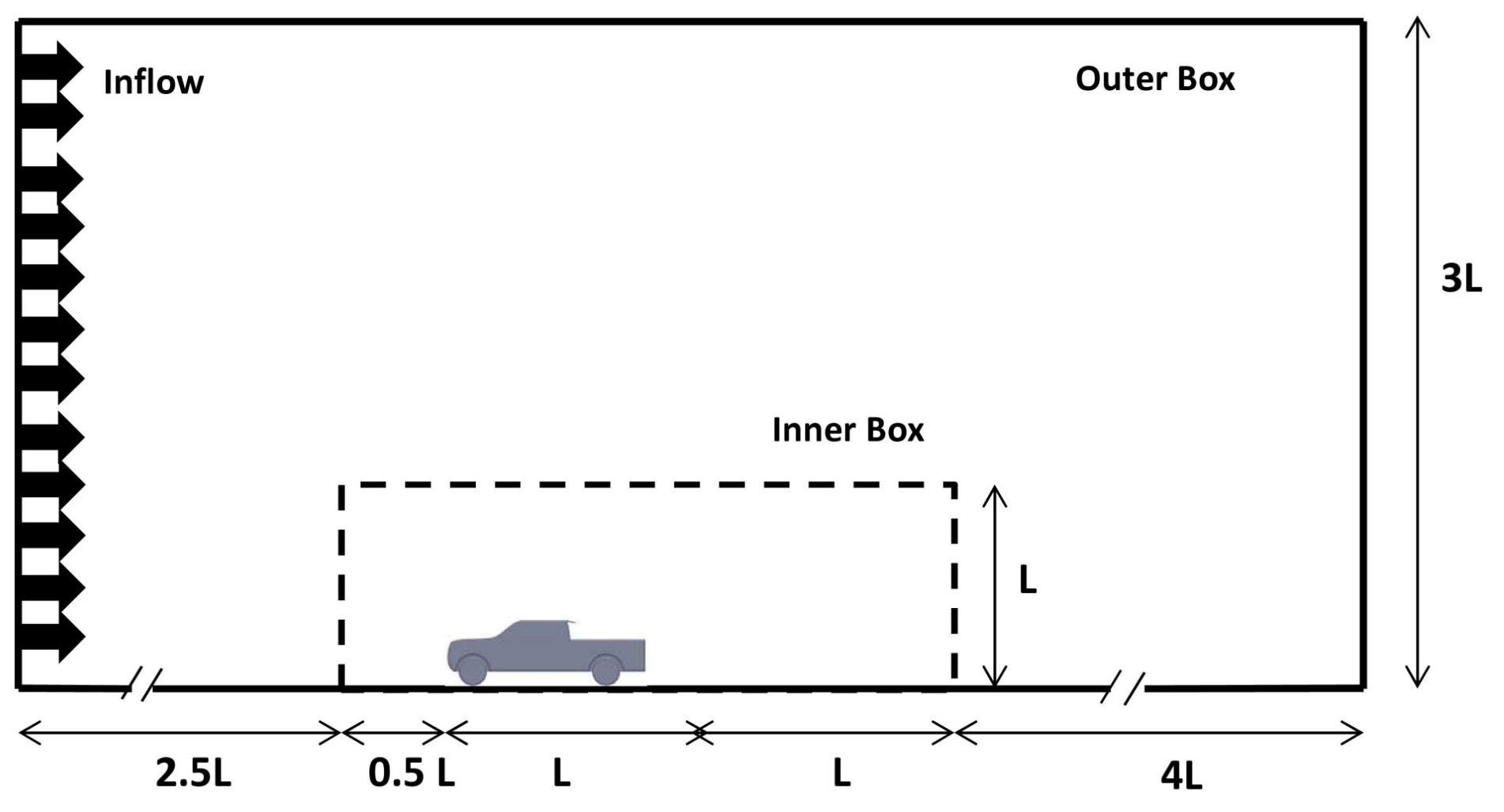

Fig. 3: Simulation Box

Meshing

An inflation layer was added over the surfaces of the vehicle and the road as shown in Fig.4; the prisms were grown with a first aspect ratio of 10 and a growth factor of 1.2 extruding 5 layers. Body sizing was used for mesh refinement around the vehicle and wake region. Triangular mesh elements were used on the surface to reduce the numerical diffusion and to align with the real flow near the model. The remainder of the computational domain was filled with tetrahedral volume cells that were adjacent to the prism layers.

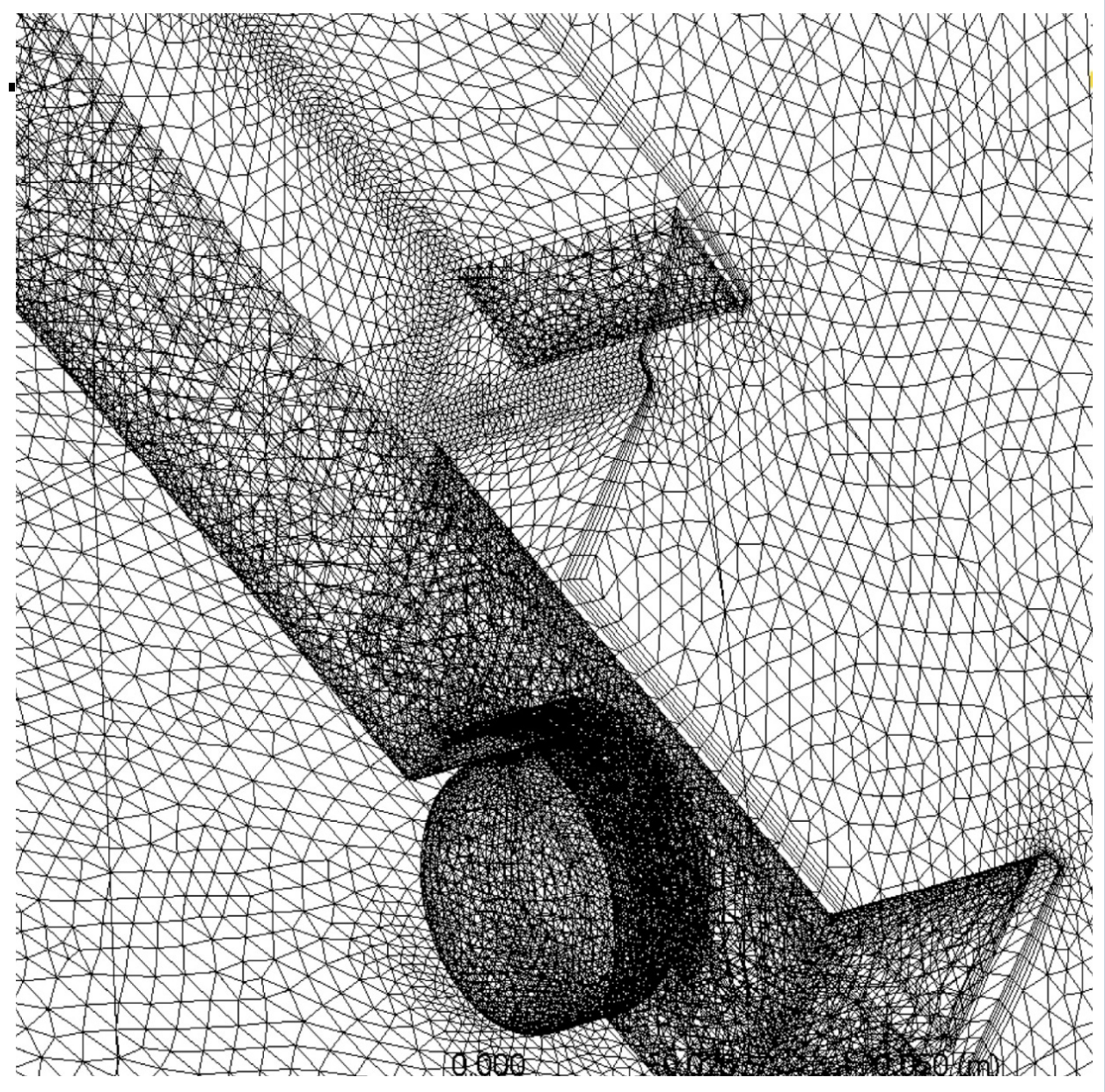

Fig. 4: Meshing

Simulation Results

l(H)	θ(o)	% reduction
0.15	12.0	5.10
0.19	12.5	5.39
0.22	12.4	5.82
0.24	12.2	6.03
0.26	12.2	6.03

Table. 1: Simulation Results

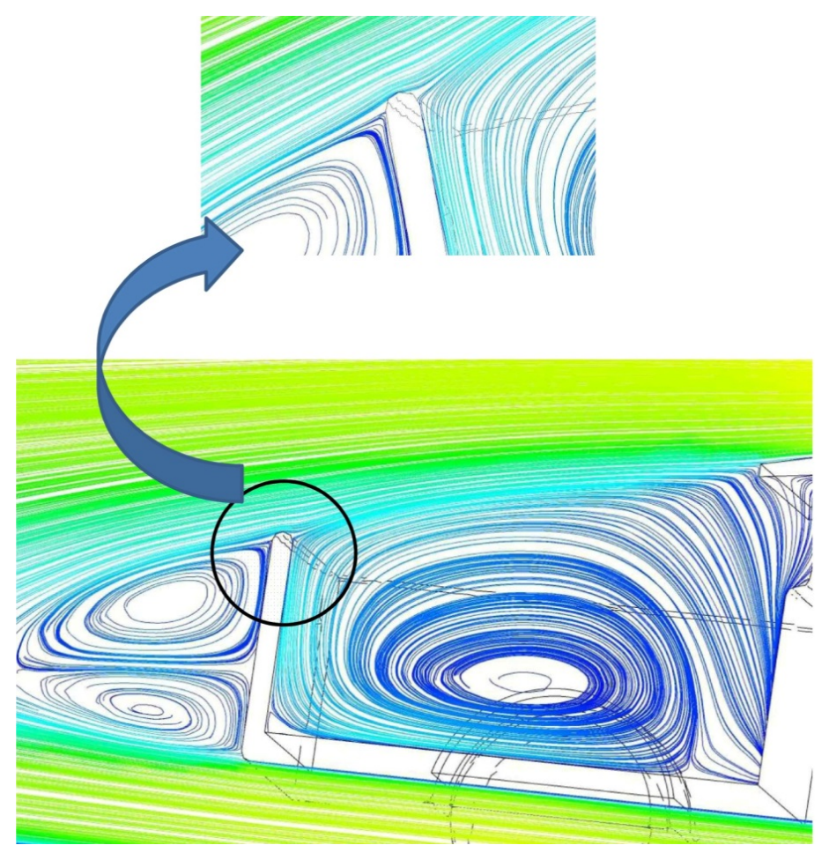

Fig. 5: Streamlines colored by the pressure coefficient around the bed in the symmetry plane for the model truck with flap, l = 0.24 H and θ = 12.2º. The insert visualizes the flow attachment over the tailgate. (CFD data)

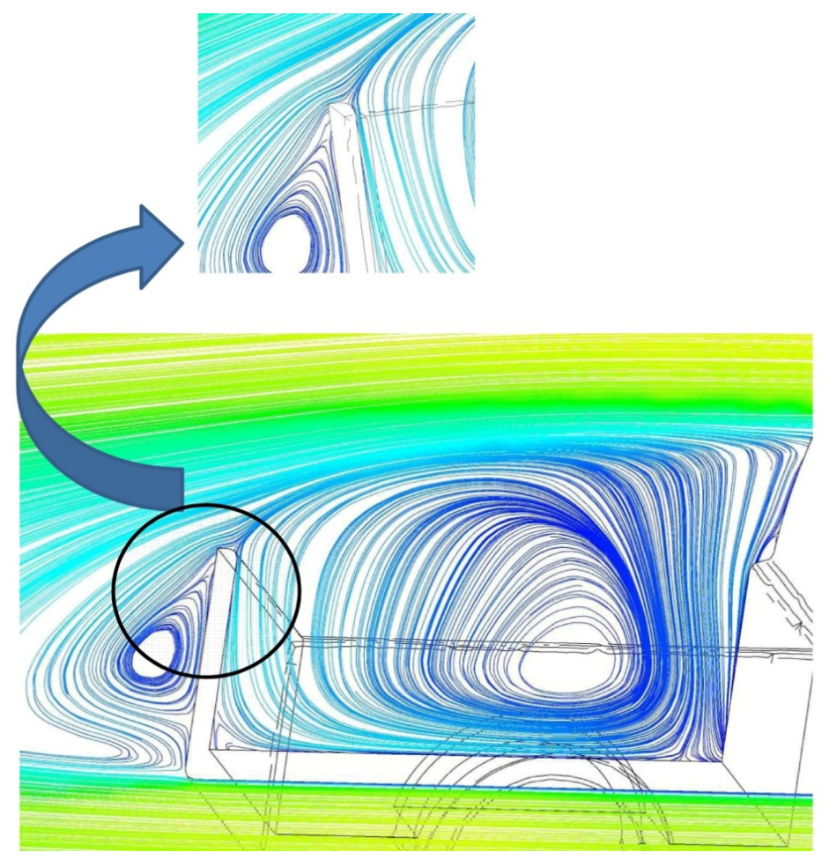

Fig. 6: Streamlines colored by the pressure coefficient around the bed in the symmetry plane for the model truck without flap l = 0.24 H and θ = 12.2º. The insert visualizes the flow attachment over the tailgate. (CFD data)

Wind Tunnel Test Section

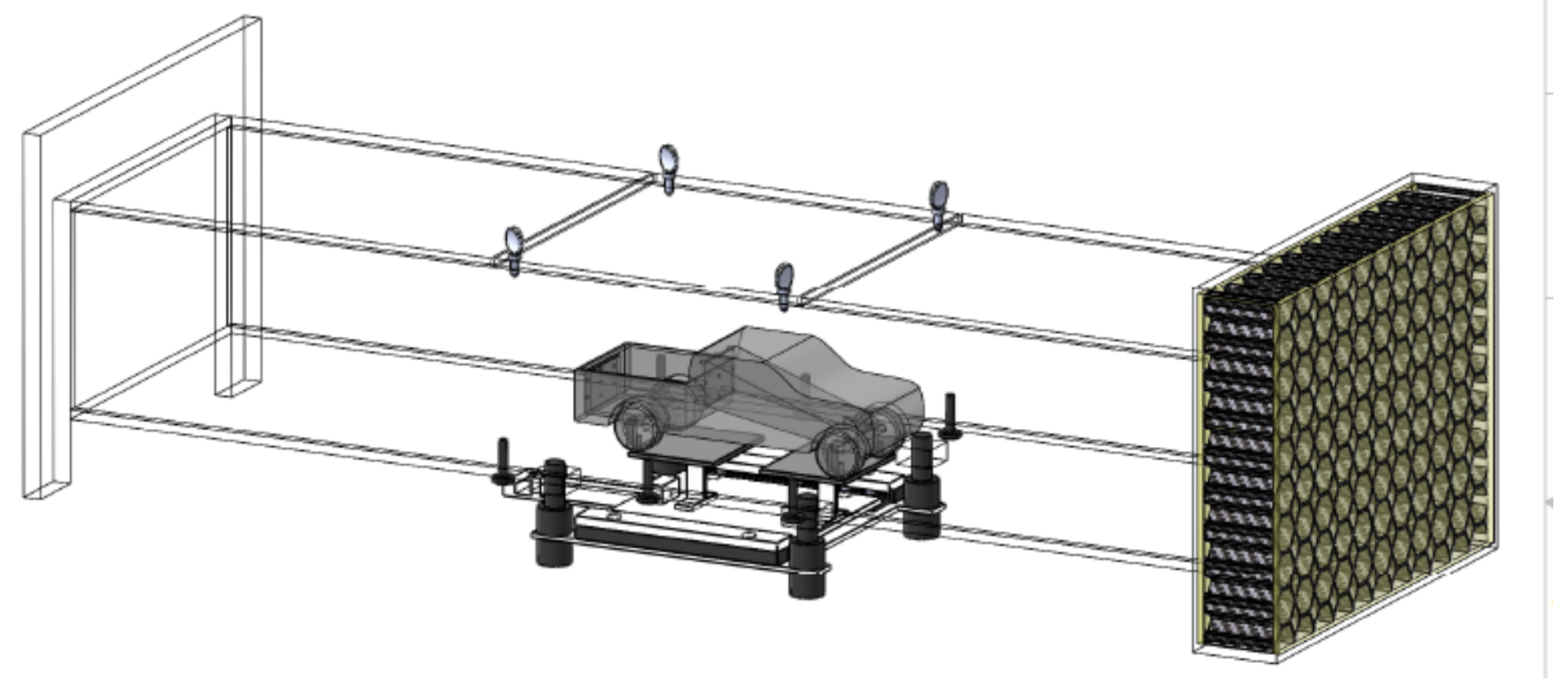

Fig. 7: SolidWorks rendering of the test section

The design of the modified test section (fig. 7) was truly a balancing act between the size and capabilities of our wind tunnel and the wind speeds required to obtain a turbulent flow around the model. On one side of the spectrum, attempting to use the wind tunnels original test section, at 10cm X 10cm, would only allow a scale model on the order of 3cm, this small model would require wind speeds upwards of 450 mph to get beyond the critical velocity which is beyond the capabilities of the wind tunnel fan. On the other side of the spectrum, increasing the size of the test section allows for larger models to be used and thus lower wind speeds can be used to obtain a turbulent flow however, increasing the size too much will make critical velocity airflow impossible. The final inner dimensions that were settled upon were 21cm wide X 14cm tall (fig. 8).

Fig 8: Custom built test section for use with the UCO wind tunnel

Measurement System

There are two types of sensors that we use in our measurements; load cells measure forces applied to the model by the air flow and pressure sensors measure pressure differences along the model allowing us to compare the experimental pressure distribution with the simulation pressure distribution. The most important of these measurements is the cumulative horizontal force applied to the model by the air flow otherwise known as the drag force. The drag force is measured directly by a load cell that sits behind the low friction platform (fig 9).

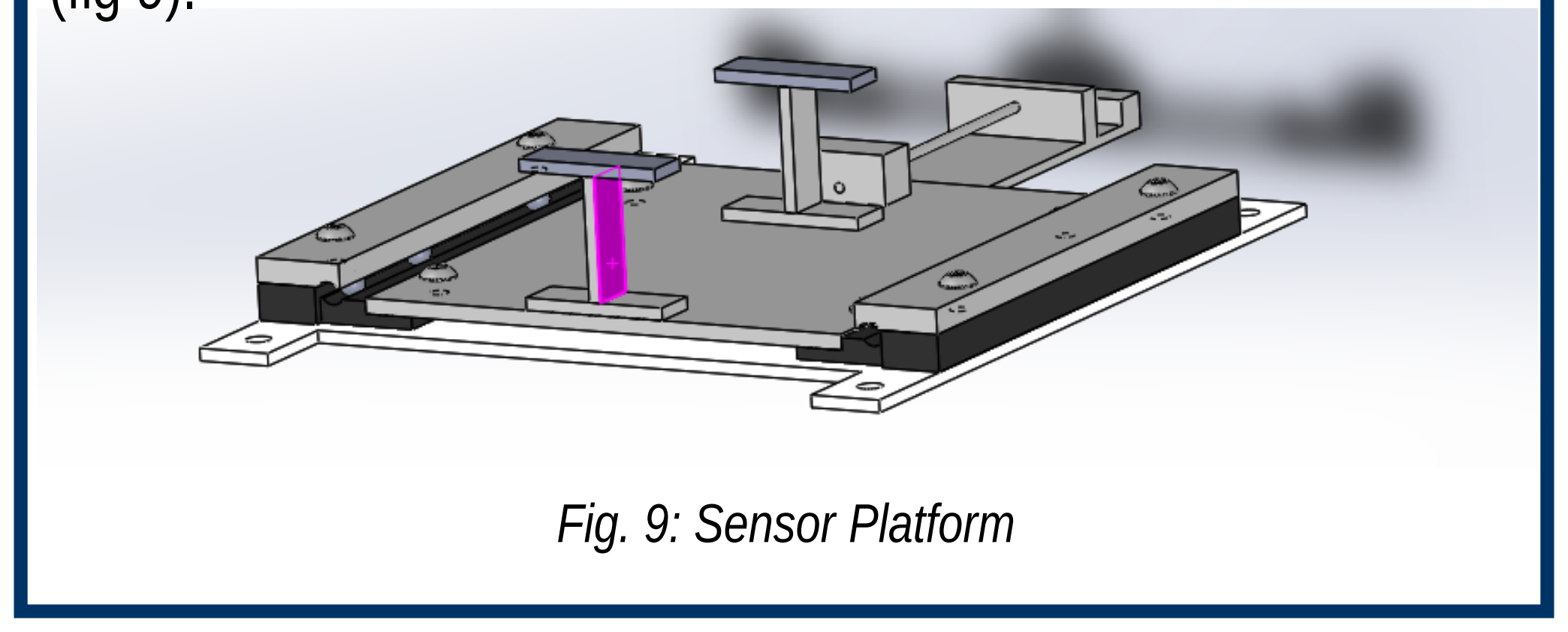

Fig. 9: Sensor Platform

To gain a better understanding of how the air is behaving as it flows over the surface of the vehicle we have also included pressure sensors that will be implemented along the symmetry of the vehicle. To obtain our readings from the various sensors we will use a National Instruments data acquisition system (DAQ). We interface the DAQ with a National Instruments Labview program that works directly with the DAQ, this will allow us to view the sensor inputs in real time as well record the values for drag force as well as the pressure differences along the symmetry of the vehicle.

Scaled Model

To create a 3-D representation of a generic pick-up truck we use a feature in SolidWorks that allows the user to underlay an image on the sketching window. An image of a Ford F-150 was used in the creation of the truck model. A detailed sketch was then created around the image and scaled to give us a dimensionally accurate model. The SolidWorks file was sent to a firm in Tulsa, OK to produce the physical model. The model was created in a 3-D printer using ABS plastic (fig. 10).

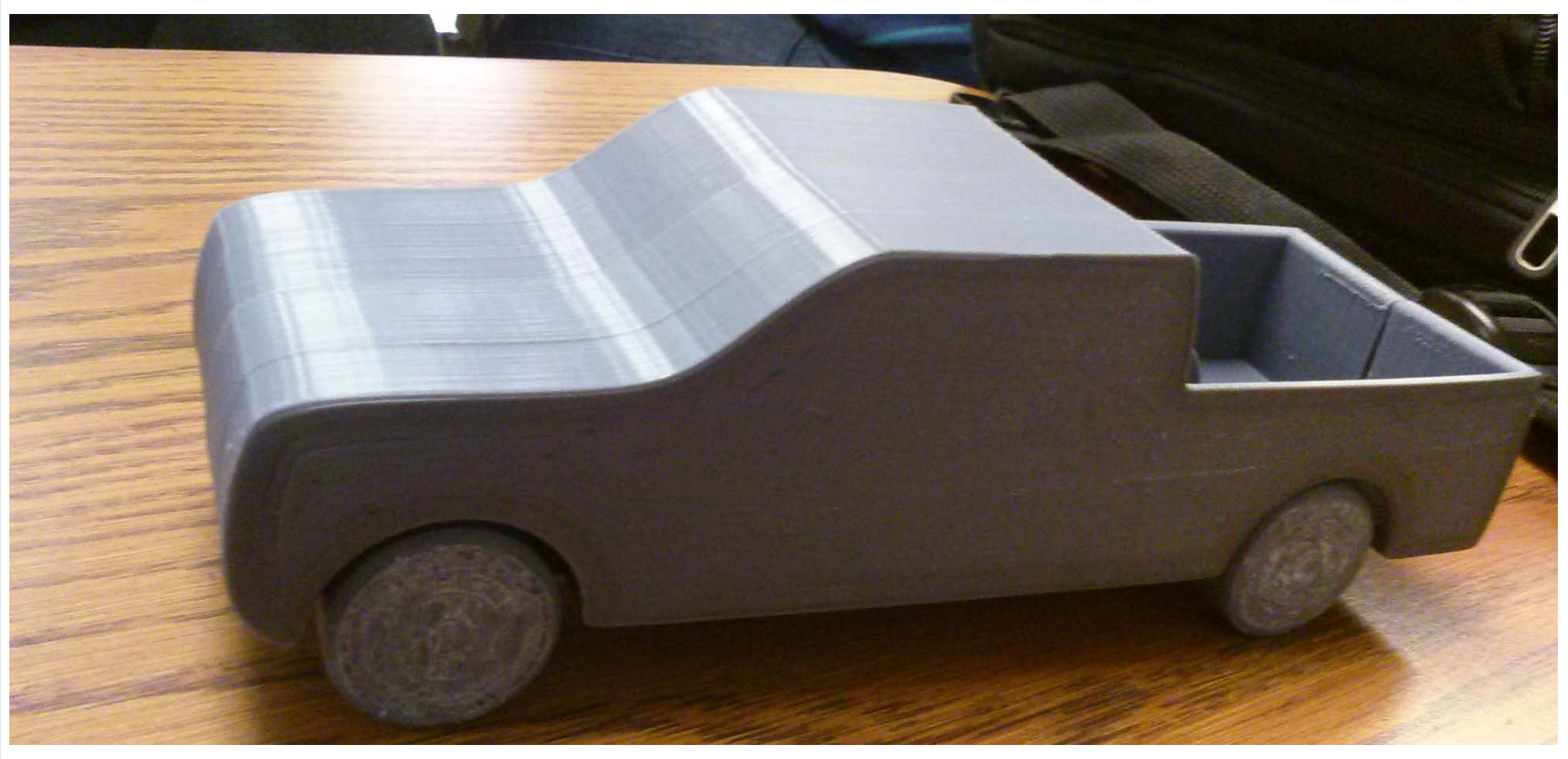

Fig. 5: 3-D printed model of a pick-up truck

Experimental Results

	TRIAL 1 (C_D)	TRIAL 2 (C_D)	TRIAL 3 (C_D)
0 Degree	0.852555	0.835242	0.783913
8 Degree	0.82036	0.791202	0.775712
12 Degree	0.789076	0.787254	0.734102
18 Degree	0.844962	0.815804	0.770853

Table. 2: Experimental Results

The results we have obtained from our wind tunnel experiments agree closely with our simulation results providing further evidence that our methods are sound. The drag coefficient corresponding to the 12º add-on shows a 3.3% improvement over the 8º flap, a 5.1% improvement over the 18º flap, and a 6.7% improvement over using no aerodynamic add-on device at all.

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