Toward Heavy Truck Fuel Efficiency Using CFD

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Motivation

- - 70 % of the oil used in the US is for transportation.

  - Among them 23% fuel consumption and greenhouse gas emissions are from heavy duty vehicles.

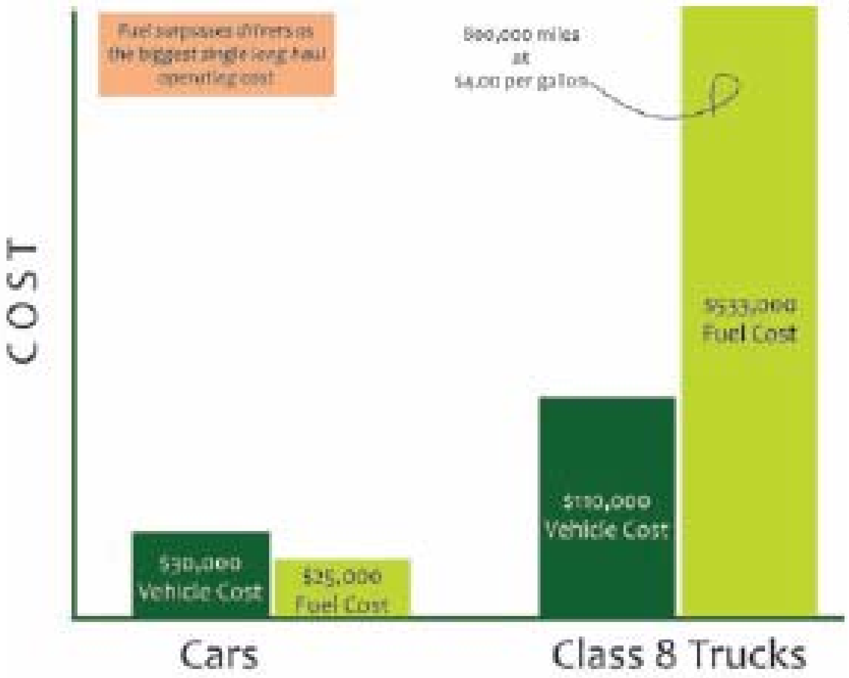
  - About 65% of heavy truck fuel consumption is attributed to aerodynamic drag on highway.
- Oil price is on the rise, despite recent downfall, fuel saving in heavy trucks is becoming a national economic and strategic issue.
- The understanding of truck aerodynamic physics using CFD method is an efficient way to improve its design in reducing fuel consumption.

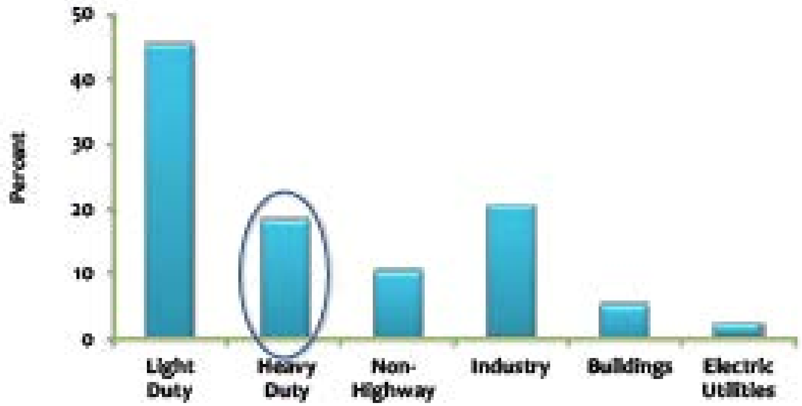
Heavy Duty Vehicles

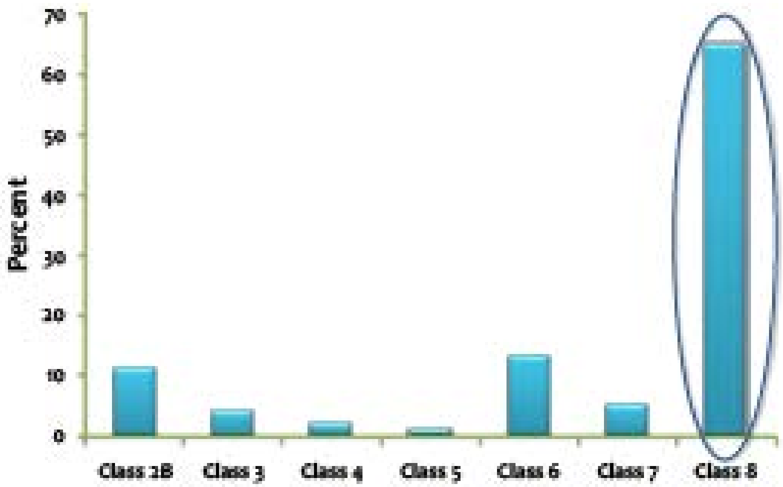
- 70% of oil used is for transportation, and heavy duty vehicles contribute 20% on-road energy, and greenhouse gas emission. (photo taken from White House document)

Heavy Trucks = Heavy Weight Fuel Consumer

(data from US DOE)







EPA and DOT Target Fuel Efficiency

- Targeted areas to improve fuel efficiency

  - Aerodynamics (could be the most effective)

  - Weight reduction

  - Improved tire rolling resistance

  - Hybridization

  - Automatic engine shutdown

  - Accessory improvements (water pumps, fans, auxiliary power units, air-conditioning, etc.)

Rear End of Heavy Vehicles Contributes a Lot on Energy Consumption

- Heavy duty ground vehicle: about 65% of fuel consumption is attributed to aerodynamic drag.
- US heavy duty vehicle fuel consumption represents 18% of overall energy consumption, (vs. air vehicle:8%, railway: 2%).
- Rear end pressure drag represents about 1/3 of the overall aerodynamic drag.
- 1% of fuel economy increase (FEI) represents about 200M gallons of diesel fuel if employed by the entire US HV fleet.

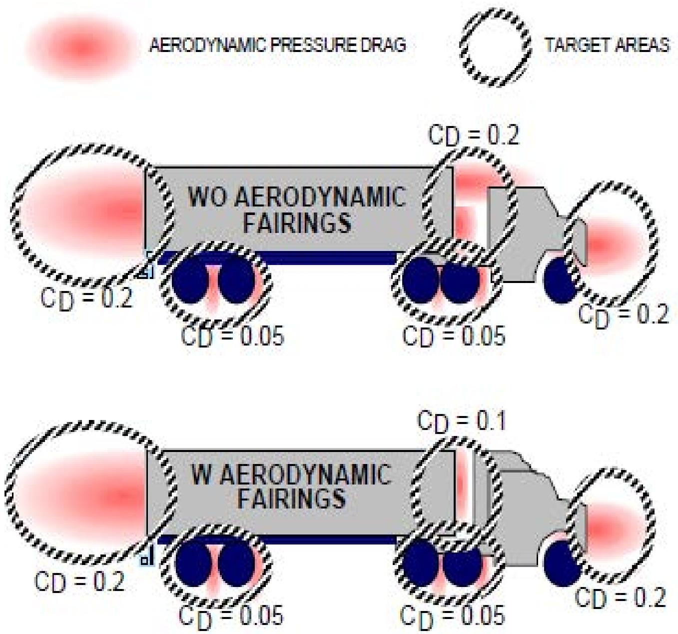
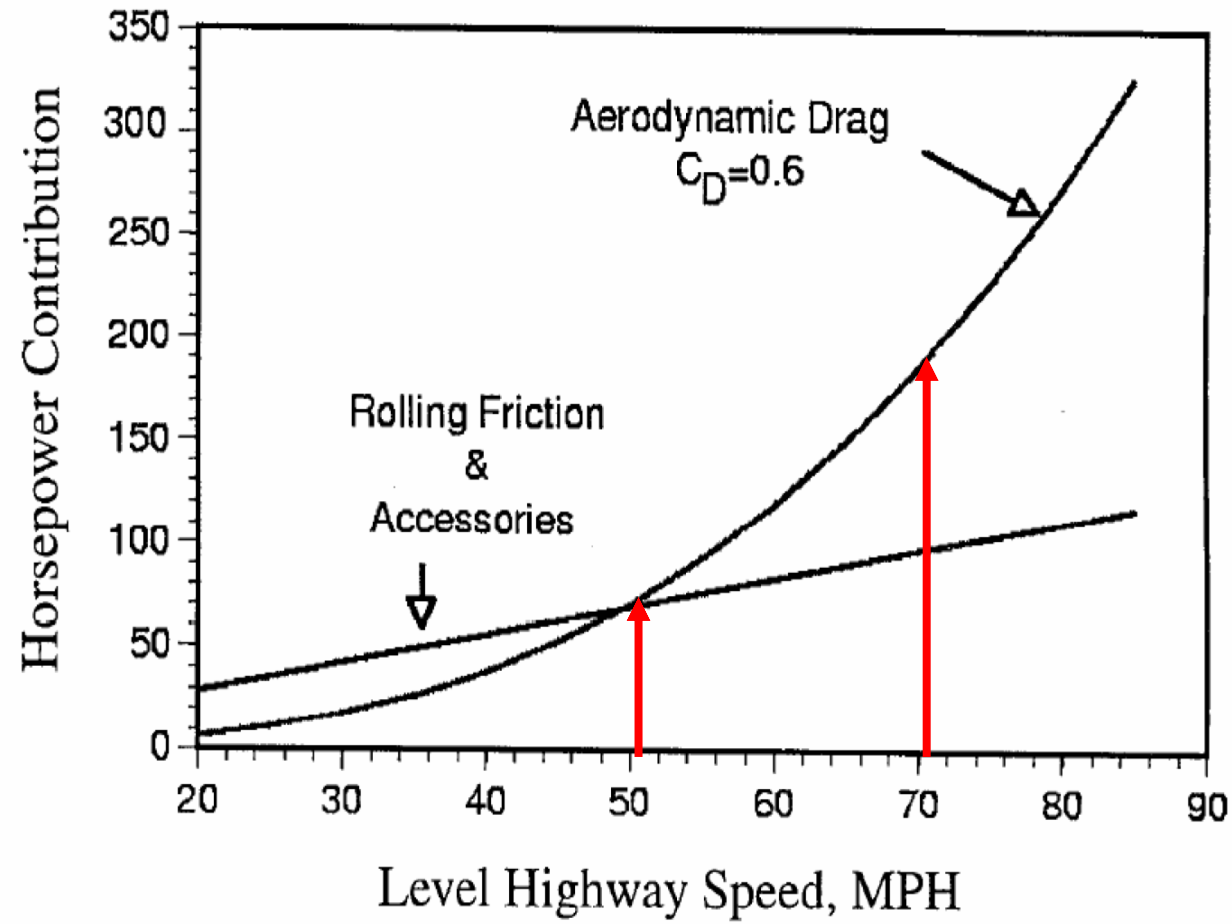


Photo from Solus

Higher Road Speed Means More Aerodynamic Drag



At 50 MPH (80km/h) the frictional drag = aerodynamic drag

At 70 MPH (112km/h) the aerodynamic drag =2 x frictional drag

What Fuel Saving Means to Trucking Company

- Example: “S” Company
- 2013 Revenue: $4 billions USD
- Corporate market value: $4 B
- Net profit: $150 M
- Fuel consumption: $800 M (more than 5 times the profit)
- 5% of fuel saving means $40M more profit, or about $1 B higher corporate market value !

Approaches to the Drag Reduction Design

Approaches	Pros	Cons	Remarkes
Wind Tunnel Test	lower cost	accuracy, limited flow information	
CFD	detailed flow physics, quick and efficient, lower cost	not generally accepted by industry	
Road Test	generally acceptable	expensive to test, limited information, test data varies with protocol	$20K per test, $75-120K EPA certified

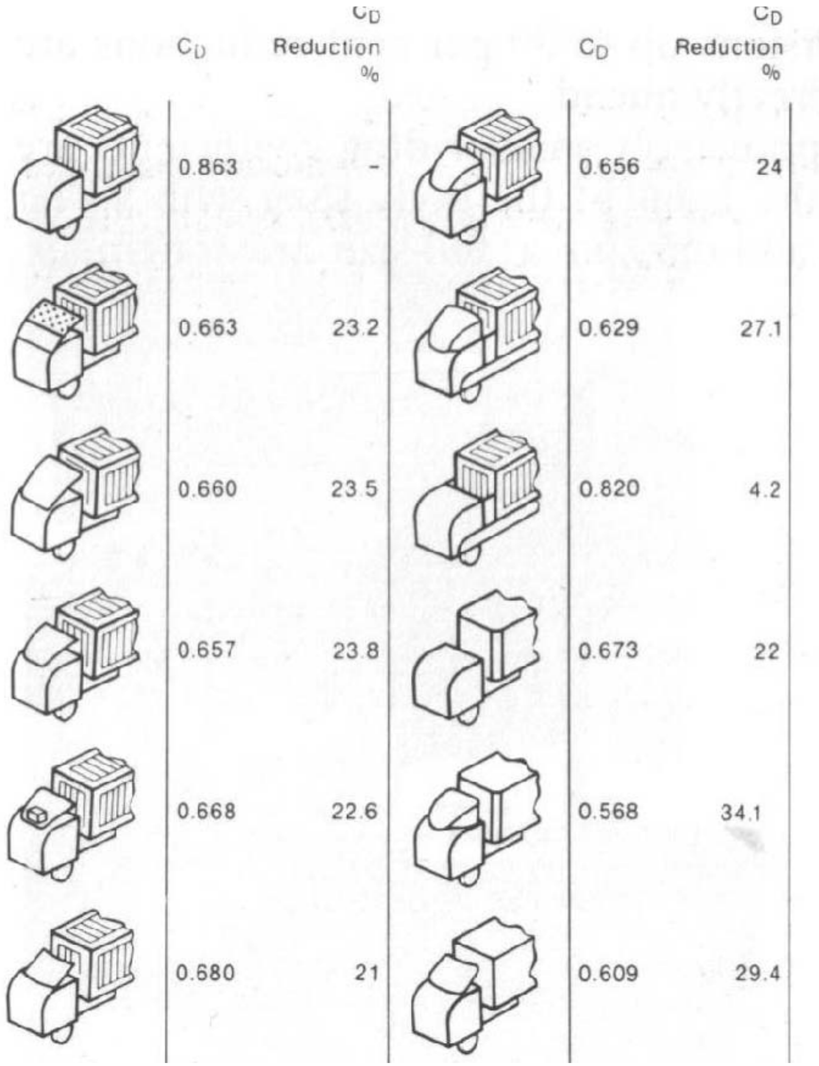
- All 3 approaches are adopted in the present study, with CFD approach for verification and design iteration.

Evolution of Tractor Configuration

Photos from NASA/TP-1999-206574

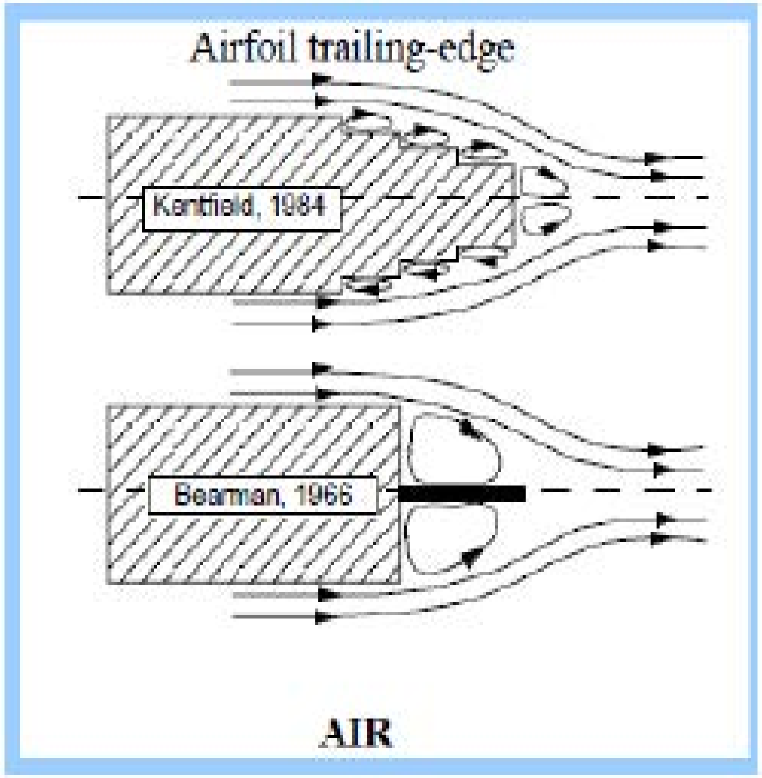
Car Front End Drag Reduction is Reaching a Limit

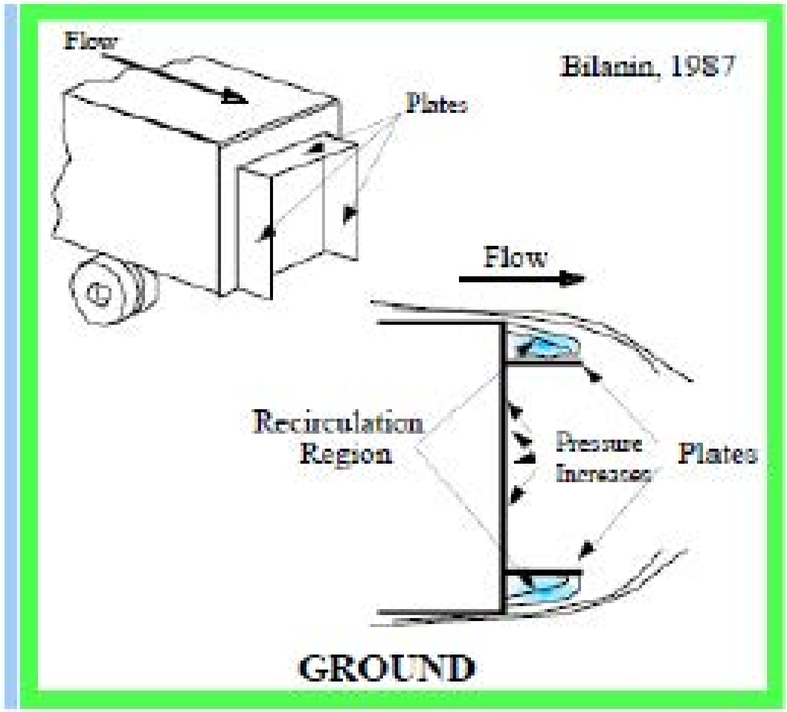
- The hood design
  - To reduce the front end pressure and energy loss has been studied extensively.
  - Berta & Bonis (1980, SAE) reviewed designs.
  - Fewer studies to reduce drag are being done recently in the front end.



	C_D	C_D Reduction %		C_D	C_D Reduction %
	0.863	-		0.656	24
	0.663	23.2		0.629	27.1
	0.660	23.5		0.820	4.2
	0.657	23.8		0.673	22
	0.668	22.6		0.568	34.1
	0.680	21		0.609	29.4

Rear End Drag Reduction: add-on device
(photos from Wood (Solus))

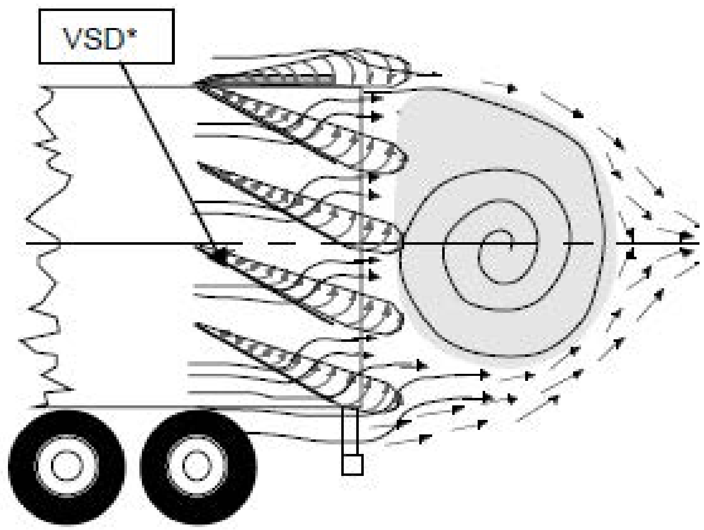




Vortex Strake Device

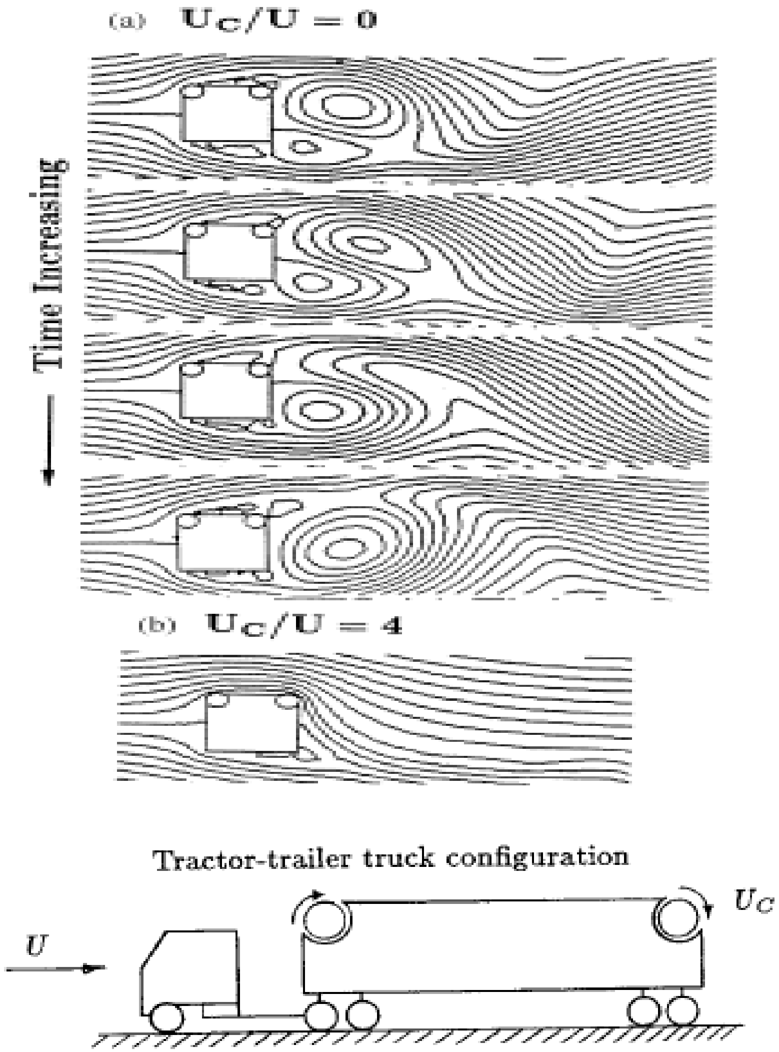
- Vortex Strake Device (VSD)
  - Richard M. Wood & Steven X. S. Bauer (2003, Solus) use VSD to energize the vortex flow and reduce the separation at truck rear end.
  - Reduce fuel consumption by 1%.

Vortex Strake Device



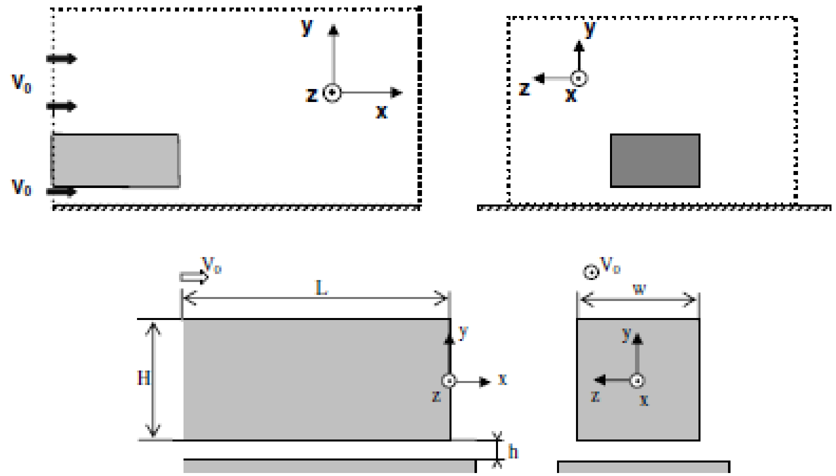
Rotating Cylinders

- Munshi et. al. (1995) the first one proposed the use of rotating cylinder to energize the flow, improved the flow separation and vortex flow.
- Modi (2001)，use leading edge cylinder and trailing edge cylinder rotating clockwise on trucks to increase lift and reduce drag.



Blowing Slot at Rear Corner

- Mathieu et. Al. (2008) studied the continuous blowing device at rear end corner of a simplified square-back geometry using numerical method.
- 29% drag reduction with 1.5V blowing speed and 45 deg angle.
- Static pressure increase and less total pressure loss in the wake region



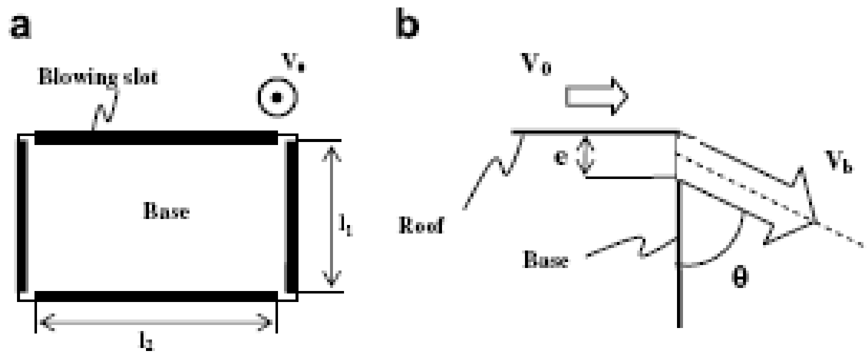
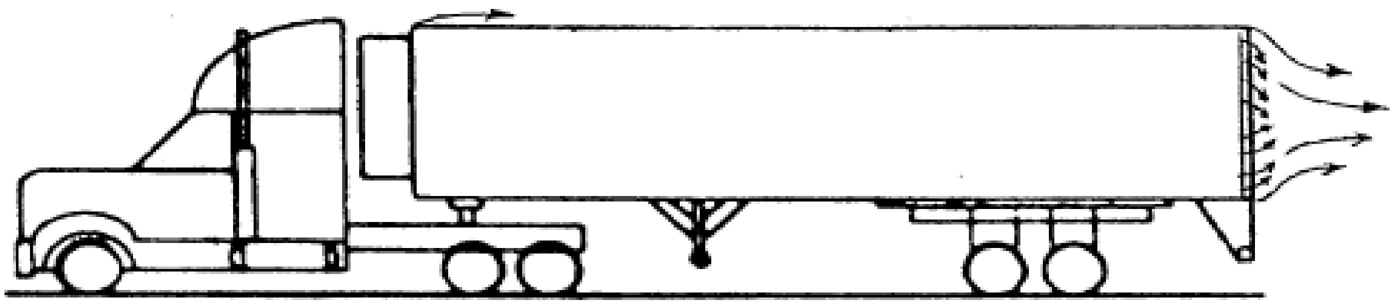


Fig. 8. Schematic of the blowing devices set up.

Tangential Blowing at Rear End

- Englar (2001) pneumatic heavy vehicle (PHV) concept.
- Use tangential blowing to reduce the drag generated by the heavy vehicles. Drag reduction accomplished by blown concept without moving surfaces
- 20~30% fuel saving can be achieved, but consumes extra blowing energy.



Rear End Drag Reduction Device

- Inflatable Aero-Tail: AeroVolution

Base-flaps

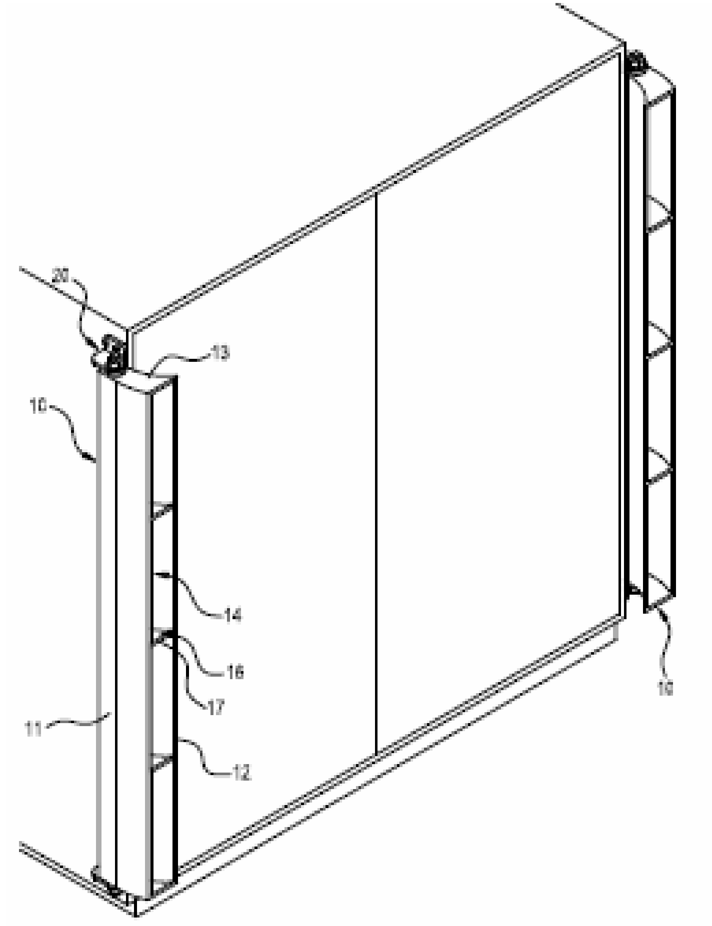
Present Study
Rear Corner Nozzles

- Patented conceptual design -> Proof of concept
- Work collaboration between university and industry
- 3 steps implemented

(1) scaled model wind tunnel test

(2) numerical simulation

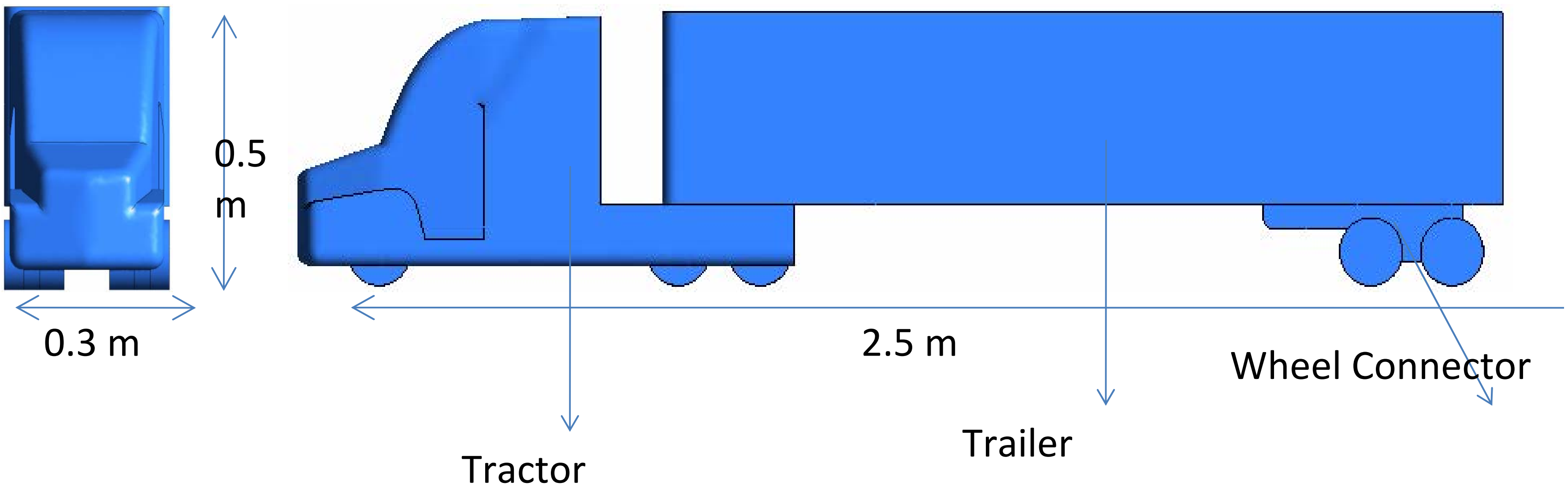
(3) road test: in progress



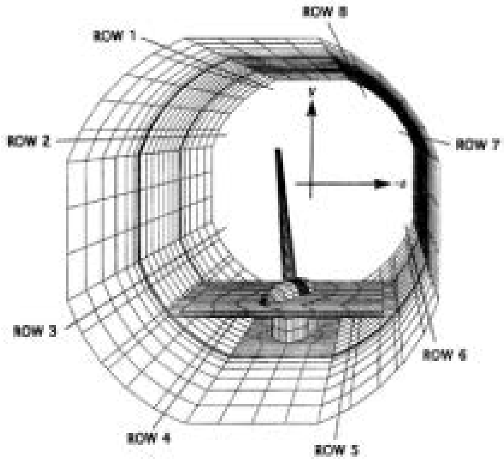
Wind Tunnel Test

Geometry Description

- The model used in the study is called GCM (Generic Conventional Model), a simplified representation of a conventional US tractor-trailer truck.
- The GCM is approximately 2.5 m long, 0.5 m high, 0.3 m wide.
- It consists of 5 main parts, i.e. the tractor, the tractor wheels, the trailer, the trailer wheel connector, and the trailer wheels.
- The reference area used is 0.15443 m^2.



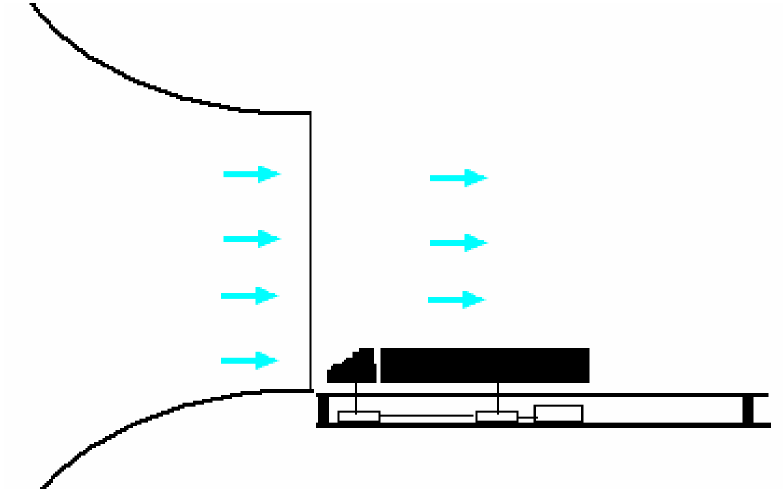
NASA Wind Tunnel Test

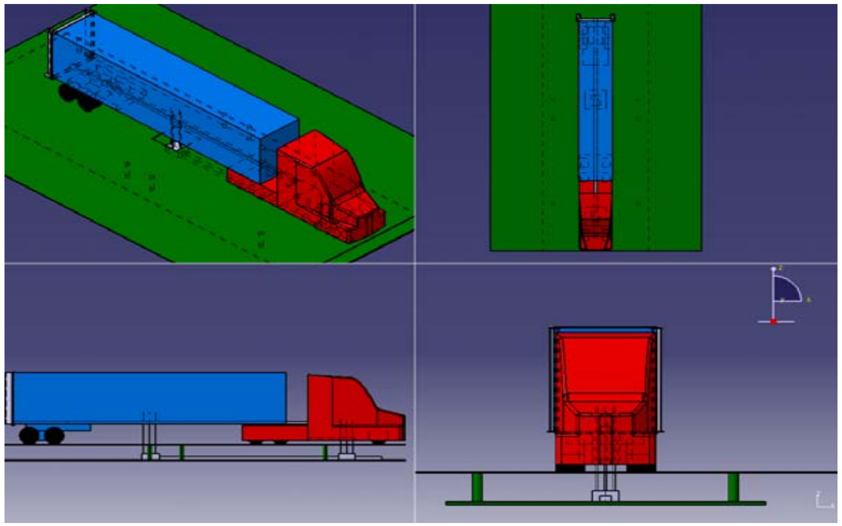


Temperature (°C)	18.9
Density (kg/m^3)	4.762
Velocity (m/s)	51.475
Trailer Width (m)	0.3239
Reference Area (m^2)	0.1544

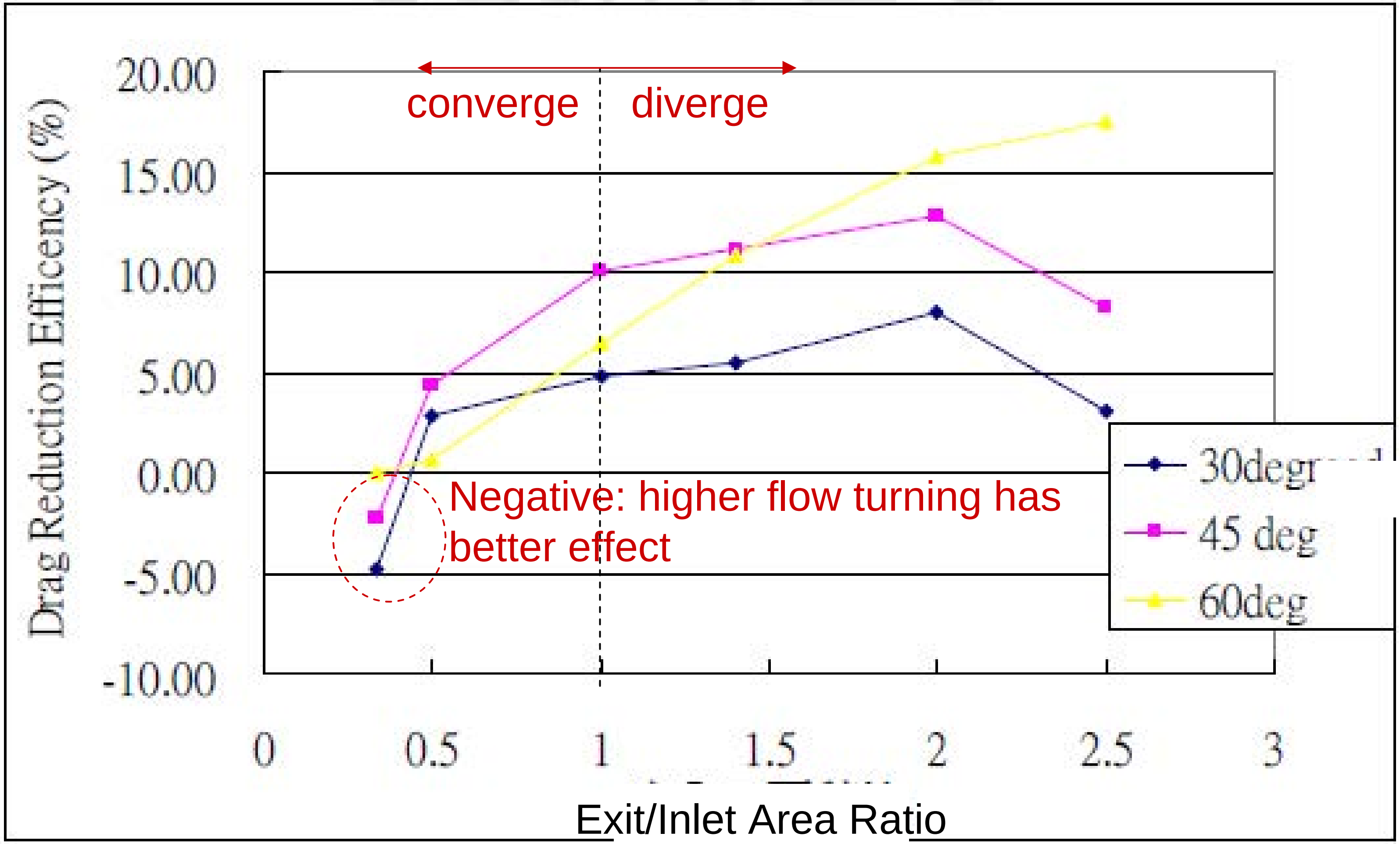
Reynolds Number	4.2162×10^6
Drag (N)	400.73
Standard Deviation of Drag (N)	2.026
Drag Coefficient (C_D)	0.41139
Standard Deviation of C_D (%)	0.002 (0.51%)

Wind Tunnel Test Facility





Flow Turning and Area Ratio Effects

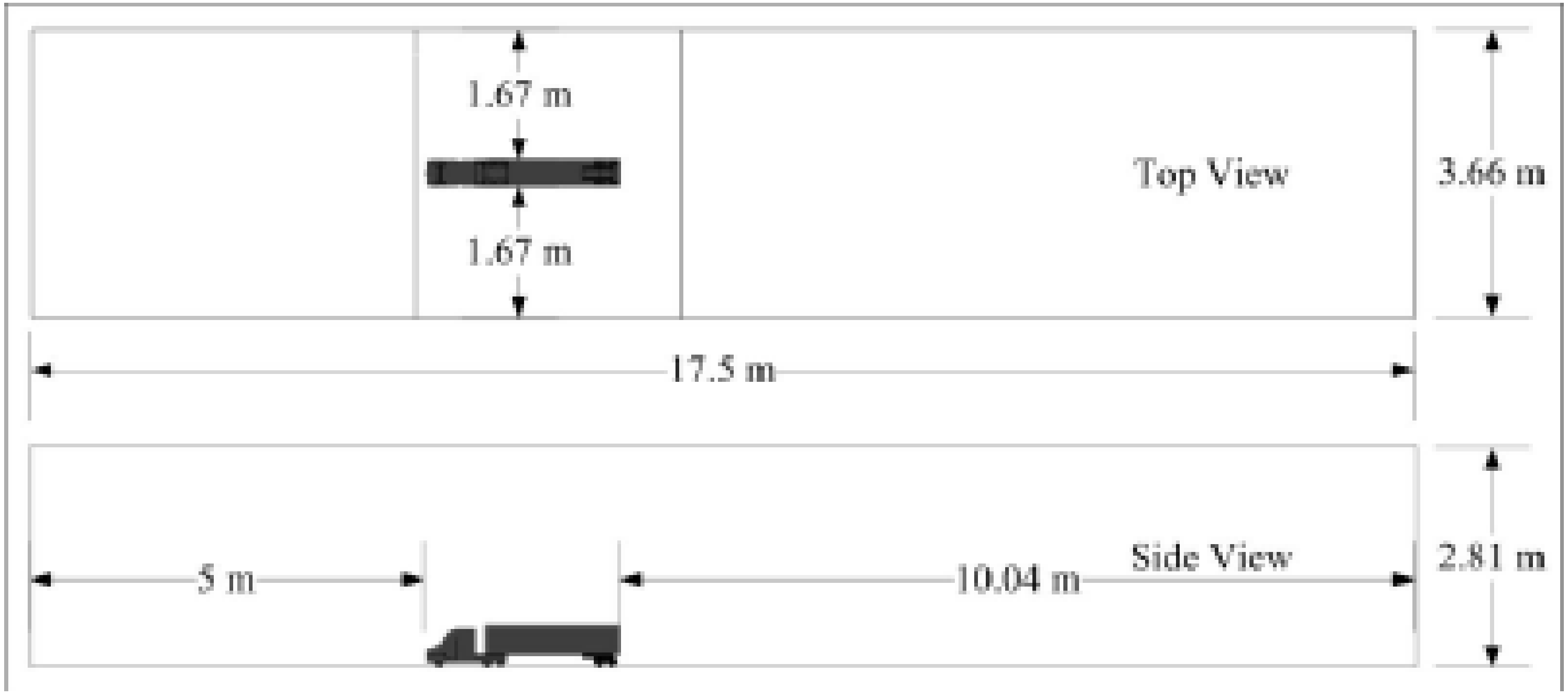


CFD Simulation

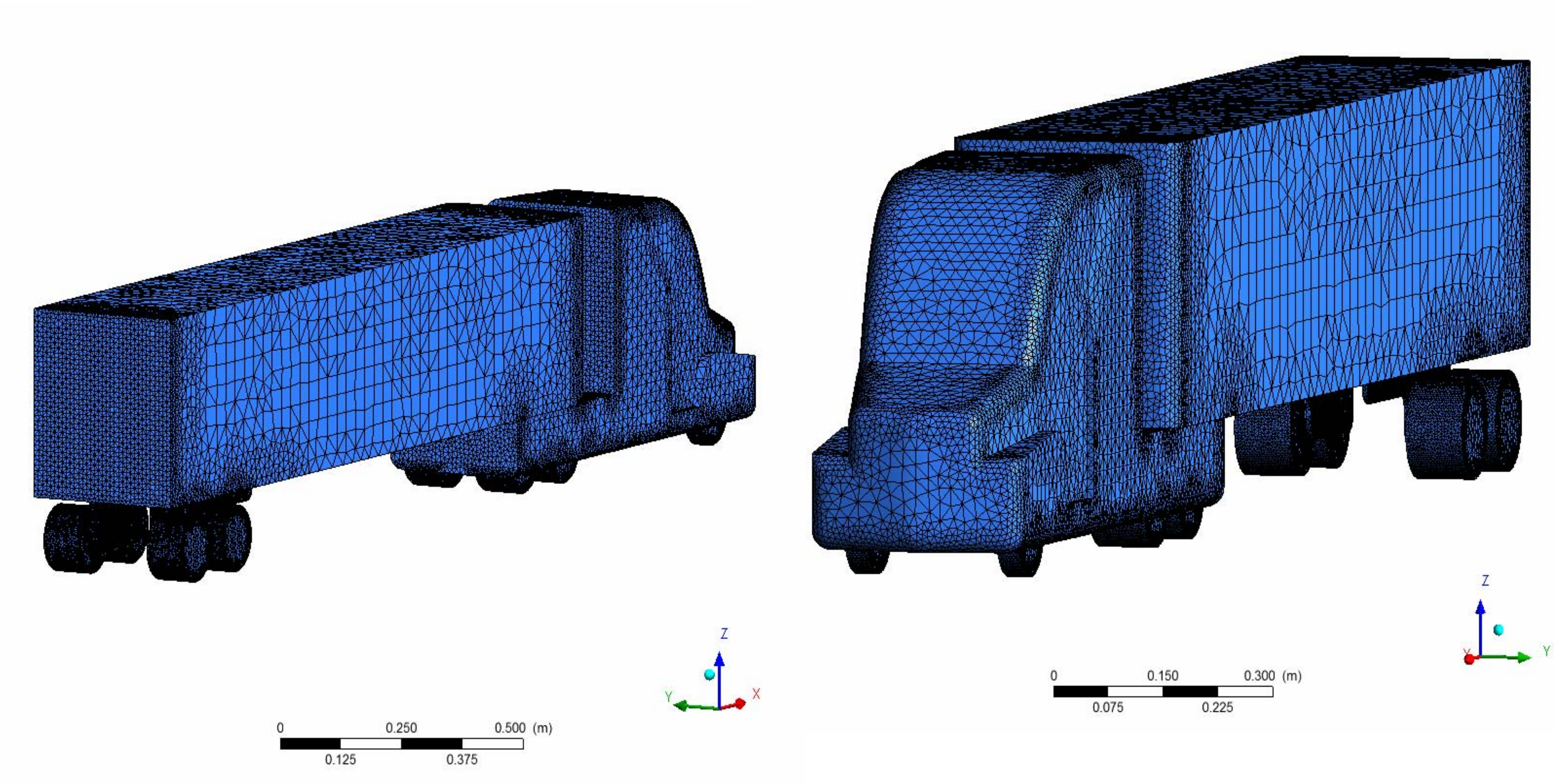
with and without add-on devices

Computational Domain

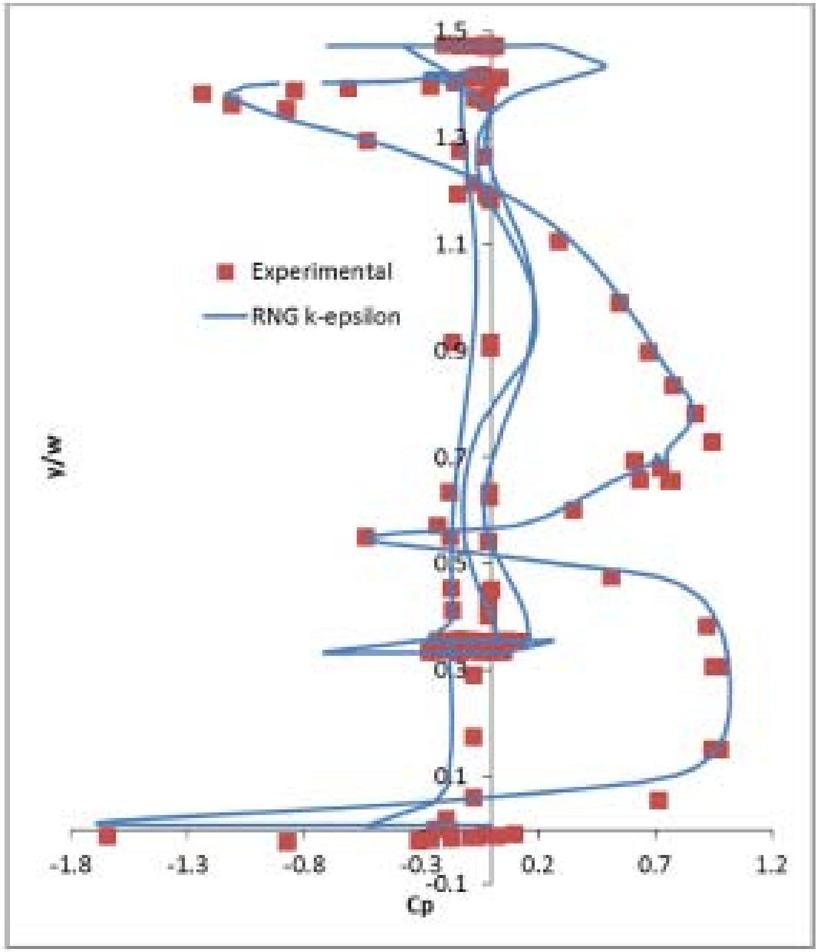
- Top View (upper) and Side View (lower)

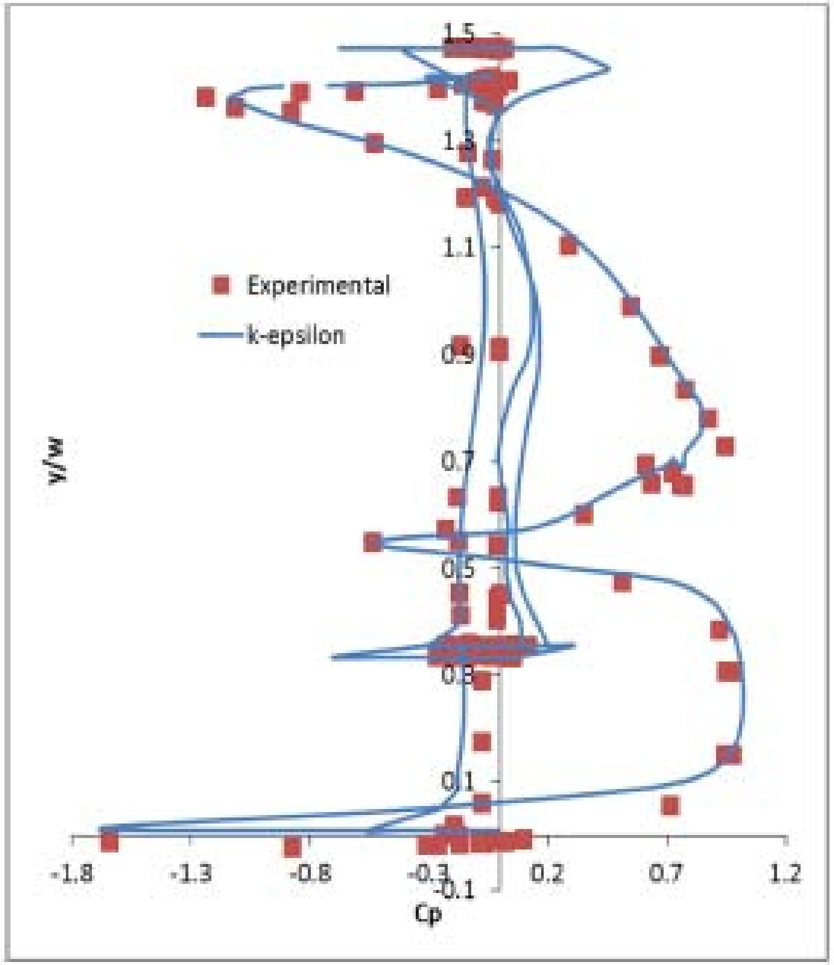


Surface Mesh View

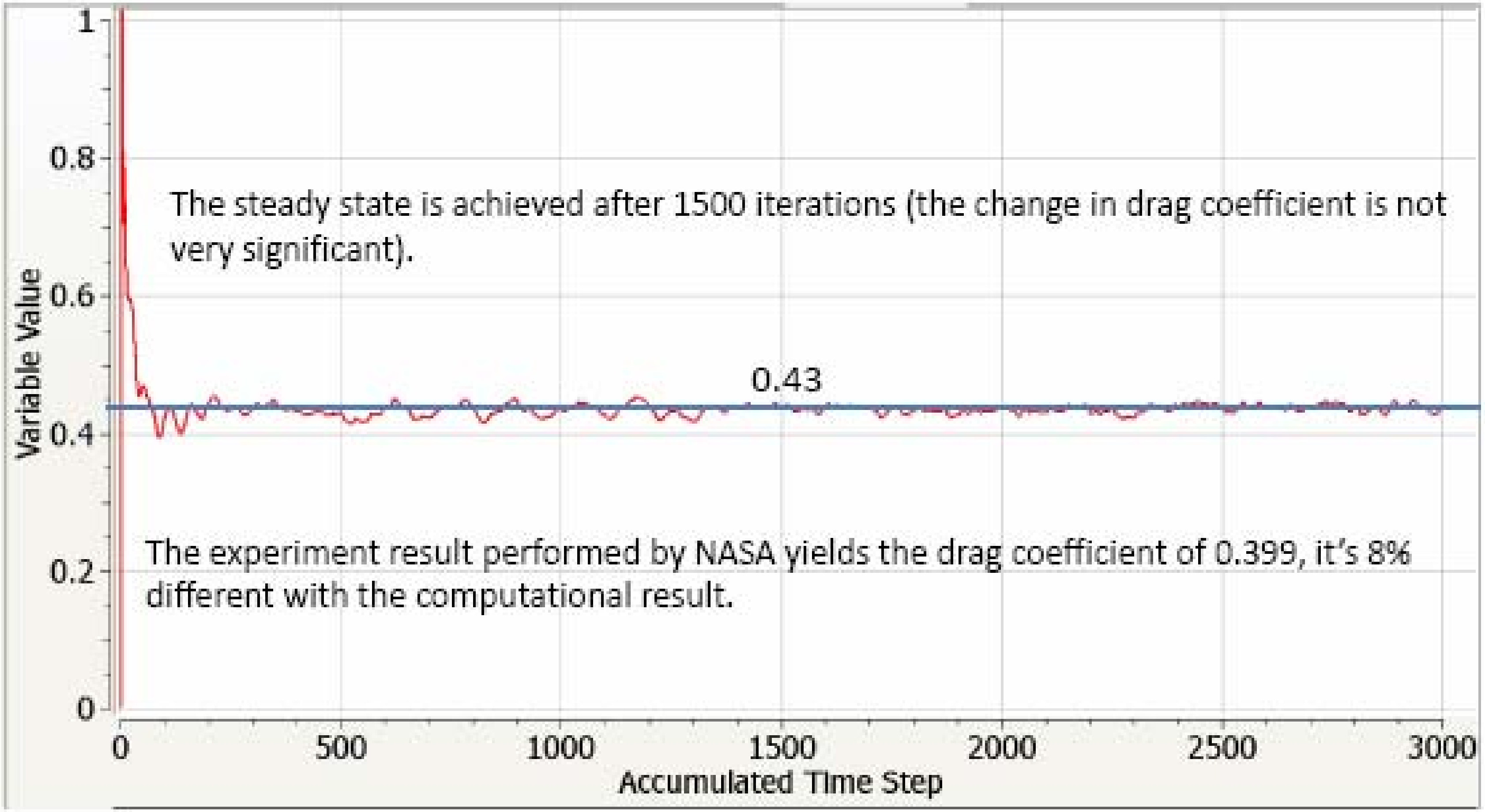


Pressure Distribution at X-Y Plane



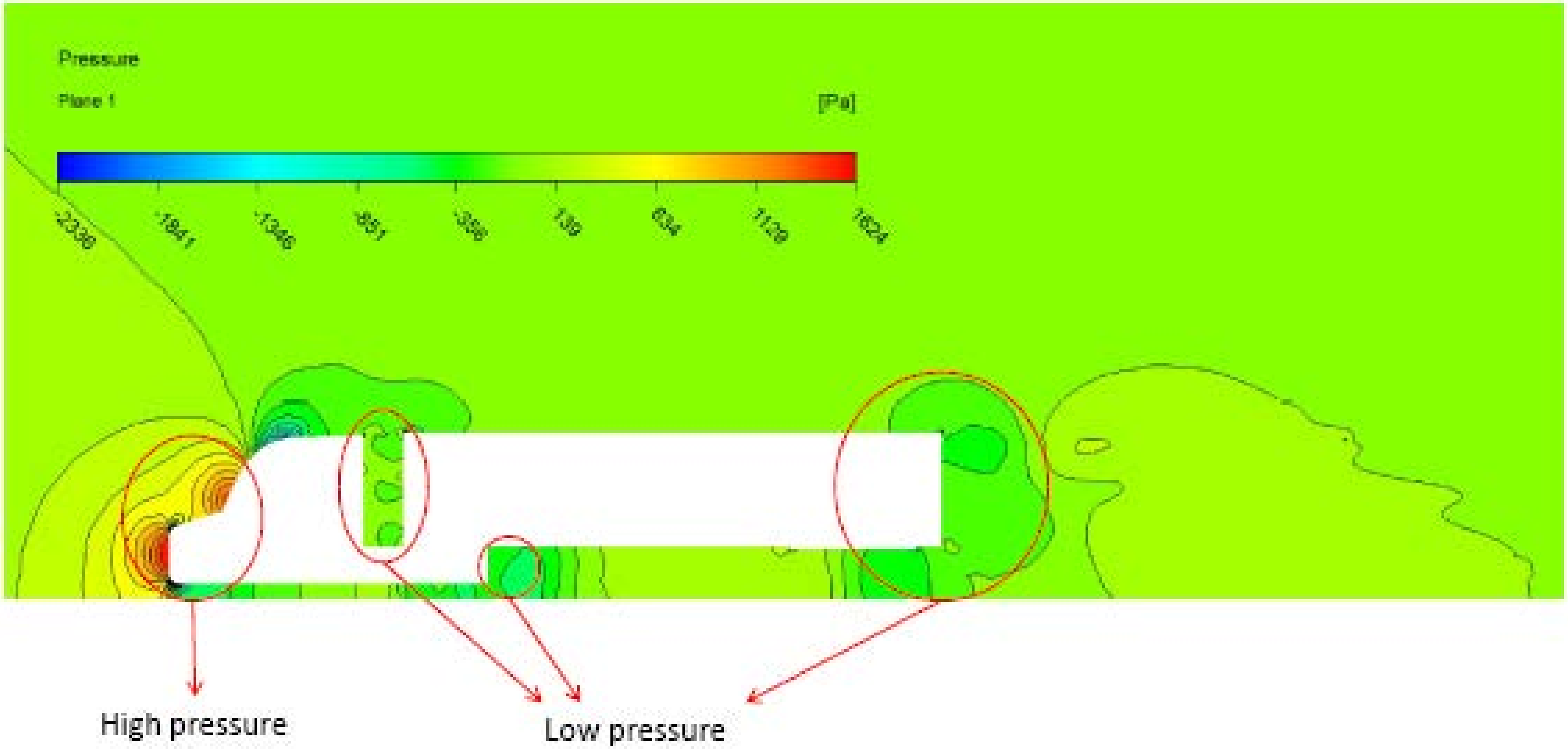


Drag Coefficient



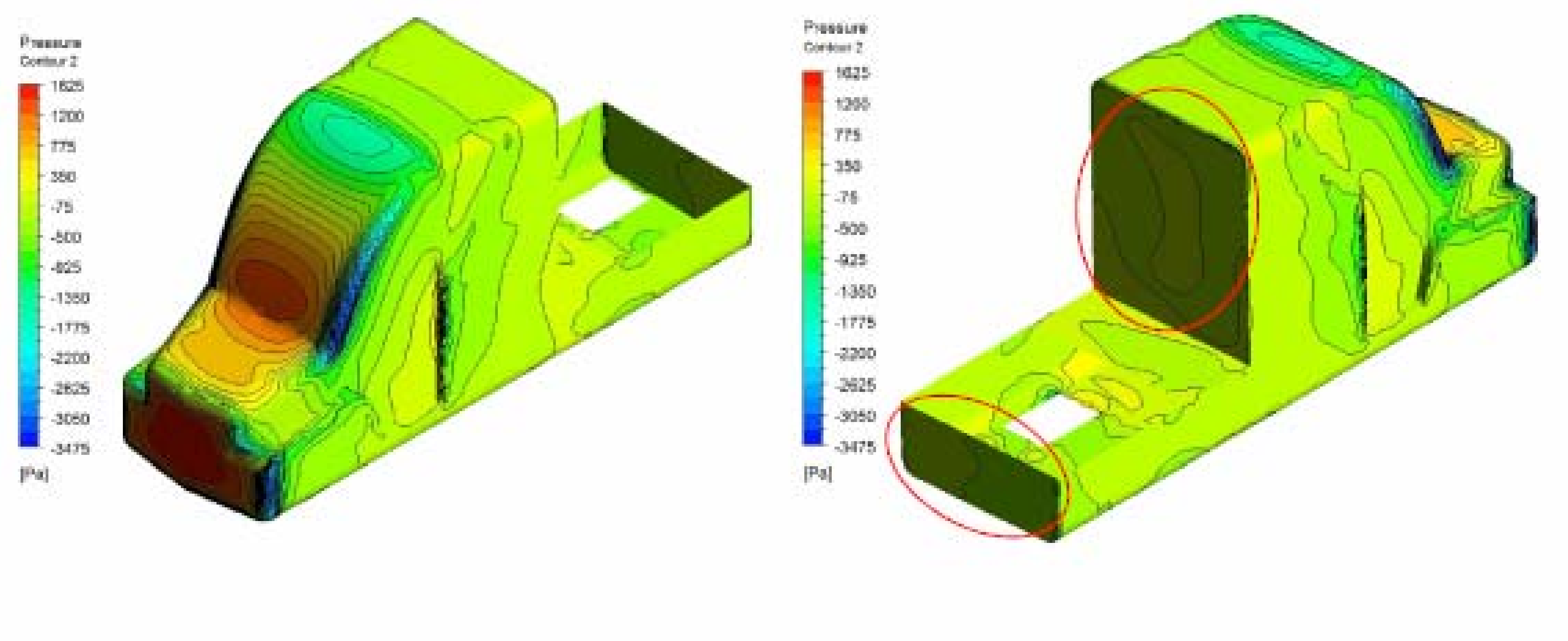
Pressure Coefficient in X-direction

Pressure Contour (symmetry plane)



High pressure on frontal surface and low pressure on the gap, back of trailer, and bottom of the trailer create high pressure drag

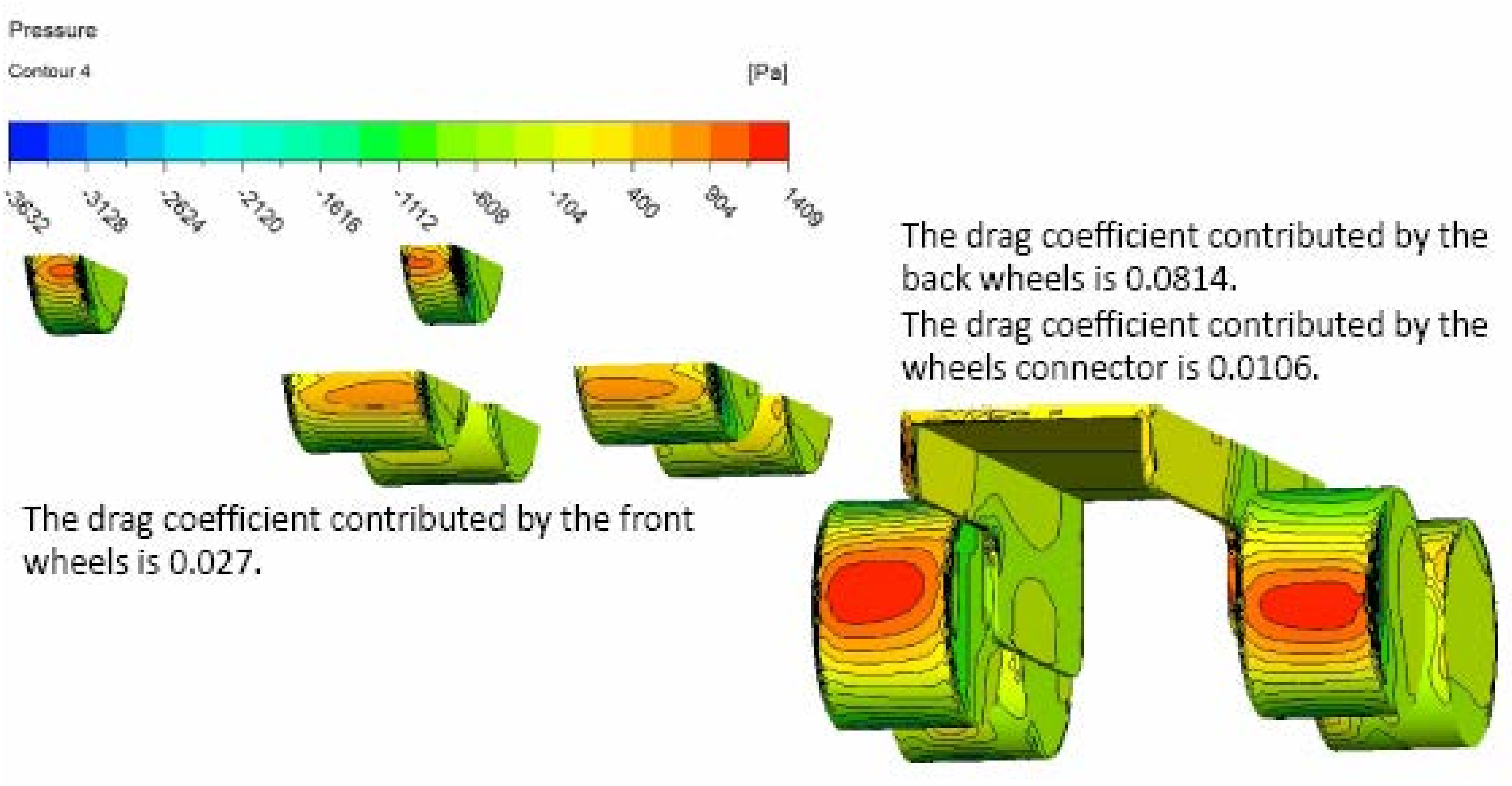
Pressure Contour (tractor)



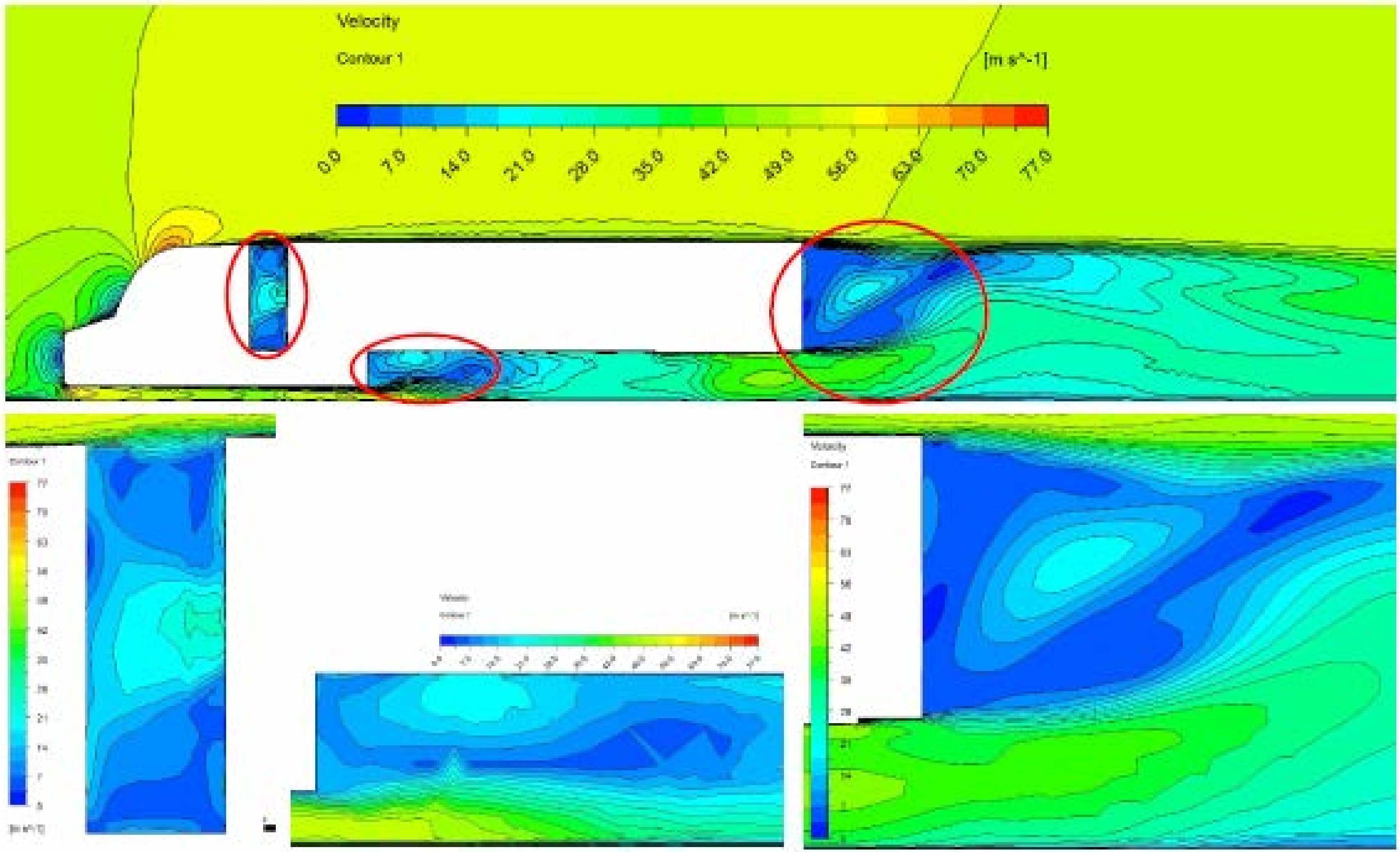
It can be noticed that the pressure on the back surface of the tractor is not symmetrical.

The drag coefficient contributed by the tractor is 0.217.

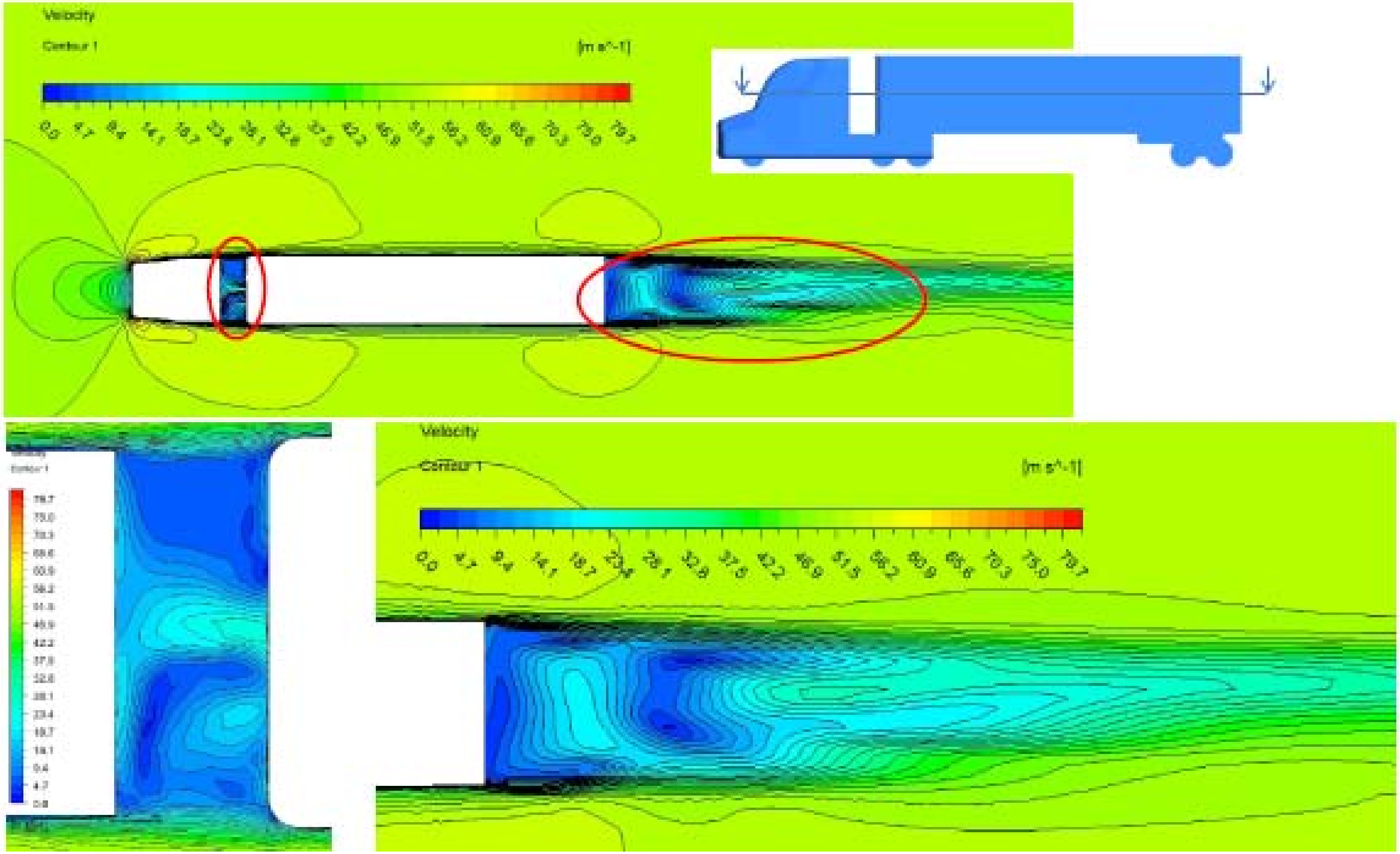
Pressure Contour (wheels)



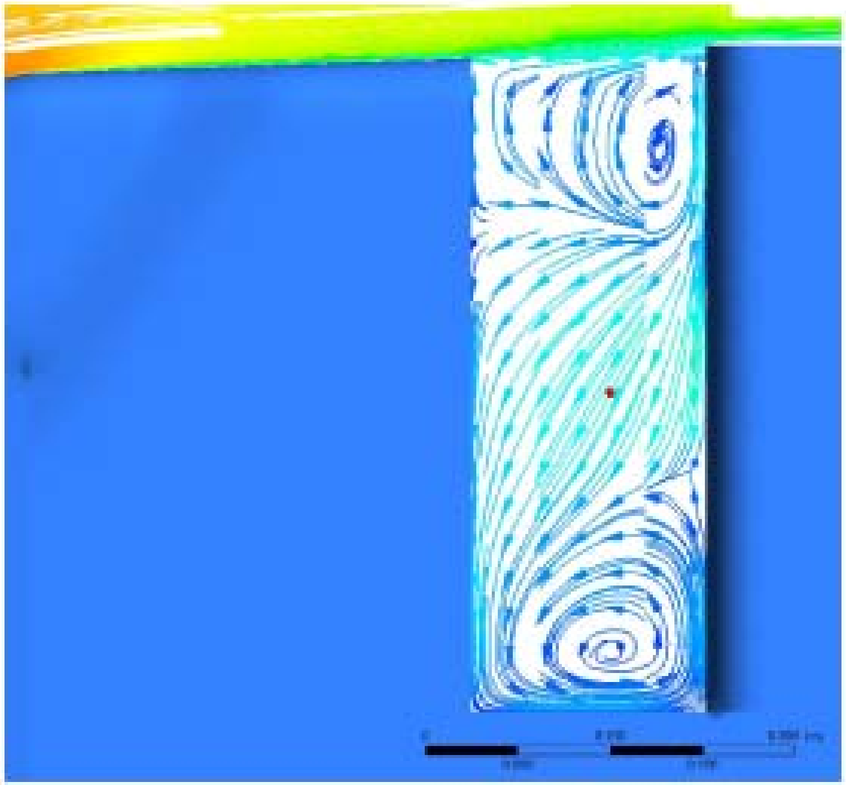
Velocity Contour (symmetry plane)



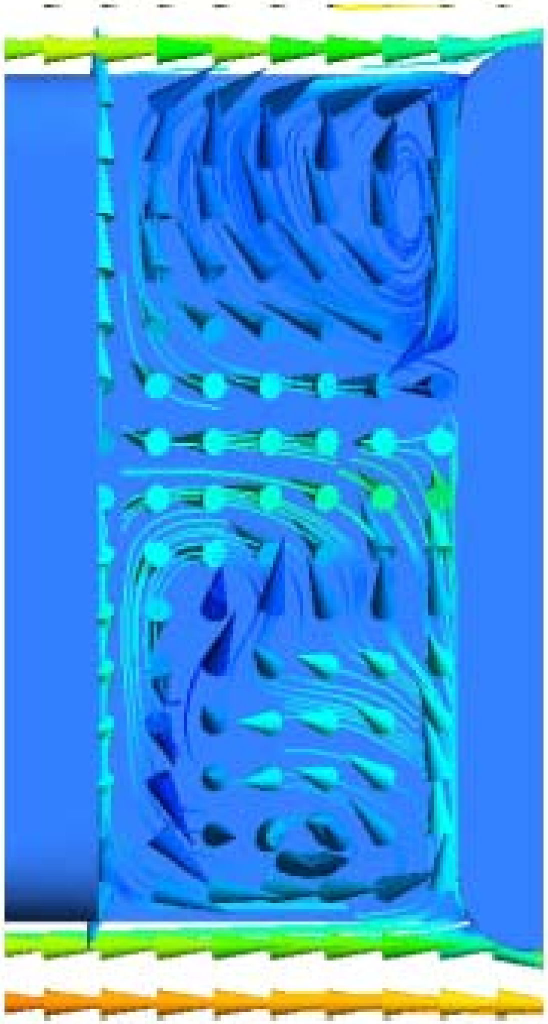
Velocity Contour (Z-plane)



Velocity Streamline (gap)

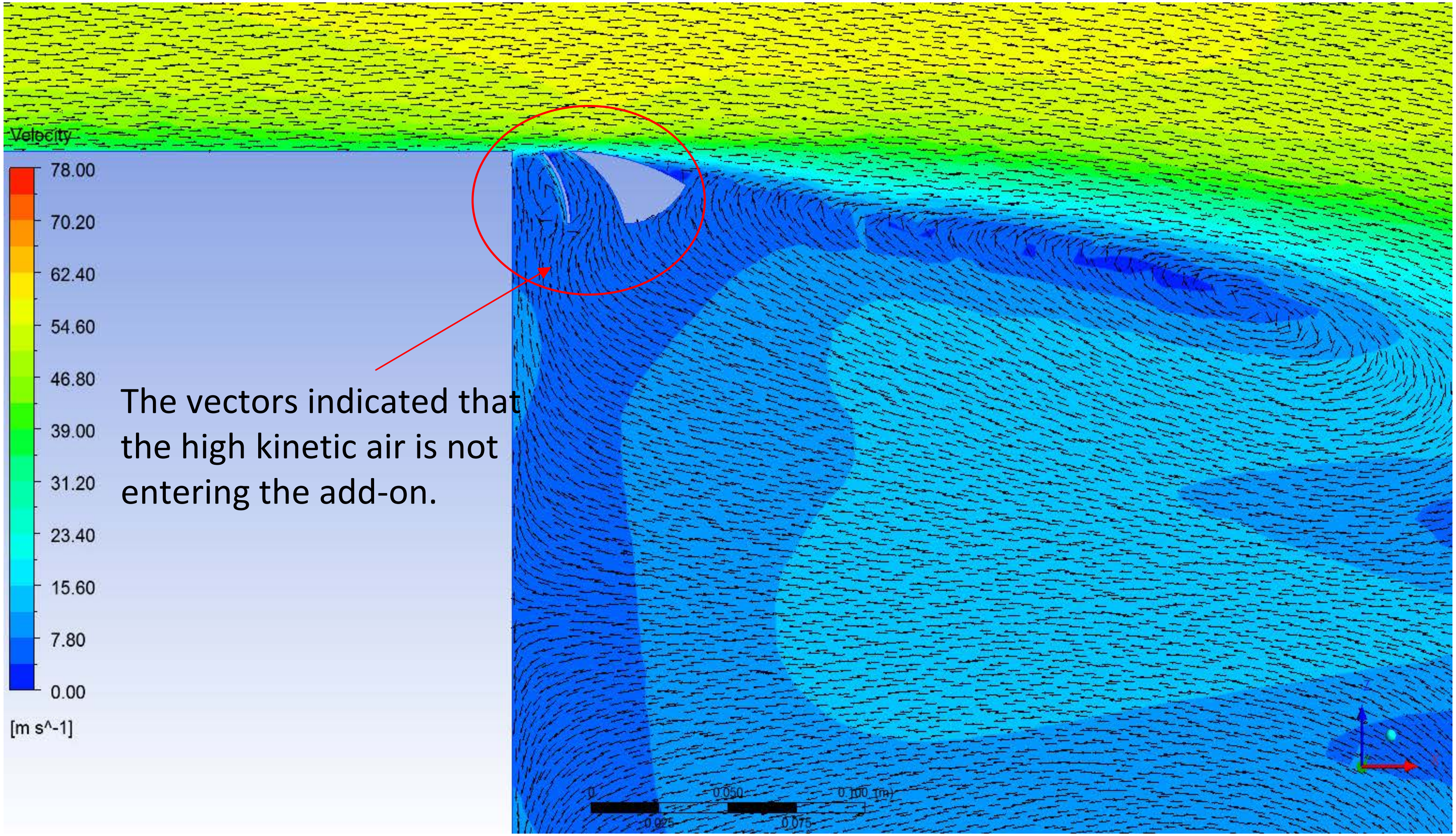


Side View

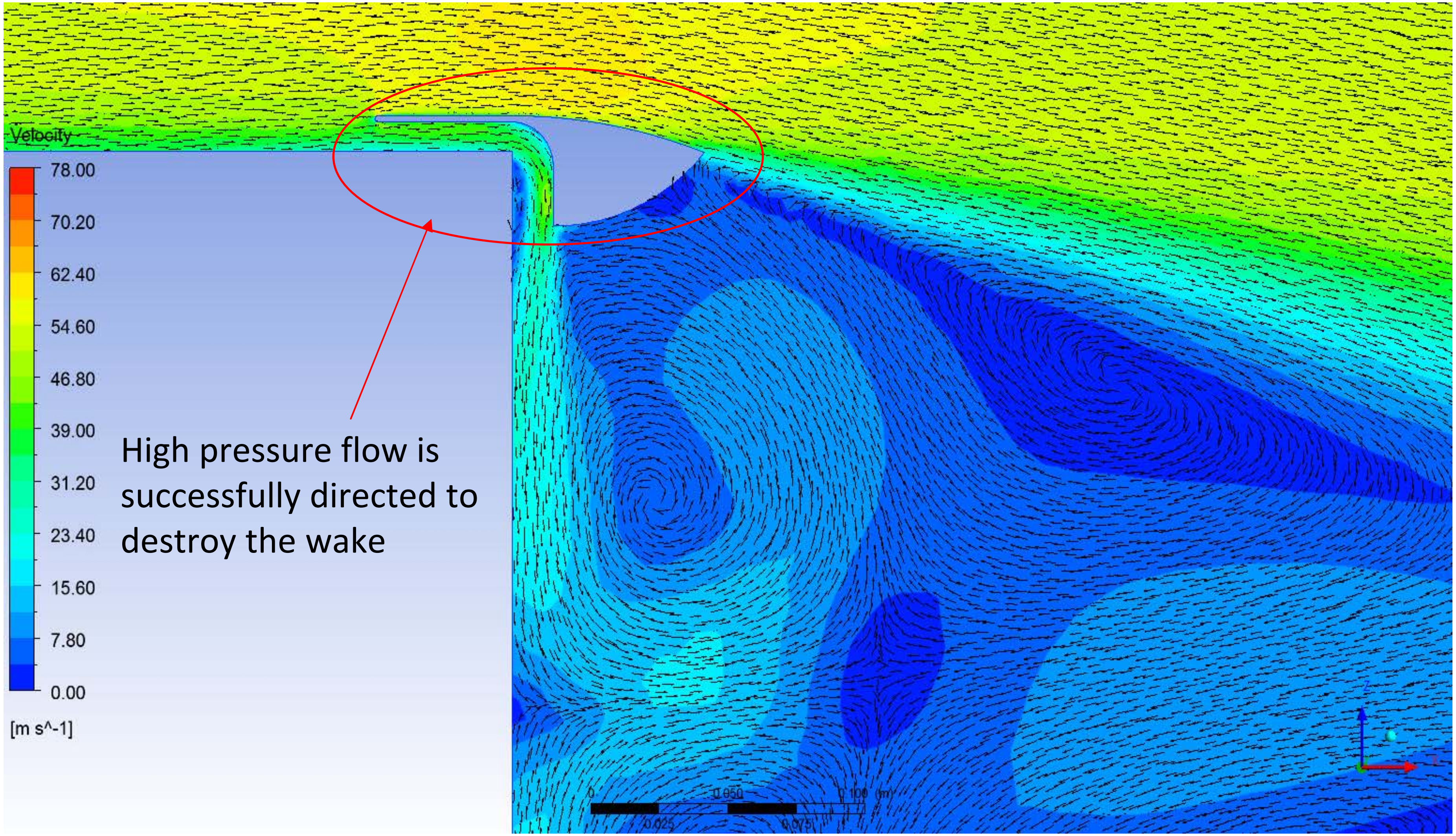


Top View

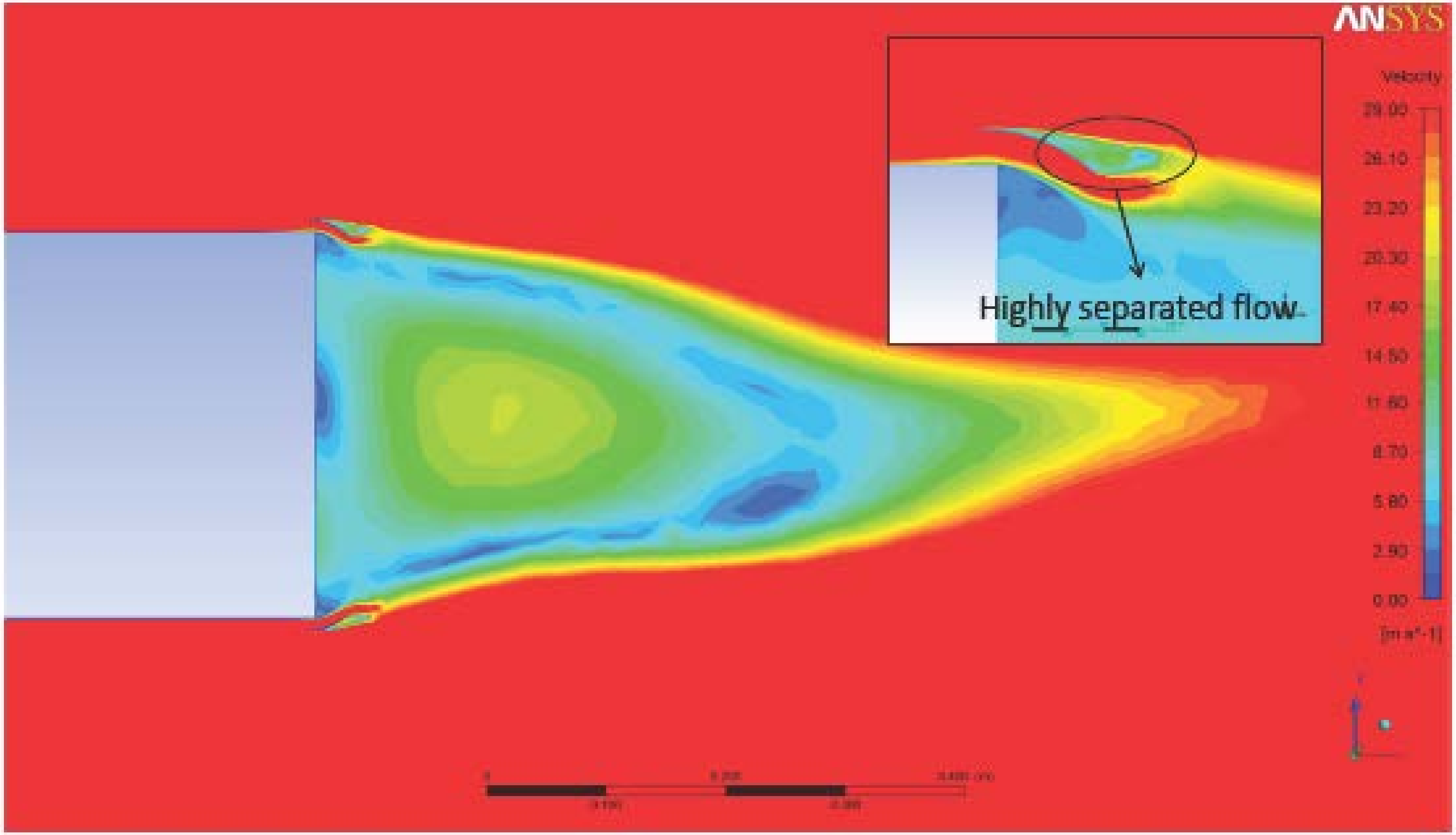
Velocity Contour of Add-on No. 1



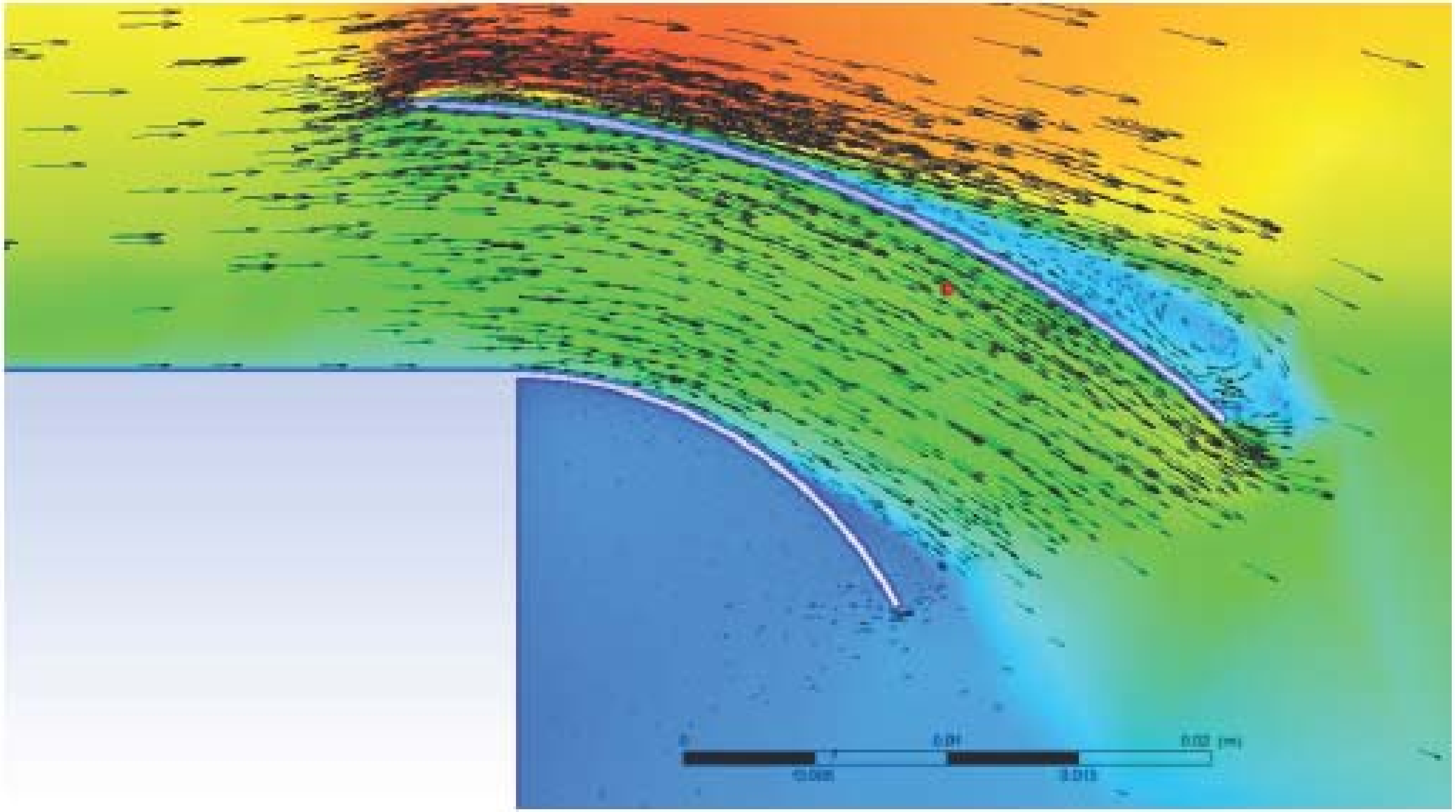
Velocity Contour of Add-on No. 2



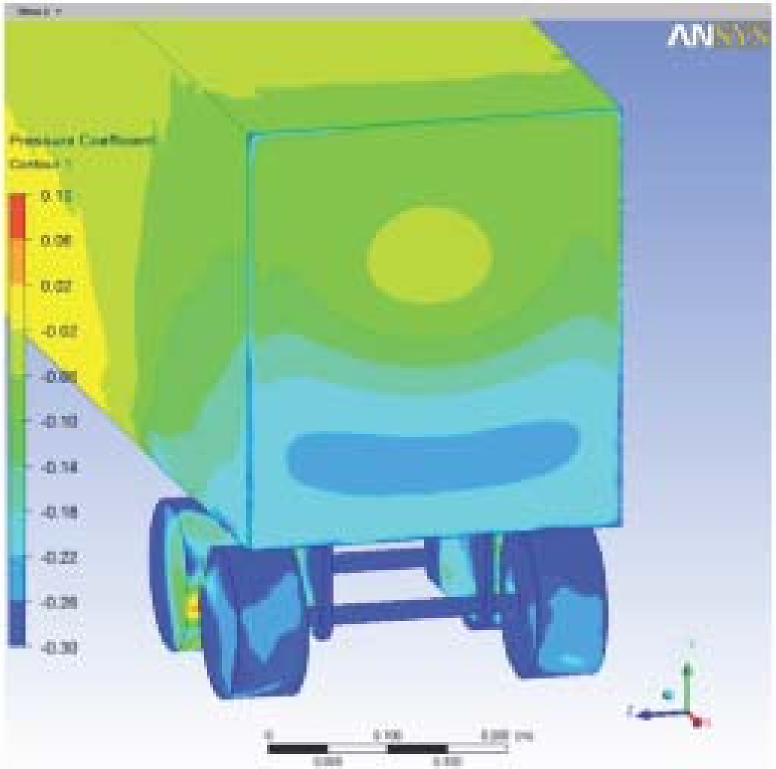
Velocity Contour of Add-on No. 3



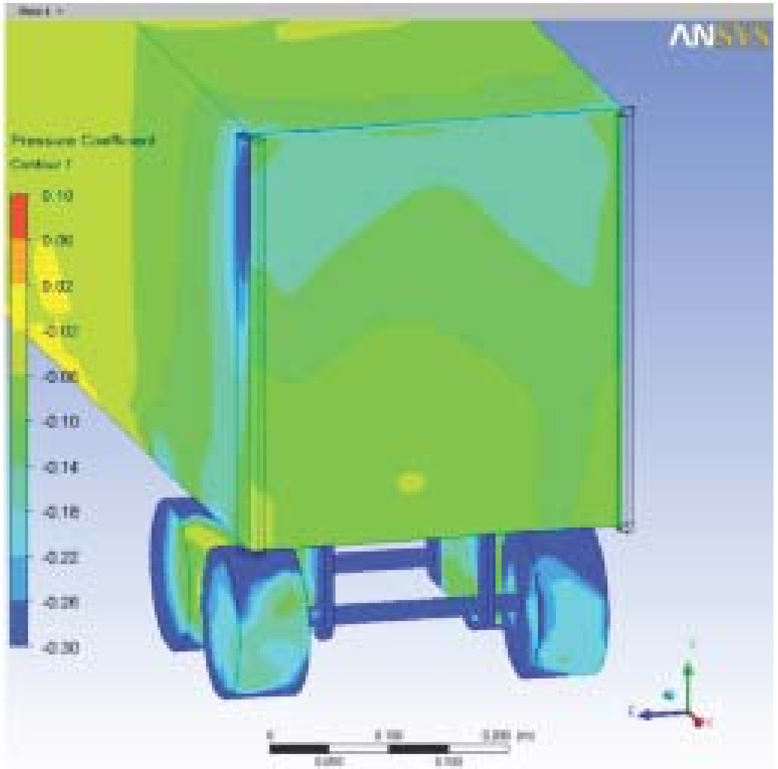
Velocity Vector of Add-on No. 4



Pressure Distribution Comparison

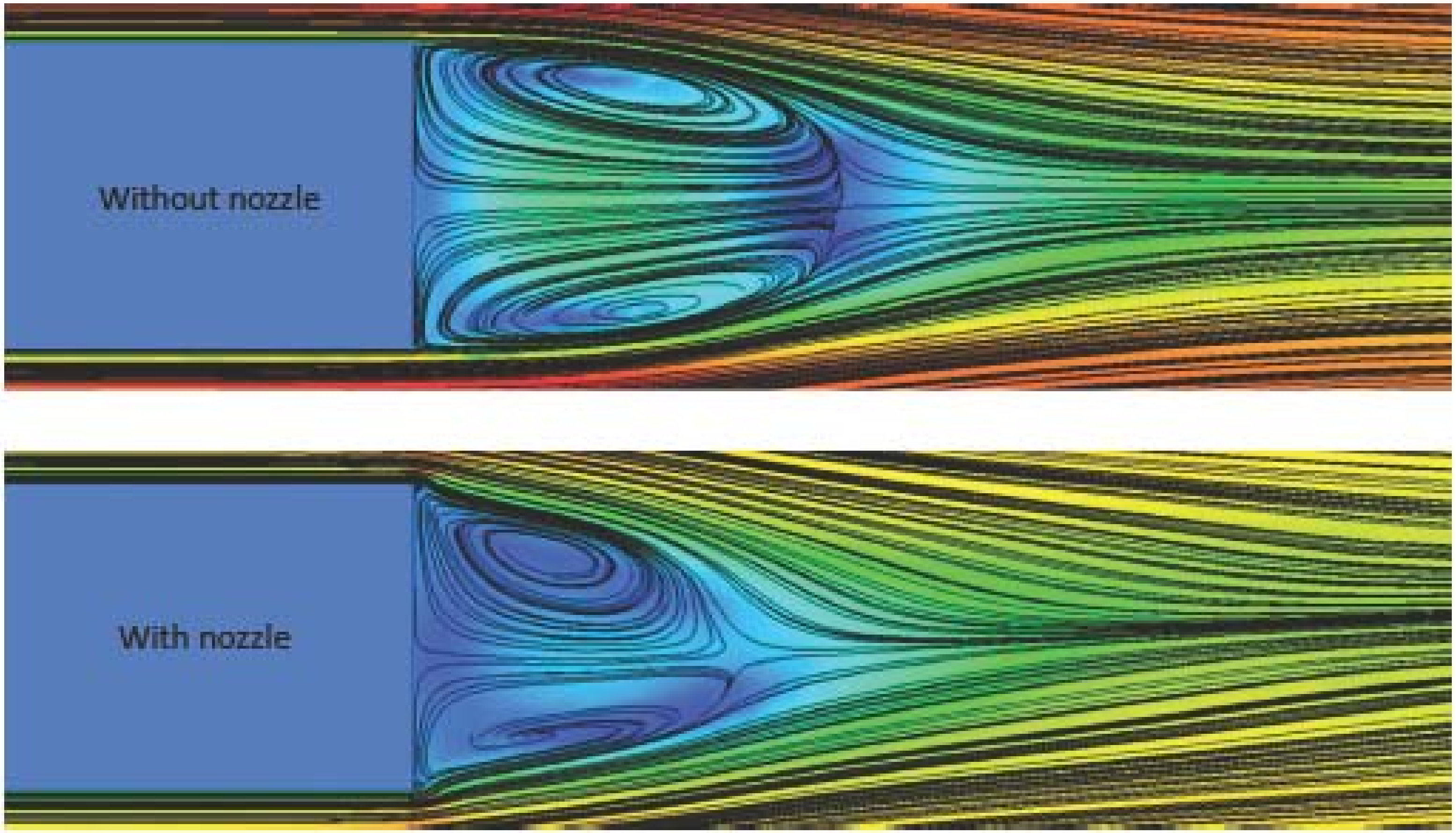


Without nozzle



With nozzle

Streamline Comparison



Road Test

Road Test

- Germany China USA
- AR=1.4, turning 45D AR=2.0, turning=60D AR=2.0, turning=60D

3.5% at 90kph 10.5% at 100kph underway

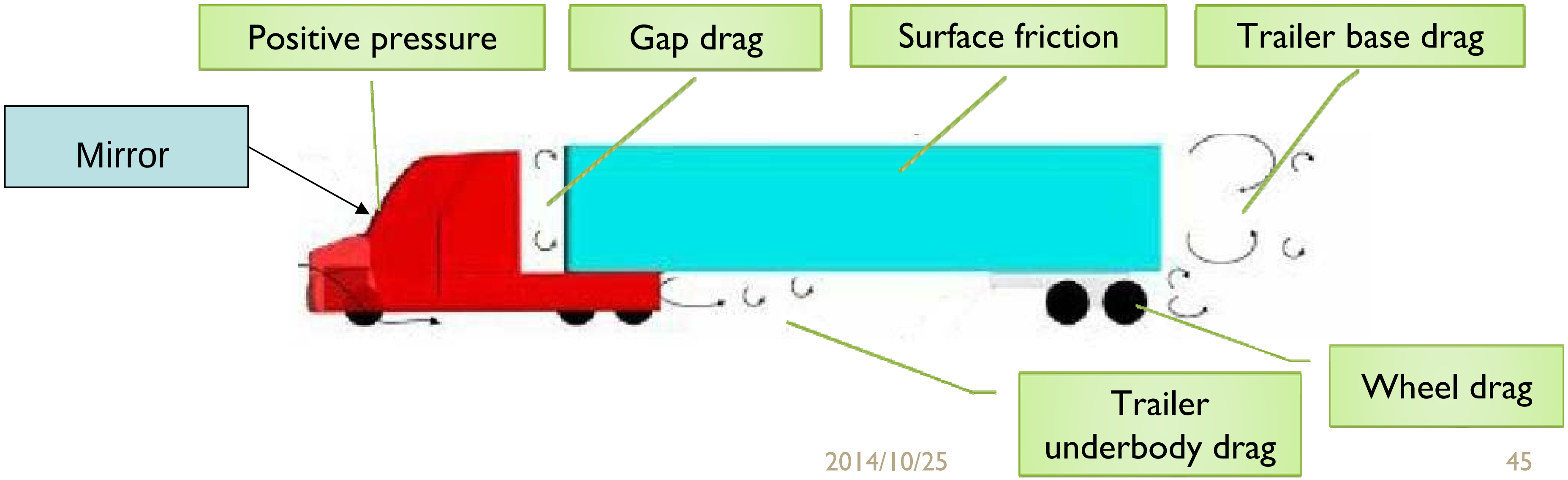
Future Work

Aerodynamic Drag Reduction in Several Areas

- Current trailer rear end drag reduction device can reduce about 10% of fuel consumption.
- Work in progress on future fuel consumption reduction in these areas:

  (1) tractor, (2) gap, (3) surface friction, (4) side skirt

  (4) underbody, (5) wheel, (6) mirror



Future Work -Truck Rollover Reduction

- Each year there are about 30,000 rollovers which claimed 6000 lives and huge economical losses in the US alone.
- Working on truck rollover prevention using wind tunnel testing and CFD (Computational Fluid Dynamics) simulations to understand the physics and methods.
- Wind tunnel testing shows 95% rollover torque can be reduced when using our unique design of trailer base drag reduction device.
- New invention to suppress an inceptive rolling over motion is being studied, and will be patented.