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Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii: Develop and Calibrate a Data Verification Process for External CFD Simulations

Task 7

Prepared For
Hawaii Natural Energy Institute

Prepared By
Sustainable Design & Consulting LLC, UH Environmental Research and Design Laboratory, UH Sea Grant College Program & HNEI

March 2014

HNEI
Hawai'i Natural Energy Institute
University of Hawai'i at Mānoa

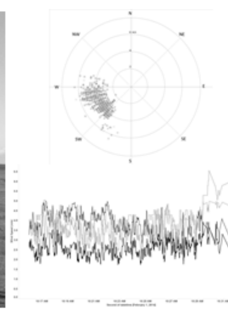
Project Phase 1- 7.A

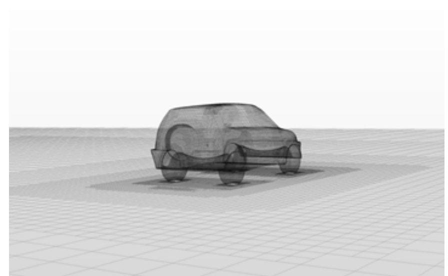
DEVELOP AND CALIBRATE A DATA VERIFICATION PROCESS

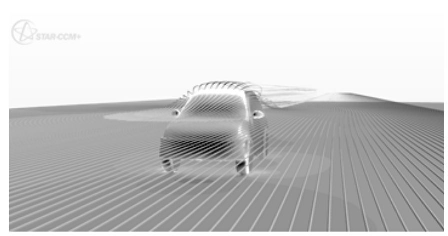
3

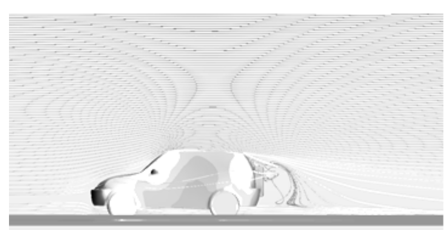
FINAL REPORT

March 3, 2014









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ERDL HNEI

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Prepared for Hawaii Natural Energy Institute

in support of

Contract #N000-14-13-1-0463

March 3, 2014

Prepared by:

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Team effort

The project work performed on the development and calibration of the data verification process was a significant team effort that exceeded the initially scheduled time period. The results of the work effort, however, proved that the additional time was well spent. The experiences gained will help the team to successfully conduct the subsequent phases of the project. The documentation of the work performed and lessons learned will help incoming team members and expedite their learning curve in relevant research efforts.

The research team members that conducted the shake down field work, the CFD test simulations and the data analyses are shown in the photo below. Not shown is the photo is Mr. James Maskrey, MEP, MBA, Project Manager, as well as Dr. Stephen Meder, D.Arch, Director of ERDL.

<u>In photo, from left to right:</u> Sanphawat Jatupatwarangkul, D.Arch, (active in research team through December 2013, now faculty in his native Thailand); Charles Siu, D. Arch candidate; Aarthi Padmanabhan, D. Arch; Tuan Tran, D.Arch; Eileen Peppard, M. Sc.; Christian Damo, B.S. Electrical Engineering candidate; Manfred J. Zapka, PhD, PE; Phyllis Horner, PhD.

EXECUTIVE SUMMARY

This report is the final report on developing and calibrating a data verification process for external CFD simulation. This report represents project deliverable No. 3.

Assessments of wind movements and pressure distributions around buildings by CFD simulations need verification by actual measurements in the field. In order to develop proficiency in verifying CFD results with actual measurements in the field, so-called "shakedown" tests were conducted during which all procedures and phases of the overall verification process could be developed, tested and fine-tuned.

The overall verification process developed and calibrated during the shakedown tests included the following phases:

<u>Selection of the test site and the test structure:</u> The CFD research team identified two candidate sites where the wind movement and pressure distribution around a simple test structure could be measured. The first candidate site (Candidate test site A) was located next to the ERDL laboratory facilities on the University of Hawaii Manoa campus. This candidate site offered the significant advantage of direct access to the test site and therefore easy logistics. Scoping wind measurements, however, revealed significantly varying wind directions and velocities and therefore not the steady wind conditions that were sought by the CFD research team. A second site candidate (Candidate test site B) was located close to the ocean at a distance of about nine miles from the ERDL laboratory facilities. The second test site featured the advantage of easy access and relatively few upwind obstructions, resulting in more steady wind directions and higher constant wind velocities.

After considering alternatives of fixed temporary structures the research team decided to use a vehicle (e.g. a Toyota RAV 4 – SUV) as the test structure that creates obstructions to the wind. The vehicle had the advantage of easy and no-cost deployment.

<u>Performing initial CFD scoping simulations:</u> Initial CFD simulations were performed using most probable wind direction and speeds at the test site. The initial CFD runs used a simplified 3D-geometry of the test structure (e.g. RAV-SUV) and a coarser CFD computational domain and generic physical setting. The main objective of the initial CFD runs was to identify locations of higher velocity and pressure gradients around the test structure so that wind speed sensors and pressure tubing terminal units could be deployed appropriately at these locations. The initial CFD results were also used to determine the predicted differential pressures around the test structure, so that the pressure transducers ranges could be selected correctly.

<u>Selection of the instrumentation</u>: Three properties were measured in the verification process: wind direction, wind speed and differential pressure. The team had ready access to six high sensitivity

anemometers (wind speed sensors) and one weather station. The anemometers were used to measure wind velocity but not wind direction around the test structure (RAV-SUV). The weather station was used to measure the wind direction and velocity of the wind approaching the test structure. The research team had to identify and procure suitable differential pressure transducers which offered the high sensitivity (e.g. low pressure ranges) required to detect the small pressure differentials around structures at typical (normal) wind conditions. The selection and procurement of suitable pressure proved to be a considerable challenge, since the small pressure differentials on the building envelope under normal wind conditions require a very high resolution of pressures (e.g. low differential pressure ranges). It was found that there are few vendors who offer low differential pressure transducers. After identifying about ten candidate differential pressure transducers the team selected two vendors, Setra (US company) and Halstrup-Walcher (German company), based on a favorable cost-benefit ratio.

The team selected a signal multiplexer by National Instruments (NI) as the data acquisition system. The data acquisition hardware was complemented by proprietary NI signal conditioning and analysis software.

Preparation of the instrumentation in the laboratory: The anemometers, differential pressure transducers and the data acquisition were prepared and tested under laboratory conditions before being deployed in the field for the shakedown tests. The wind sensors and pressure transducers required correct signal excitation and the measured signals required calibration and signal condition. A simple ad-hoc wind tunnel was used to establish qualitative wind speeds and pressure differentials. The preparation and fine tuning of the instrumentation operation was finished in two stages, each following preceding field test days. The lessons learned from the first and second test days were used to identify shortcoming in instrumentation deployment, signal management and data analysis. The final instrumentation set-ups were used in the third and final day of field tests.

Deployment of the instrumentation in the field: Tests were conducted at the site on three days, spread over a period of six weeks, between December 2013 and February 2014. On each of the three test days, important lessons were learned by the CFD research team. The team developed proficiency in test planning, test execution, instrumentation set-up and retrieval and data acquisition. The team developed a test check-list that will be of significant help to plan and conduct the remaining field test of the project and also serve to document field test procedures for future projects at ERDL. The field test concluded with a successful third day of testing when a comprehensive data set for two test scenarios was collected.

Final data analysis: A comprehensive data analysis process was applied to the results of the third and final day of field testing. A variety of unsteady wind speed and differential pressure signals required the development and application of specific filtering procedures in order to produce statistically robust data sets to be used in the comparison of the field data and final CFD simulation results.

Final CFD simulations: The final CFD simulations depicted a more precise assessment of wind movement around the test structure (e.g. RAV-SUV) and of the pressure distribution on the test structure envelope. The final CFD simulations used the prevalent direction and speed of the approaching wind determined in the field tests. These representative wind conditions were used as CFD boundary conditions. The final CFD also used a more refined mesh and 3D-model of the RAV-SUV. The final CFD simulations provided the data for the comparisons of the theoretical (calculated) wind velocity and pressure data with the actual field measurements of these properties. In addition to contoured property slices the final CFD simulations used small data grid to extract averaged CFD wind velocity and pressure data for those locations in the computational domains that corresponded with the actual locations of the sensor and pressure tubing terminals.

Comparison of CFD predictions and actual field measurements: The results of CFD simulations and actual field measurements of wind velocity and differential pressures around the test structure were compared. The team identified good correlation between CFD predicted wind velocities and the actual field measurements. The comparison of CFD predicted and actually measured differential pressures resulted in lesser correlations between theoretical and actual data. The team identified measures or procedures that might decrease diverging theoretical and actual values for velocities and pressures in future test. In general, the team results indicated a better agreement between theoretical (predicted) and actual wind velocity than for differential pressures.

Summary: The work on the development and calibration of a data verification process resulted in a much longer time and more effort spent than was originally allocated to this project task. The team could, however, was able to make significant advances in its proficiency to prepare and deploy instruments and carry out the data acquisition and analysis for the physical properties that are of importance to the subsequent field test of the CFD project. The lessons learned and the process and procedures developed and fine-tuned during the work have been thoroughly documented. The resulting documentation will be available to subsequent phases of the project and also to incoming members of the project team. Furthermore, the documentation will provide essential documented processes and procedures for future project work of ERDL.

TABLE OF CONTENTS:

SECTION 1: SELECTION OF THE SHAKE-DOWN TEST SITE AND SIMPLE TEST STRUCTURE

The first phase of the work on a data verification process was concerned with the design of the shakedown testing and especially with the selection of a suitable test site. The shakedown testing was carried out to establish operations proficiency of the CFD research team to carry out complex testing in the field. Furthermore the shake down testing showed the reliability of wind velocity and pressure sensors and data acquisition under field conditions. This section provides a description of the selection process of the test site and also a selection of a suitable wind obstruction around which the shakedown testing for external CFD was carried out.

1.1 Candidate Test Sites and selection of the site

The two main criteria for the selection of a suitable test site were:

1. Ease of deployment of the test equipment
2. A site with sufficient wind, which means a site with largely unobstructed wind approach.

An initial scoping suggested two candidate test sites. Test site one (Shakedown Candidate Test Site A) was located on a grassy area next to the School of Architecture building on the University of Hawaii Manoa campus. This site offered an easy deployment of the wind and pressure sensors. A second candidate test site (Shakedown Candidate Test Site B) was located on a vacant lot close to the Pacific Ocean, some nine miles away from the School of Architecture where the CFD laboratory is located. Figure 1.1.1 shows the two candidate test sites.

An initial wind velocity scoping measurement test at the test site one suggested that winds vary considerably in direction and strength, so it was deemed that the wind conditions at this site were not sufficient. A sample record of wind direction and speed measured at candidate test site A is depicted in Figure 1.1.2. Wind was measured only on days when wind movement could be detected; on several days no appreciable wind could be detected at all. The average wind velocity at test site one was found to be in the order of 1.4 m/sec, with wind directions that changed significantly. The wind speeds coupled with the significant shifts in wind direction at this candidate test site were not considered appropriate for test purposes. The wind conditions at test site 2, Shakedown Candidate Test Site B, were found to be much more steady and predictable in terms of wind direction and speed.

Consequently test site two (Shakedown Candidate Test Site B) was selected for the shake down tests.

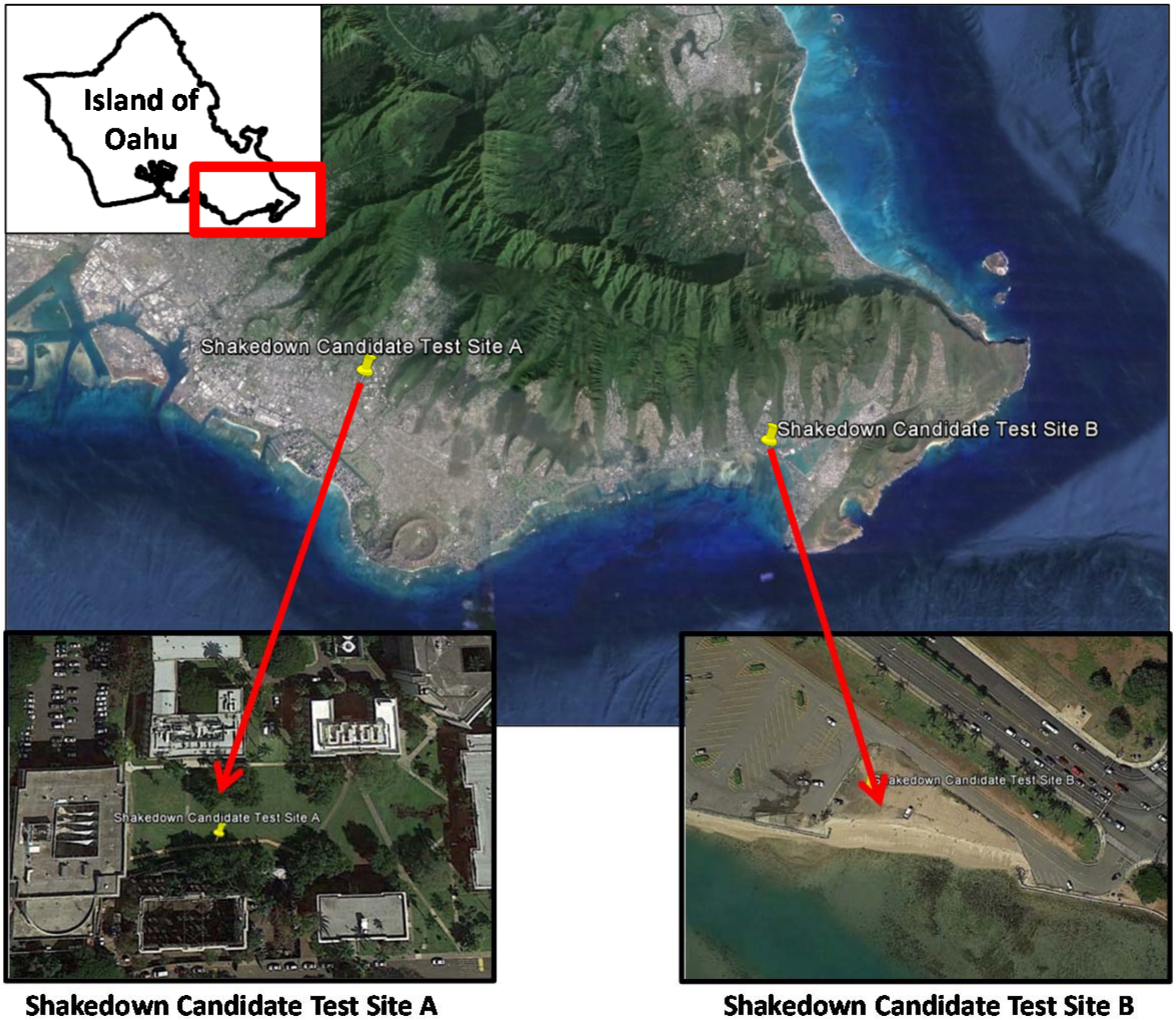


Figure 1.1.1 Two Shakedown Candidate Test Sites A and B

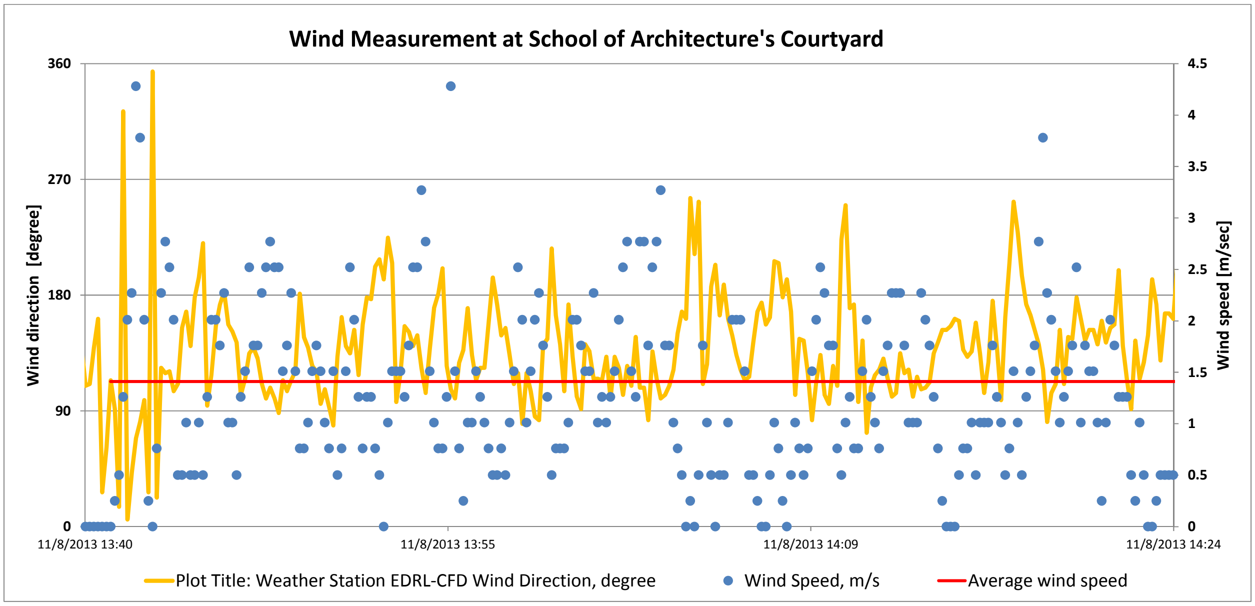


Figure 1.1.2: A sample record of wind direction and speed measured at the candidate test site A

1.2 Selection of Simple Structure for Wind and Pressure Distribution Measurements

For the shake down tests, the qualitative and quantitative distribution of wind and pressures were measured around a test structure. The test structure caused an obstruction in the wind stream and therefore developed local variances in pressures and wind velocities and stream lines. For the shakedown tests the test structure was selected with a medium size-- not a too large size in order to provide easy access to measurement points at all sides of the structure and not too small since the test structure needed to create a sizable obstruction to the wind movement. In addition the test structure needed to be easily transportable and be installed at the test site.

It was found that a vehicle would serve as a mobile test structure and also would provide enough obstruction to the wind flow, while all sides of the structure could be easily accessible. The small SUV (RAV4) of a member of the CFD research team served as the test structure of the shake down tests. The vehicle is shown in Figure 1.2.1. where several stands for wind sensors are arranged around the vehicle.

A more complete description of the test site and the test structure (the SUV) is provided in Appendix A.

Figure 1.2.1: The RAV-SUV used as the test structure

SECTION 2: CFD SIMULATION OF A SIMPLE TEST STRUCTURE

This section describes the creation of the CFD 3D-model of the simple test structure (RAV SUV) as well as the preparing and execution of the CFD analysis.

2.1 Constructing the 3D-Structure of the test structure

For the purpose of CFD simulation research, Autodesk Inventor Professional was chosen for 3D CAD modeling of the test structure. Inventor was preferred over the other competitors because of its CAD file conversion and compatibility with the CFD software STAR-CCM+ used for the CFD analysis of the shake down tests.

Modeling a car or any forms with curvature in Inventor requires knowledge of creating a network of splines to derive surface patches. Stitching the surface patches together fabricates the 3D objects which can then be exported to the CFD software for subsequent simulation. Objects for CFD simulation should be simplified for the type of analysis conducted. For this instance, only the exterior geometric volume was modeled, considering that only external CFD was being simulated and verified with field measurements. Refer to **Figure 2.1.1** for a snapshot of the completed model. Refer to **Appendix E** for a description of the detailed CAD modeling process and the importation of the CAD model into the CFD software.

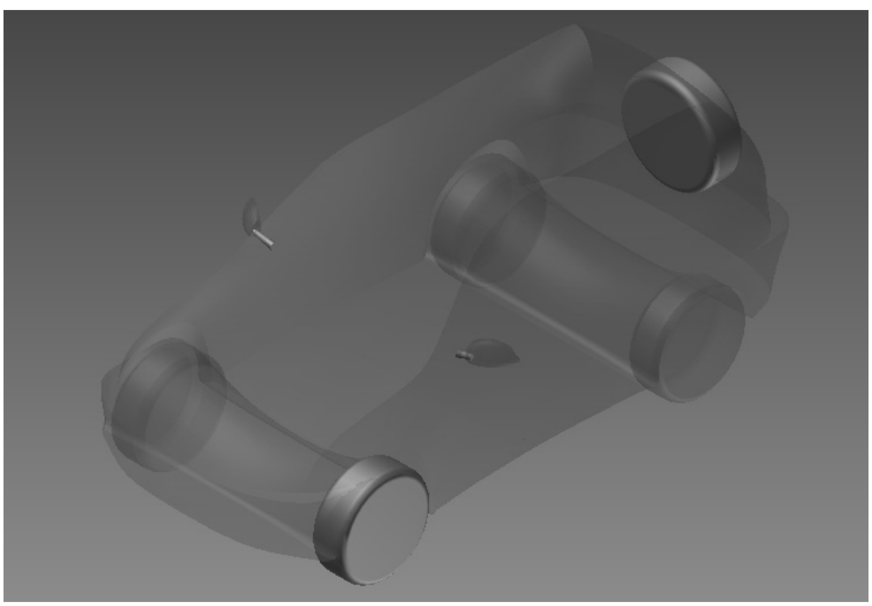


Figure 2.1.1: Rav4 3D Model created with Autodesk Inventor Professional

2.2 Carrying out Initial CFD Analysis to Select Placement of Sensors at the Test Site

The initial CFD analysis allowed for estimating the airflow movement around the car and the resulting the pressure distribution on the car surface. The main objective of the initial CFD test was to determine where to locate the anemometers and differential pressure terminals. The placement of the sensors should occur at those places where relative large wind velocities and pressure gradients exist. This means that locations were identified where relative large scalars of wind velocities and differential pressures exist. To reiterate, the objective of the shake down testing was to acquire operational know-how of measuring, data logging and data analysis of wind speed and direction as well as differential pressures. Therefore, in order to maximize the readings, locations around the test structure (RAV-SUV) were selected for the placement where high or high-gradient of wind speed and pressure differentials exists. The locations were also selected based on initial CFD analysis where the anemometers and differential pressure transducers would work properly within their signal ranges.

For the initial CFD simulations a wind approach direction and speed was selected that was based on historical weather data at the test site. The final CFD simulations were then carried out with the actual wind speed and directions measures in the field.

For the initial CFD simulations, two orientations of the test structure (RAV-SUV) relative to the wind approach were performed. One CFD simulation was performed with a wind approach direction parallel to the longitudinal axis of the RAV-SUV (see Figure 2.2.1); this is referred to as Wind direction 1. The second CFD simulation was performed with a wind approach direction perpendicular to the longitudinal axis of the RAV-SUV (see Figure Fig.2.2.2). For simplification, the wind velocity for the inlet boundary was set constant at 5m/s. Steady state RANS-based Realizable k-e turbulence model with two-layer for wall treatment was used (Appendix E2).

2.3 Interpreting the Initial CFD Results to Select Test Scenarios

The initial CFD results were used to identify and select the most appropriate locations for the anemometers and differential pressure transducer terminals. Using the identified locations of the anemometers and pressure terminals for the differential pressure transducers of sensors ensured that data could be recorded within their reading ranges and accuracy thresholds.

The results of the initial CFD simulations for wind velocity and pressures were visualized with contour slices at an elevation of 3 feet. This height was selected because the anemometer stands were also designed to place the anemometer sensors at the same 3 feet elevation. Since the CFD research team had only a limited number of anemometers and pressure transducers typically several test scenarios were used and sensors where shifted to different locations around the RAV-SUV in order to test as many possible scenarios that could be accomplished during the different days of testing.

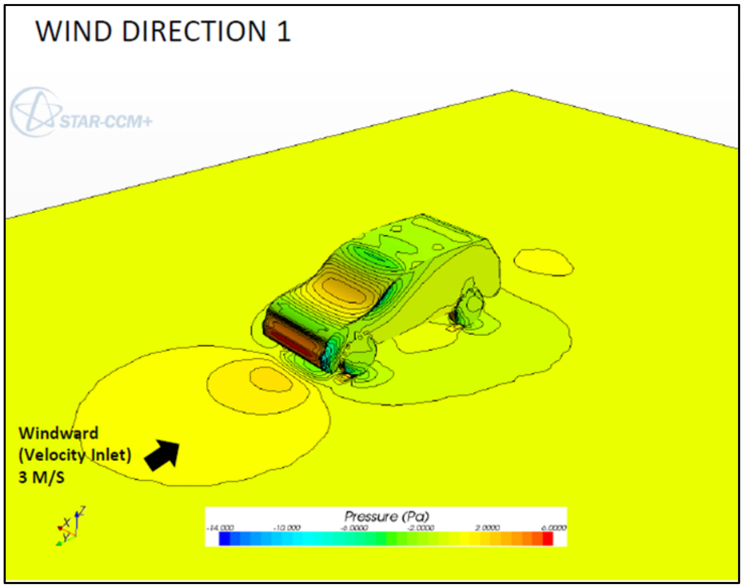


Figure 2.2.1: Initial CFD analysis results showing pressure distribution on the car surface and the ground (the parallel approach wind direction; Wind Direction 1).

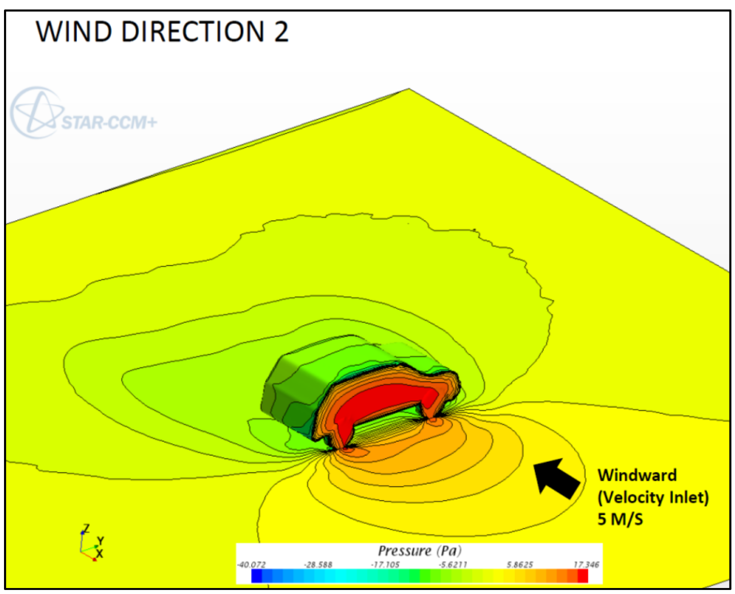


Figure 2.2.2: Initial CFD analysis results showing pressure distribution on the car surface and the ground (the perpendicular approach wind direction; Wind Direction 2)

Figure 2.3.1. shows a sample visualization of two contoured slices which depict the wind velocity and pressure results of the initial CFD simulations. As can be seen in Figure 2.3.1. sensor locations were placed in areas of higher wind velocity or pressure gradients.

Based on the initial results, locations close to the edges of the car, where the air accelerates as it passes the obstruction (The RAV-SUV), were chosen for anemometers to capture the for high wind velocities. Stagnation regions at the upwind sides of the RAV-SUV were chosen for pressure terminal to capture high pressures, while downwind regions were selected for the location of the low pressure terminal. In order to allow correlation between different scenarios, at least one anemometer was kept at the same location between two test scenarios for a given approach wind direction.

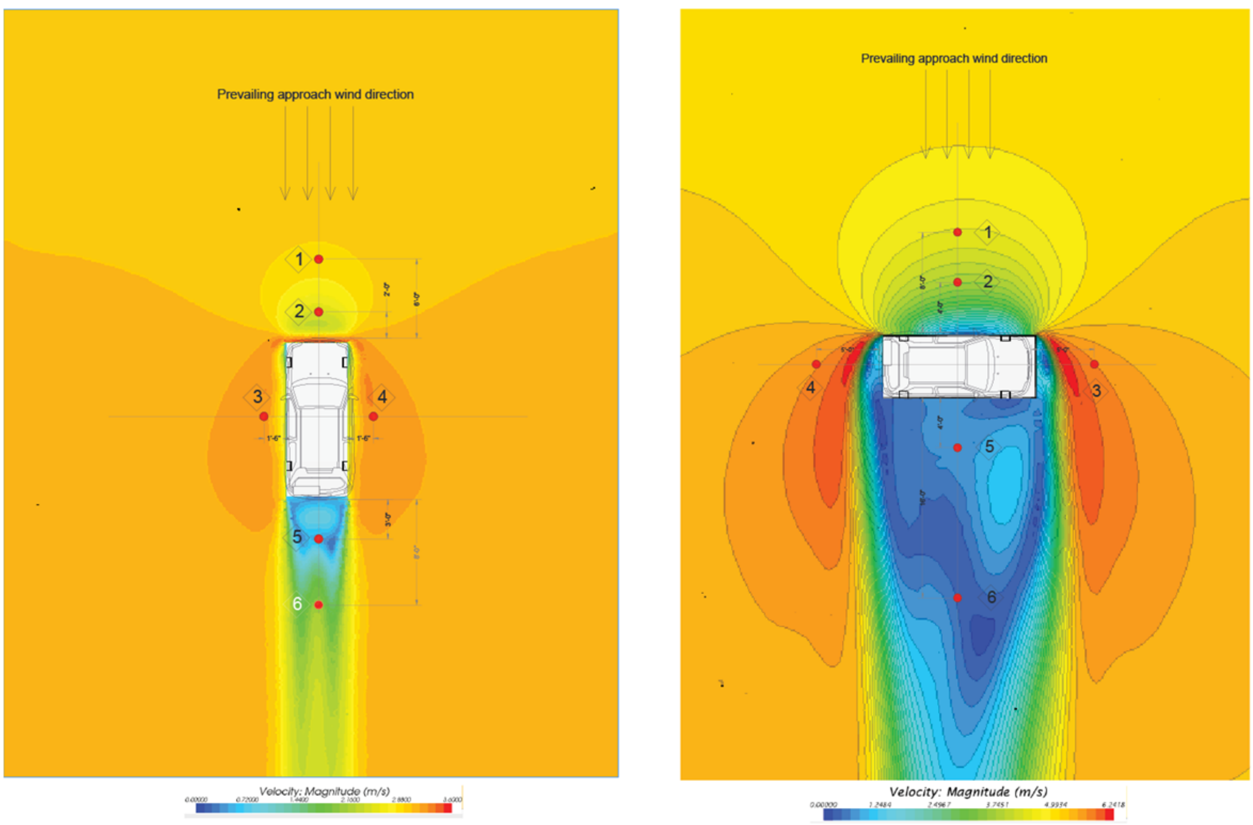


Figure 2.3.1: The example of sensors locations mapping on the initial CFD analysis for measuring test scenarios.

2.4 Lessons Learned - Autodesk Inventor Professional

While gaining proficiency in the modeling process with Autodesk Inventor Professional, various challenges arose that affected the process of CAD modelling and subsequent import of CAD model into the CFD software. Listed below are several simple guidelines to for the CAD modelling which should be implemented early in the project:

- Verify axes are correct for CAD modeling and simulation (X, Y, and Z).
- Inventor defaults the Y axis as the vertical component, rather than the Z axis in other modeling applications.
- Verifying CAD plans do not cause errors when exporting as a parasolid file. This can easily established by importing the CAD file, create a test mass, and export as a parasolid (.xt) file.
- CAD plan information should be reduced to provide only the necessary components for modeling. Excess amount of data can cause Inventor to crash or delay loading.
- Understand all elements in Inventor are interconnected, deleting or editing a certain element can cause errors to occur.
- Surfaces are acceptable for CFD simulation.
- Surfaces can intersect if using STAR CCM+ surface wrapping.

SECTION 3: INSTRUMENTATION

This section describes the process of identifying and selecting the instrumentation used in the validation of the CFD simulation results.

3.1 Candidate Instrumentation Identified

Three types of sensors or transducers and the data acquisition hardware had to be chosen for the field measurements.

Types of sensors / transducers:

1. Anemometers
2. Differential pressure transducers
3. Weather station (for the determination of the background weather conditions)

Data acquisition:

- Data logger and multiplexer

Anemometers and weather station:

Sufficient anemometers and one weather station were available from earlier field test.

Differential pressure transducers

The CFD research team had to identify and select differential pressure transducers, which could measure the expected low differential pressures across the wind and leeward sides of buildings under normal wind conditions.

The team encountered challenges to identify suitable pressure transducers since the expected differential pressures expected between the windward and leeward sides of buildings under normal natural ventilation are very small when compared with pressure differentials in regular wind engineering design.

A literature review and interviews with researchers in the filed suggested that pressure differential resulting from normal wind movement around buildings are very low, such as 8 Pa were measured between. Since accuracy is typically a percentage of full scale the full scale for candidate pressure sensors was selected as 25 Pa.

There are very limited pressures transducers on the market that are able to detect pressures as low as 5-8 Pa. A search and performance review of differential pressure transducers suggested to following ten suitable differential pressure units:

1. Dwyer Instruments, Series 616KD Differential Pressure Transmitter
2. Greystone LP3 Series Low Pressure Transducer
3. Halstrup-Walcher P26 Pressure Differential Transducer
4. Magnehelic LPG0025 Differential Pressure Gauges
5. Motorola MPXV5004G ultra-low-pressure measurements
6. Omega PX160 Series Low Pressure Transducer DifferentialMeasurements of Clean Gases
7. Sensirion Inc. SDP600 Series: Low differential pressure transducer
8. Setra Model 264 Differential Pressure Transducer
9. Siemens QBM65 differential pressure sensors for air and non-aggressive gases
10. Validyne DP103 Very Low Pressure Variable Reluctance Sensor

<u>Data logger and multiplexer:</u>

The CFD team opted for only one supplier, National Instruments, because of previous experience and good purchase conditions.

3.2 Instrumentation Selected and Used for the Field Measurements

<u>Differential pressure transducers</u>

As discussed before, the CFD research team had ready access to several anemometers and one weather station. Therefore the only instrumentation that needed identification and selection were the differential pressure transducers. After interviews with vendors and specific performance and cost comparisons the CFD research team selected two products:

1. Setra Model 264 Differential Pressure Transducer
2. Magnehelic LPG0025 Differential Pressure Gauges

Figure 3.2.1 shows the Setra Air Pressure Transducer Model 264 , which has a range of zero to 0.1 inches of water column (zero to 25 Pascals) and 0.5% accuracy of full scale (FS). The Setra 264 comes with either a voltage output signal or a current output. Figure 3.2.2. shows the Halstrup Walcher P26 pressure transducer (shown in Figure 3.2.2.) with a range of zero to 0.055 inches of water column (zero to 10 Pascals) and 0.5% accuracy of full scale.

Figure 3.2.1..: Setra Differential Pressure Transducer Model 264

Figure 3.2.2.: P26 Halstrup-Walcher Pressure Differential Transducer

Figures 3.2.3 and 3.2.4 show the installation of the pressure transducers in the field and one pressure tube terminal unit that was fabricated for the differential pressure measurements. The pressure tube terminals were designed and built for this project. They consist of a 1 ¼ inch PVC pipe section of 12 inch length. The pipe section is sealed at both ends by means of pipe caps. Approximately 15 3/16-inch holes were drilled into the pressure tube terminal unit. The holes were evenly distributed around the circumference and length of the pipe section. The function of the pressure tube terminal unit is to provide an averaged pressure reading by evening out possible small scale eddies in the vicinity of the tubing ends, which could generate local velocity variations. A brass coupling connects the pressure tubing to the pressure tubing terminal unit. Since a differential pressure reading is recoded between two locations around the test structure, two pressure tubing terminal units are connected to the differential pressure transducers. One tube connects to the high pressure port and the other to the lower pressure port.

Figure 3.2.3.: Dr. Tuan Tran sorting the Setra and Halstrup-Walcher differential pressure transducers with the signal multiplexer (NI USB-6341) device (shown in the rear of the car).

Figure 3.2.4.: Pressure tubing terminal unit used to provide undisturbed and averaged pressure conditions for the Setra and Halstrup-Walcher differential pressure transducers.

<u>Anemometers and weather station:</u>

The <u>weather station</u> used was an Onset HOBO U30 device, powered by its 4-volt, 10-AHr on-board battery and 1.2W solar panel. Data acquisition is onboard the U30 and was downloaded with USB cable to a laptop computer using Hoboware software.

The height from the sensor to the ground is 9 feet. The U30 weather station consists of two sensors: wind speed sensor S-WSA-M003 and wind direction sensor S-WDA-M003 (seen in Figure. 3.2.5). Figure 3.2.2 depicts the set-up of the U30 weather station on the 9 feet stand.

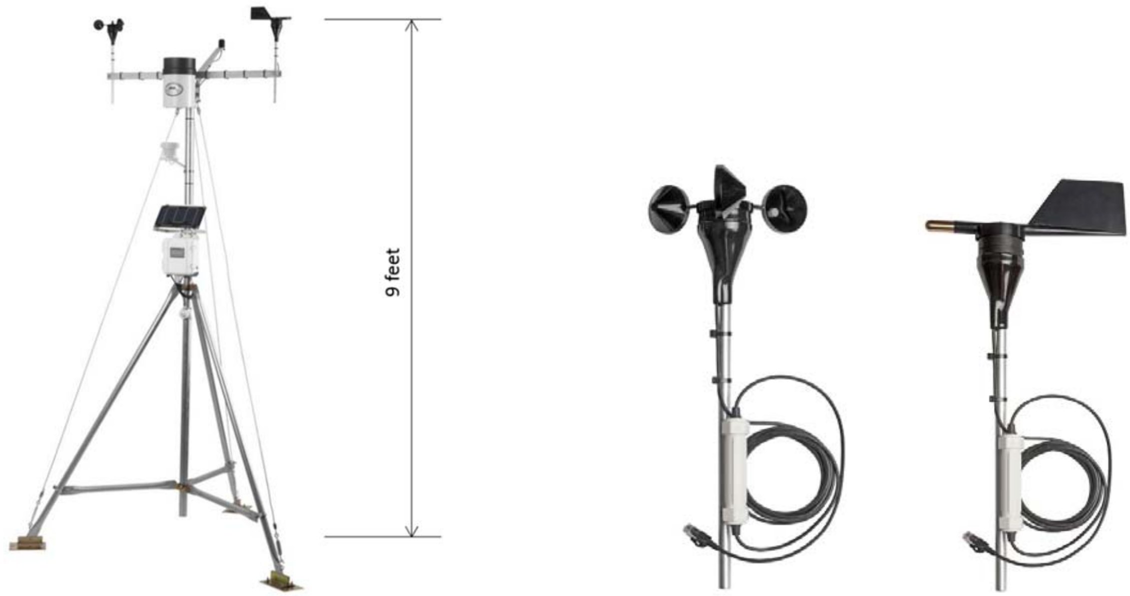


Fig. 3.2.5.: Hobo U30 Weather Station (with a 1.2W photovoltaic panel)

Wind Speed sensor Hobo S-WSA-M003:

- Measurement parameters: average wind speed and highest 3 second gust in logging interval
- Measurement range: 0 to 45 m/s (0 to 100 mph)
- Accuracy: ±1.1m/s (2.4 mph) or ±4% of reading whichever is greater
- Resolution: 0.38 m/s (0.85 mph)
- Starting Threshold: 1 m/s (2.2 mph)

Wind direction sensor Hobo S-WDA-M003:

- Measurement Range: 0 to 355 degrees, 5 degree dead band
- Accuracy ± 5 degrees
- Resolution 1.4 degrees
- Starting Threshold 1.0 m/s (2.2 mph)

Figure 3.2.6.: Setup of the Onset U30 Weather Station at Maunalua Bay Beach Park

The anemometers selected were the Degree Controls Accusense F900-0-5-1-9-2 with the XS blade which has a range of zero to 5 m/s air speed and an accuracy of 0.5 % of reading or 1% of full scale. Figure 3.2.7 shows the anemometer sensor with the data conditioning unit (the cylindrical unit in the figure). The cylindrical unit connects to the external port on the Onset U12 Data Logger (bottom on Figure 3.2.3 and labeled "CFD-)5") via the grey cable. Figure 3.2.8. depicts the sensor tip (with the XS blade) which is the actual wind velocity sensor. The anemometer has the following measurement parameters:

- Velocity range: 0.15-5m/s
- Accuracy: ± 5% reading or ±0.05m/s (10fpm)

Data logger: Six Hobo U12 data logger units were used to record signals of the anemometers. The data loggers were powered by a 12V customized battery packages (from a set of 8 1.5V AA batteries).

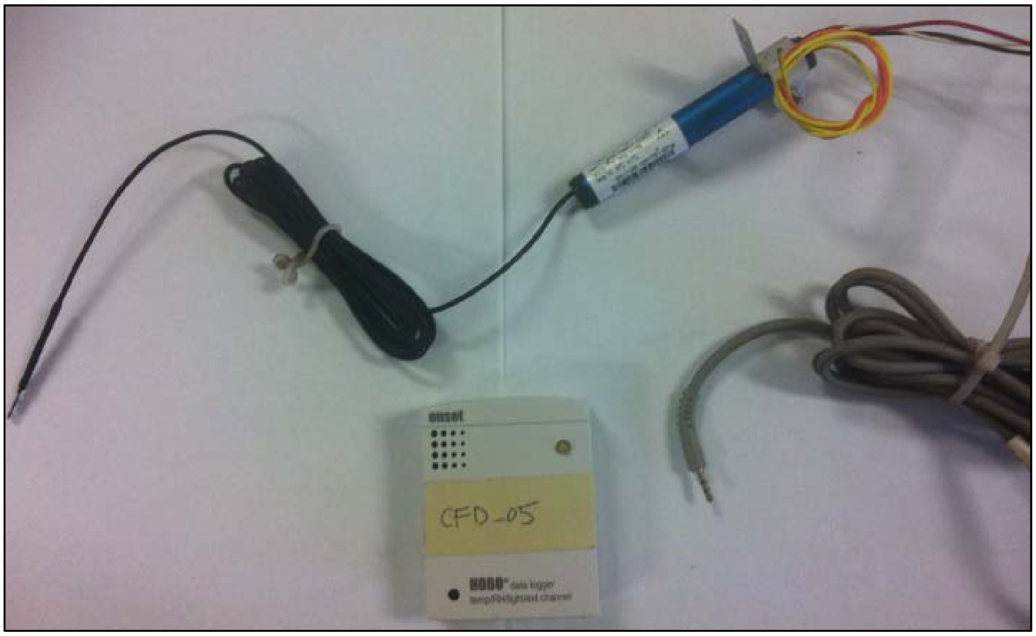


Figure 3.2.7.: The DegreeC F900 Anemometer. (shown with the cylindrical signal conditioning unit and the U12 data logger)

Figure 3.2.8.: The DegreeC F900 Anemometer.

The data acquisition device chosen was the National Instruments USB-6341 (Fig. 3.2.9) multiplexer. Excitation of sensors is not provided with this model, so sensors were powered by either battery packs or with AC to DC power adapters which draw their power from a small gas-powered generator. The multiplexer interfaces with a National Instruments data acquisition software called Signal Express. This device was not available in time for the first field test, so Onset HOBO U12 portable data loggers with external mini-jack were used. Figures 3.2.10. and 3.2.11 depict instrumentation and signal multiplexer being prepared for the field test by team member Christian Damo.

Figure 3.2.9. National Instrument USB-6341 device connected to a laptop which logs and displays the data (photo credit: National Instruments)

Instrument specification sheets can be found in Appendix B.

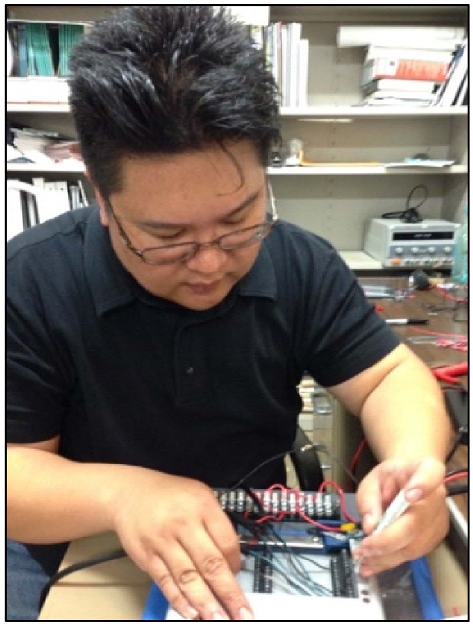


Figure 3.2.10. Integrating the sensors with the NI USB-6341 in office. Note the terminal block which distributes 24VDC electricity to the individual sensors

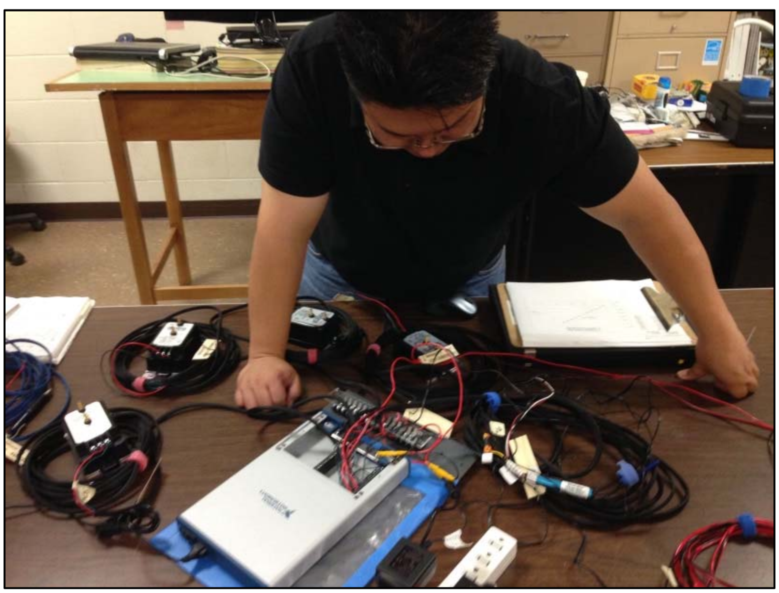


Figure 3.2.11. Overall picture of the integration of the various sensors fitted with 20' length wiring between the sensor and NI USB-6341 device

SECTION 4: SHAKEDOWN FIELD TESTS

This section reports on three field tests that were carried out over a period of six weeks. The objective field tests were to gain proficiency in the deployment of instruments, data acquisition and analysis. During every field tests new measurement scenarios were selected and tests to allow a wide range of instrument settings to be tested. The field test are an essential part of the shake down tests since in addition to correcting instrumentation issues that arose by operating in a "non-lab" and therefore not ideal environment. the team could gain important logistic experience of running preparing and conducting tests. The logistic issues included creating check lists for test equipment, securing the test site for the test equipment and conducting expeditious testing.

4.1 Description of Site for Shakedown Tests

The same site was chosen for all three field studies,. The site was located was in Hawaii Kai (southern O'ahu) in Maunalua Bay Beach Park (Fig. 4.1.1). Situated next to a paved parking lot, this site is a gravel land area which was a very suitable test site because of the typically steady wind conditions. As delineated in Appendix A the selected test site had little obstructions from the predominant wind approach direction, which was North East, the direction of the prevailing trade winds. A generally constant wind approach direction and strong wind facilitate the observation of wind pattern similar to a wind tunnel experimental setting.

The site setup and extents (lack of buildings nearby combined with a clear siting adjacent to the ocean) provided the study and the researchers with an ideal context (Fig. 4.1.2) with which to carry out the wind measurements around the test structure, e.g. the RAV-SUV temporarily parked on the test site.

Field tests were conducted on three days: December 12, 2013, January 10, 2014, and February 1, 2014.

Figures 4.1.3. and 4.1.4. show the site's view-sheds. For all three tests, an Onset HOBO U30 weather station was used to record wind speed and direction at a nine feet (9'-0") height. All field measurements included test scenarios where the test structure (RAV-SUV) was oriented to face the side and the front of the car, e.g. to create two wind approach directions (parallel and perpendicular to the car). The field-testing and angle measures were indicative of the wind direction, located in reference to the Magnetic North direction.

1: Site location on the island of O'ahu

2: Site location within southern O'ahu

3: Site location in Hawaii Kai area

SHAKEDOWN FIELD TESTING SITE

The site chosen for this field measurement is Maunalua Bay Beach Park in Hawaii Kai, on an unpaved parking lot next to the ocean. This site was chosen for Hawaii's typical strong and consistent wind velocity and wind direction pattern, which assists CFD simulation validation.

Figure 4.1.1: Location and Vicinity of Shakedown Test Site

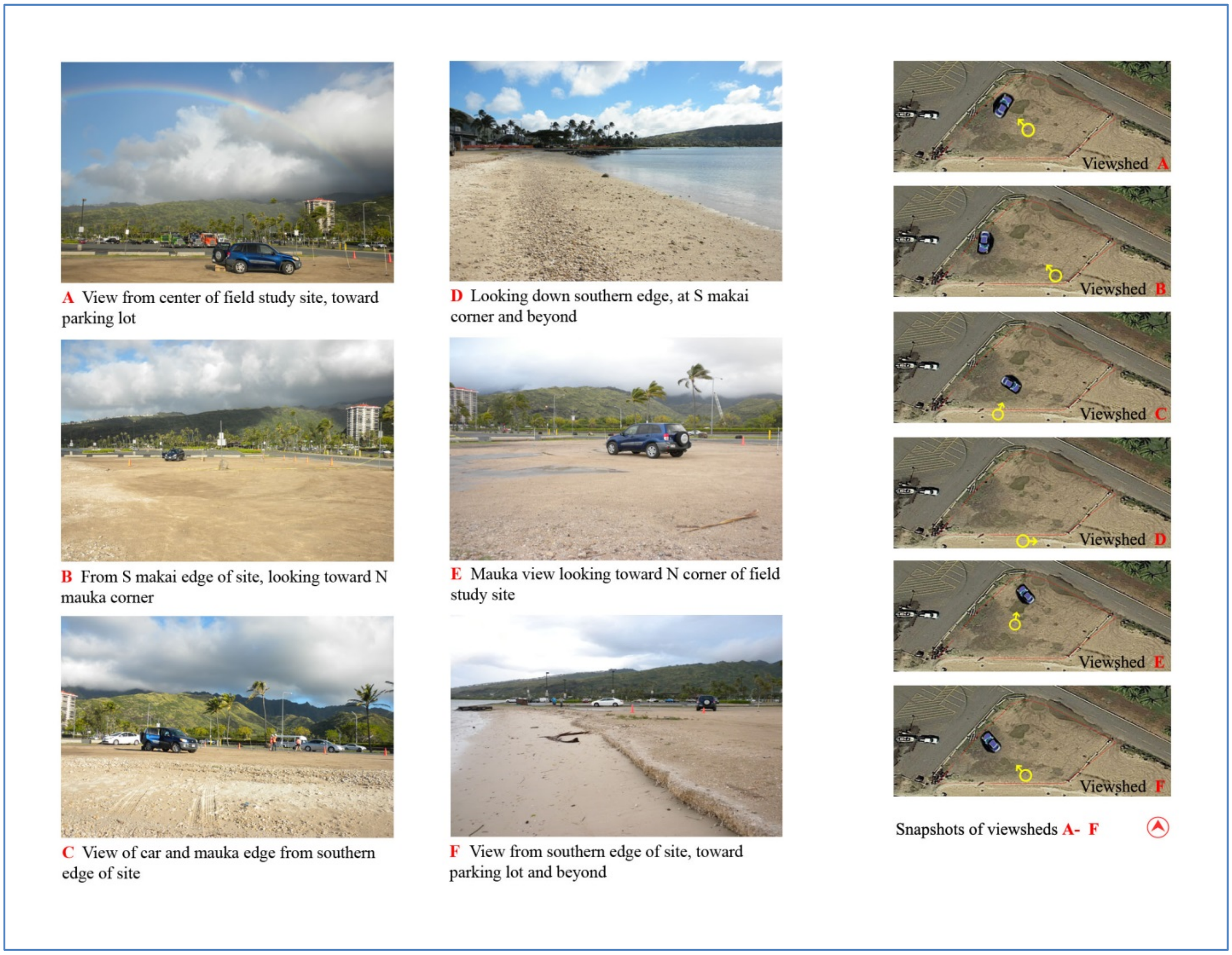
FIELD TESTS: Shakedown testing was performed at the Hawaii Kai site on the following days (during the mornings):
1) Field test #1: December 12, 2013
2) Field test #2: January 10, 2014
3) Field test #3: February 1, 2013

Figure 4.1.2: Sitemap and Existing boundaries (Maunalua Bay Beach Park)

SITE VIEWS: Definition of viewsheds:

- **A** View from center of field study site, toward parking lot
- **B** From S makai edge of site, looking toward N mauka corner
- **C** View of car and mauka edge from southern edge of site
- **D** Looking down southern edge, at S makai corner and beyond
- **E** Mauka view looking toward N corner of field study site
- **F** View from southern edge of site, toward parking lot and beyond

Figure 4.1.3: Site views and definition of viewsheds



A View from center of field study site, toward parking lot

B From S makai edge of site, looking toward N mauka corner

C View of car and mauka edge from southern edge of site

D Looking down southern edge, at S makai corner and beyond

E Mauka view looking toward N corner of field study site

F View from southern edge of site, toward parking lot and beyond

Snapshots of viewsheds A- F

Figure 4.1.4. Site views and corresponding viewshed locations

4.2 First Field Test Series

- Test date: 12/12/2013

- Six sensor units were prepared. Each unit consisted of an Onset HOBO U12 data logger with a ¼” mini jack that was used to interface with an F900 sensor. The sensor was equipped with a 9V battery clip to connect to an excitation 9VDC power supply consisting of 8 AA batteries in series. Data was logged onto the U12 internal memory. These sensors and the weather station were launched from the same computer allowing for data synchronization.

- The field measurement was set up to test two wind approach directions (parallel and perpendicular to the car). Five arrangements of anemometers around the car were set up in the following scenarios:
  - Scenarios with wind direction perpendicular to the car
  - Scenarios with wind direction parallel to the car

4.3 Second Field Test Series

- Test date: 1/10/2013

- Sensor setup consisted of the NI USB-6341 device connected to the following sensors for real-time data acquisition:
  - Three F900 sensors outfitted with a 9VDC power supply plug;
  - One Setra model 264 connected to a 18VDC power supply made from 16 AA batteries in series;
  - A laptop computer logged data from the NI USB-6341 device; and
  - A portable electrical generator was used to supply 120VAC power on site to support the three F900 sensors, the NI USB-6341 device, and the computer

- The field measurement tested two wind approach directions (parallel and perpendicular to the car). Ten arrangements of anemometers and the differential pressure transducer around the car were setup in the following scenarios:
  - Wind direction perpendicular to the car
  - Wind direction parallel to the car

- Three anemometers also were set up in order to measure the approach wind velocity profile

4.4 Third Field Test Series

- Test date: 2/1/2014

- Setup consisted of the NI USB-6341 device connected to the following sensors:
  - Three F900 sensors equipped with a 9VDC power supply plug;
  - One Setra model 264 that reported in current powered from the terminal block;
  - Three Setra model 264 that reported in volts powered from the terminal block;
  - One P26 that reported in volts powered from a 18VDC power supply;
  - Terminal block powered by a 24VDC power supply plug;
  - Laptop computer logged data from the NI USB-6341 device; and
  - A portable electrical generator was used to supply 120VAC power on site.
  - A video showing the setup can be found here: http://youtu.be/1BUXW_lhiDc
  - A video showing the P26 setup can be found here: http://youtu.be/dTus3aPhc2A

- Figures 4.4.1 through 4.4.12 show two arrangements of sensors around the car , scenarios set up as indicated in diagrams, test work carried out at the test site.

- Filtered data points post-acquisition were run as follows:
  - Run 1: 251 degrees +/- 20
  - Run 2: 256 degrees +/- 20

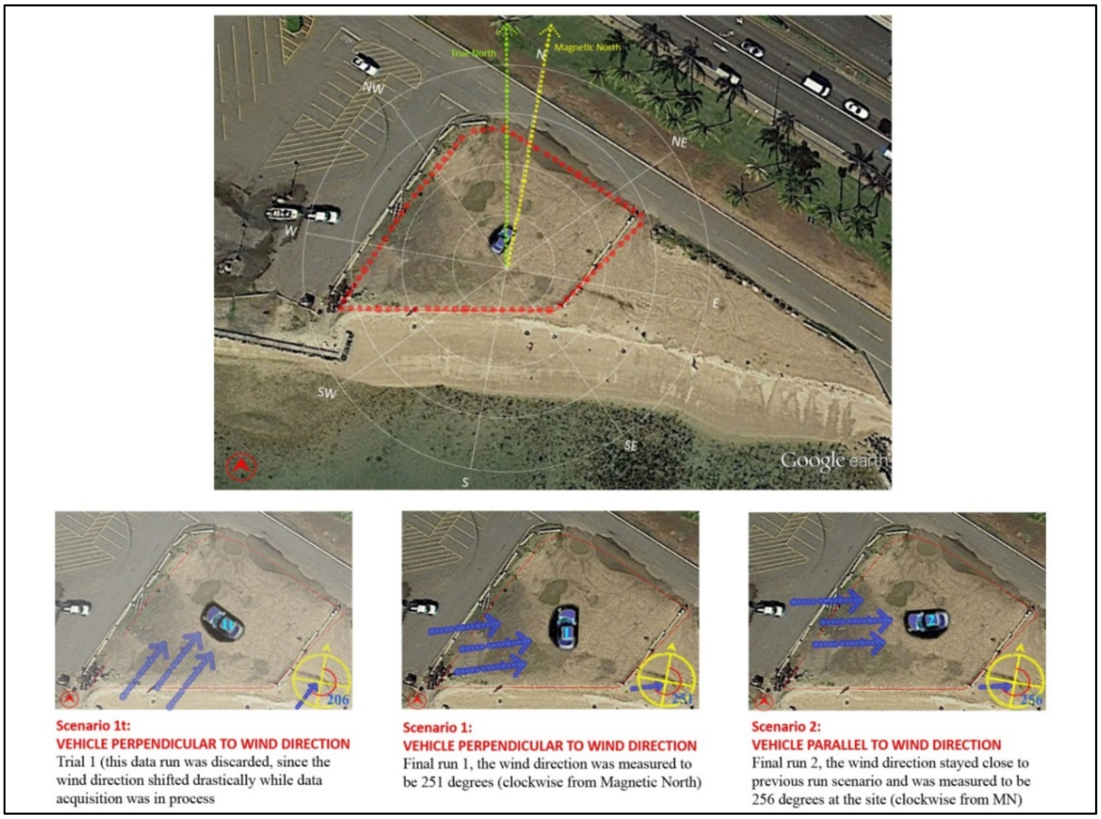


Figure 4.4.1: Field Test Series #3: Sensor layout for the third field test: (a) Scenario 1 (wind perpendicular to the car) and (b) Scenario 2 (wind parallel to the car)

Figure 4.4.2: Sensor layout for the third field test: (a) Scenario 1 (wind perpendicular to the car)

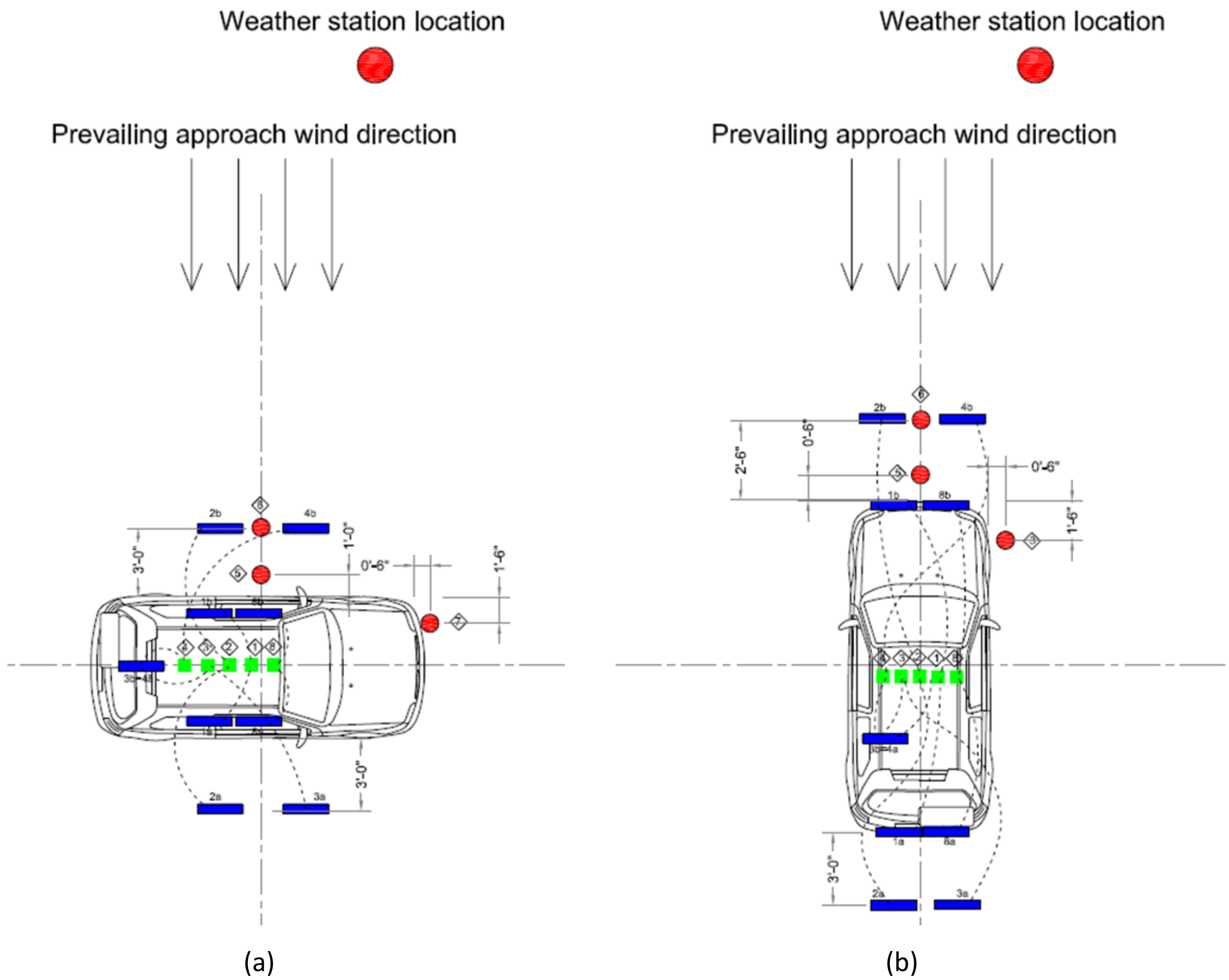


Figure 4.4.3.: . Field Test Series #3: Sensor layout for the third field test: (a) Scenario 1 (wind perpendicular to the car) and (b) Scenario 2 (wind parallel to the car)

Figure 4.4.4.: Field Test Series #3: Sensor layout for the third field test: (b) Scenario 2 (wind parallel to the car)

Figure 4.4.5.: Field Test Series #3: Setting up the Hobo U30 weather station (wind speed and direction sensors)

Figure 4.4.6.: Field Test Series #3: Setting up the pressure tubing to match heights and positions as indicated in the various CFD simulation setup scenario diagrams

Figure 4.4.7.: Field Test Series #3: Attaching pressure tubing around the car, to measure pressure differentials

Figure 4.4.8.: Field Test Series #3: Checking measurements and angles of the anemometers

Figure 4.4.9.: Field Test Series #3: Setting up and ensuring pressure transducers are connected to measure and acquire data

Figure 4.4.10.: Field Test Series #3: Running test measurements to check instrumentation setup

Figure 4.4.11.: Field Test Series #3: Final round of checks and adjustments

Figure 4.4.12.: Field Test Series #3: Final round of checks and adjustments

4.5 Lesson Learned to Conduct Efficient Field Tests

The CFD research team offers concluded it is beneficial to record lessons learned and make them available for future research teams.

Lesson 1: The Field Checklist

The field test should be conducted by following the field checklist to make sure all procedures taken properly and in the appropriate order. The checklist includes:

- Print out the sensor set-up scenario layouts
- Record the car's orientation with compass
- Calibrate the North (magnetic North) of the weather station with compass (the true North will be calculated using magnetic North after corrected by using the
- Estimated Field Calculators web-based tool from National Oceanic and Atmospheric Administration website (NOAA) http://www.ngdc.noaa.gov/geomag-web/#declination: using

zip code 96822 for Hawaii Kai, we got magnetic declination = 40' 12" E or -9.66 degrees then we subtract the wind direction readings for 9.66 degrees.)

- Measure the height of the weather station's sensor.
- Launch the weather station for 1 second interval reading with HoboWare software.
- Double-check the locations of the sensors with the sensor set-up scenario layout
- Record the heights of the anemometers. Anemometers should be mounted at the same 3feet height. However, the anemometer which measures close to the front bumper will be mounted at 2 feet height.
- Label the anemometers, pressure tubes (pressure terminals) and hoses, pressure transducers
- Attach the pressure tubes into pressure transducers with clear defined matrix.
- Uncap the anemometers and double-check the orientations of the F900 anemometers' blades. Their blades have to be almost perpendicular to the approach wind direction.
- Double check the multiplexer settings (Christian should add something here)
- Start multiplexer reading
- Take notes the starting and ending time for each scenario
- Keep taking notes and the time of any unexpected phenomenon happening during the reading time which may interfere with the experiments (wind direction shifting, large obstruction from trucks, raining, etc.)
- If the wind shifts too much to the wind directions that will not be useful for the analysis, reorientation of the car is necessary. If this happens, make sure to record the time when the restart the reading, measure the car's new orientation.

<u>Lesson 2: Data Analysis Procedure</u>

The data analysis should be conducted by following the field checklist to make sure all procedures taken properly and in the appropriate order. The checklist includes:

- The data analysis from the second field test on comparing the readings of the DegreeC F900 anemometer and the Onset HOBO U30 weather station's sensor placed next to each other.
- It showed that the readings from weather station are about 0.63 m/s on average lower than those from the anemometer and there was the time lag for data acquisition between the two sensors.
- The Hobo U30 is about 8 second lag of the F900. Identification of discrepancy from the shakedown tests is crucial for the CFD validation. Since the reading difference and the lag of two sensors were found under the field test condition, and therefore a calibrated test of those equipment should be carefully taken under controlled condition like wind tunnel for more accuracy.

SECTION 5: DATA ACQUISITION METHODS AND ANALYSIS

This section reports on methods and procedures that were developed and refined during the shakedown testing. It should be noted that the methods and procedures described hereafter reflect Field Test Series # 3 since experiences and results of Field Test Series # 1 and #2 were used to fine-tune methods and procedures. Subsequent tests in the CFD project will be based on the experience and conclusions gathered during the field tests.

5.1 Data Acquisition Methods and Procedures

Data acquired by the NI USB-6341 multiplexer and processed on SignalExpress software was exported as a tab separated text file. Data needed processing before being uploaded to a PostgreSql database. Data was acquired with a starting timestamp and collection frequency (in this case 5 times per second).

There is not a timestamp given for each data record. A Python script was written to present the data with timestamp information, take the average of the 5 readings with a trailing timestamp, scale it and re-shape it for upload to a database. Data can be stored in a vertical or a horizontal data type of structure and in this case it was stored in both while they were being evaluated (See Appendix D for details). Data from the weather station required pre-processing before upload to the database and a horizontal data structure was used.

Once the raw data was uploaded to the database, a “view” was created to filter out unwanted data. Sometimes the wind speeds exceeded the rated capacity of the anemometers (>5m/s). When that occurred, all sensor and weather station data was deleted for that timestamp. The P26 (sensor #8) was only used as a comparison to sensor #1. It had a much smaller range, so data from that sensor was selectively filtered to only include pressures of < 0.055 inches of water column (Fig. 5.1.1).

Tableau software was used to graph the “view” of the data in the PostgreSql database (which filters data). In order to create a custom wind rose, a circular image was imported into the graph and scaled. Calculated fields were created and plotted on the x and y coordinates using a scatter plot:

- Winddir_x =[wind speed m/s]*cos(radians(90-[wind direction, deg]))
- Winddir_y -[wind speed m/s]*sin(radians(90-[wind direction, deg]))

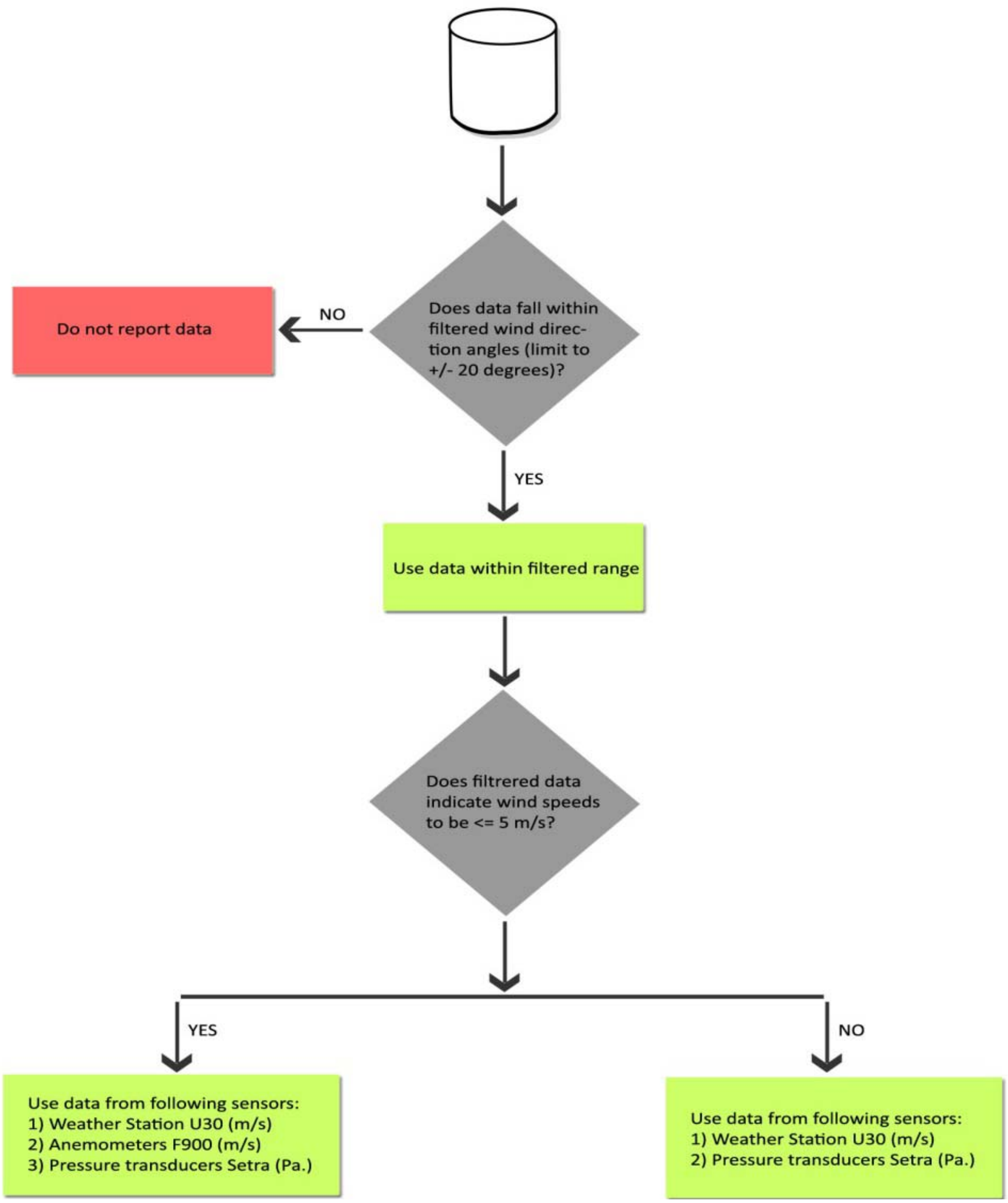


Figure 5.1.1. Flowchart indicating process applied to data through various filtering techniques

5.2 Description of Data Analysis of Field Test Series 3

There were two test scenarios carried out under the Field Test Series #3. The scenarios are described in more detail in Appendix D. The descriptions of the data analysis in this section serve to provide the logic flow of the data reduction and data analysis.

5.2.1 Data Analysis of Field Test Series 3 – Scenario 1

At occasions the measured wind velocities and differential pressures surpassed the operational range of the sensors and transducers. In order to correctly correlate the wind velocity and pressure data filters were employed.

Data Filter 1

The first filter eliminated all data when the anemometers exceeded their maximum rated velocity of 5 m/s. The P26 pressure sensor was selectively filtered when it exceeded its rated maximum. And then all the data was filtered for wind direction to limit direction 231^{o} to 271^{o}.

Weather station wind speed averaged 4.4 m/s and the anemometers ranged from 1.296 to 3.756 m/s (n=894 seconds) (see Figure 5.2.1).

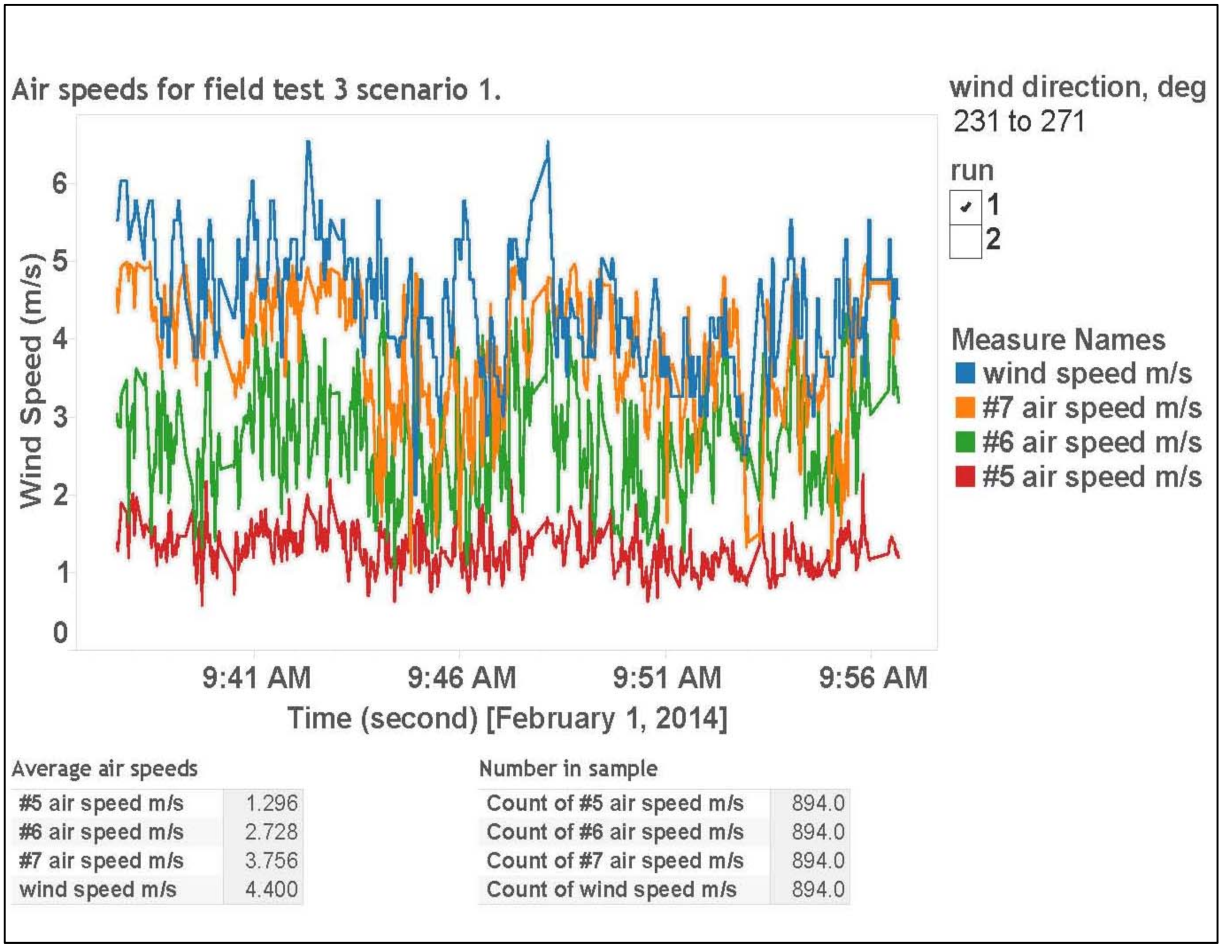
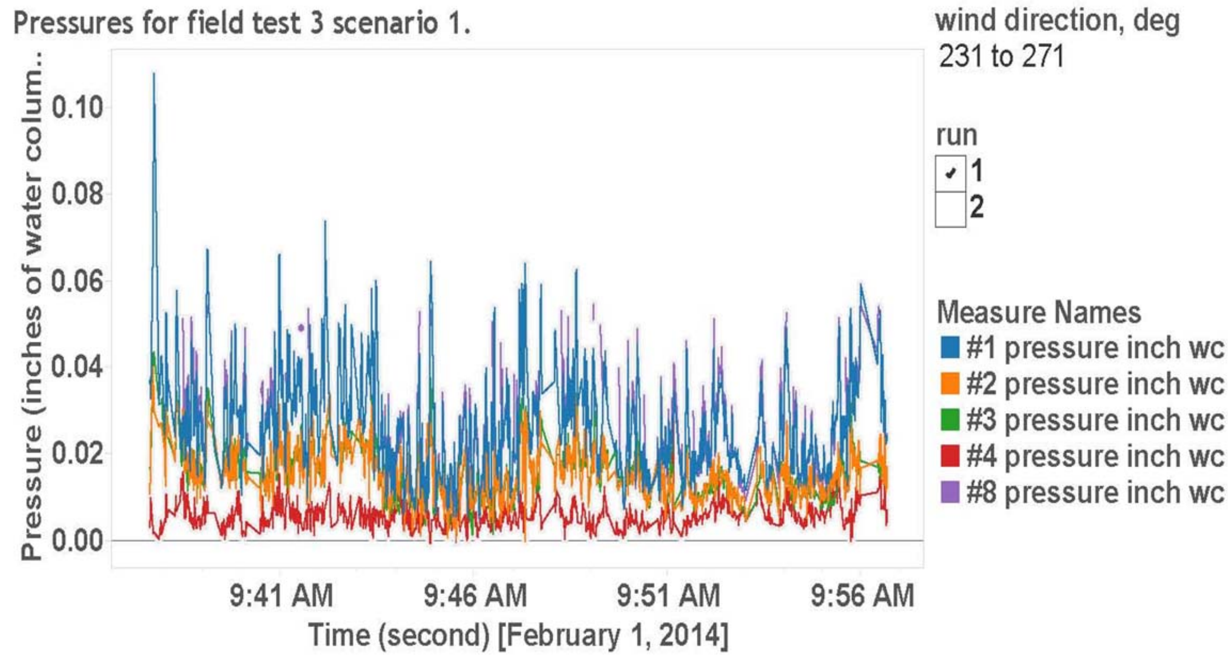


Figure 5.2.1. Air speeds (m/s) for third field test (Scenario 1)

Pressure sensors #1 (a Setra) and #8 (P26) were placed in the same location and experienced similar average pressures, 0.02640 (n=894 seconds) and 0.2440 inches of water column (n=553), respectively. Other average pressures ranged from 0.00597 to 0.01516 inches of water column. (see Figure 5.2.2).



Average pressures

#1 pressure inch wc	0.02640
#2 pressure inch wc	0.01516
#3 pressure inch wc	0.01506
#4 pressure inch wc	0.00597
#8 pressure inch wc	0.02440

Number in sample

Count of #1 pressure inch wc	894.0
Count of #2 pressure inch wc	894.0
Count of #3 pressure inch wc	894.0
Count of #4 pressure inch wc	894.0
Count of #8 pressure inch wc	553.0

Figure 5.2.2. Pressures (in inch wc) for third field test (Scenario 1)

Within the wind direction filter range, most of the wind came from the 250 to 260 direction and predominant speeds were 3 to 6 m/s (see Figure 5.2.3).

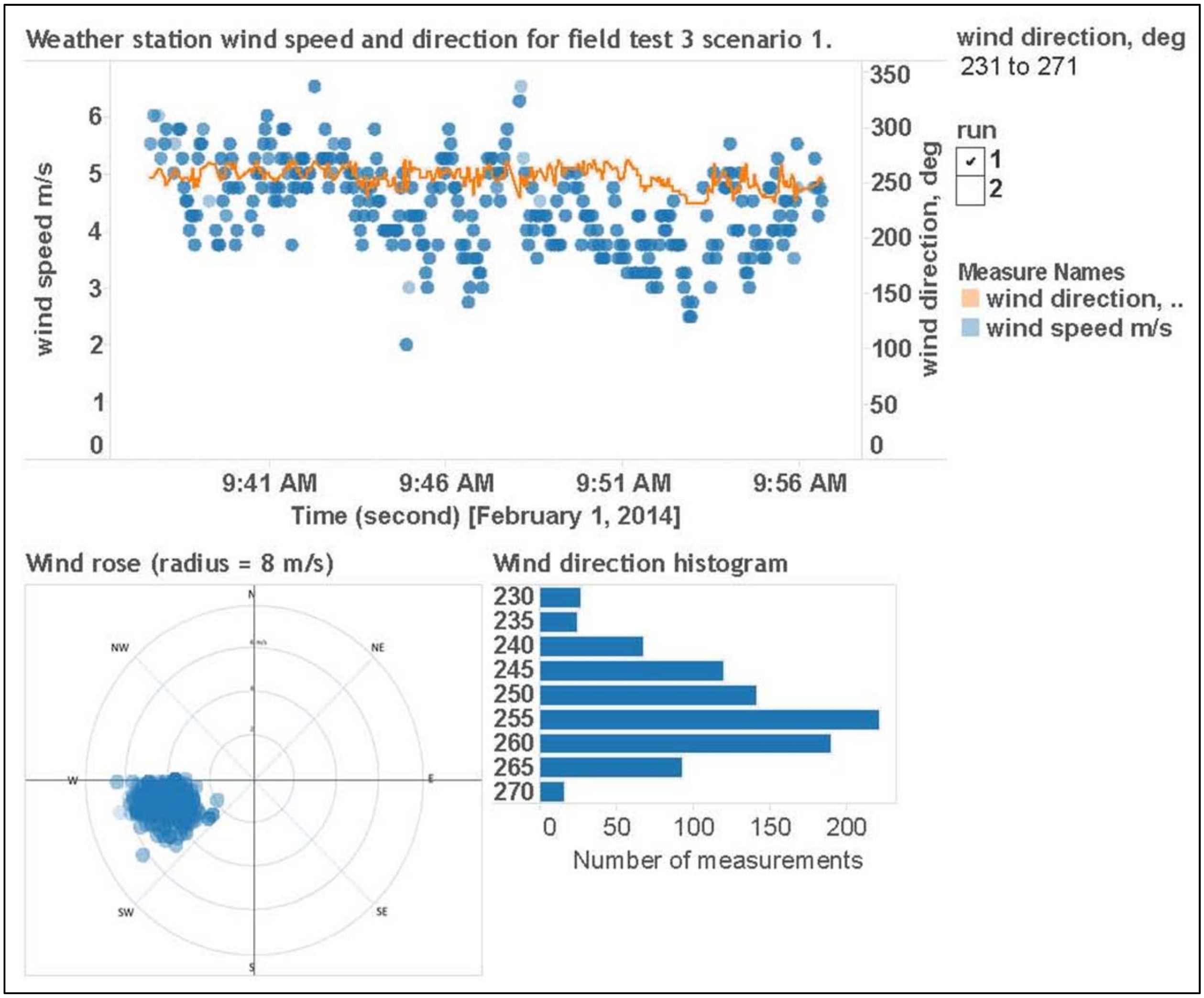
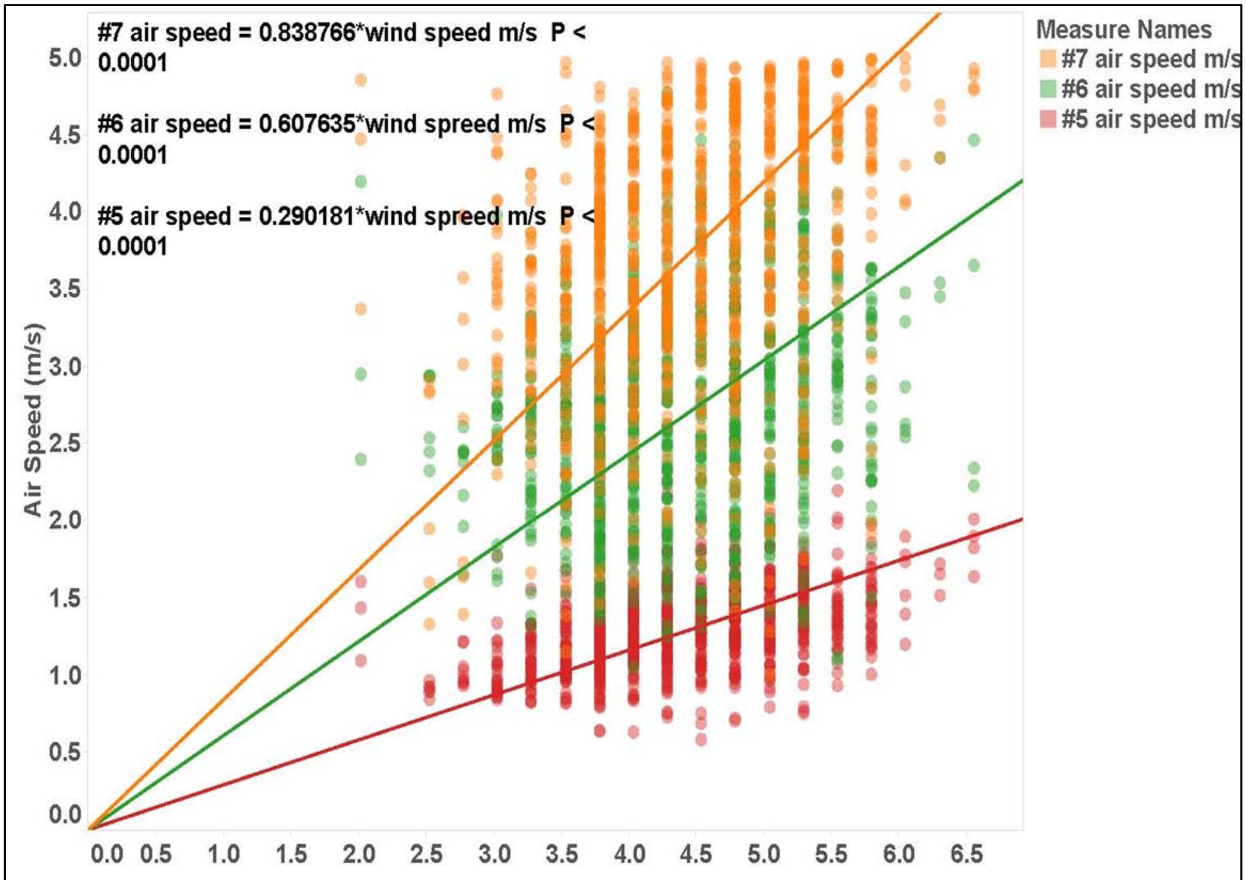


Figure 5.2.3.: Weather station for third field test (Scenario 1)

The relationships between anemometer air speeds and weather station wind speed were linear and depicted (see Figure 5.2.4).



Wind speed m/s vs. #5 air speed m/s, #6 air speed m/s and #7 air speed m/s. Color shows details about #5 air speed m/s, #6 air speed m/s and #7 air speed m/s. The data is filtered on run and wind direction, deg. The run filter keeps 1. The wind direction, deg filter ranges from 231 to 271.

Figure 5.2.4.: Wind speeds (m/s) for sensors #5, 6, and 7 for third field test (Scenario 1)

The relationships between air pressures and weather station wind speeds are depicted (in Fig. 5.2.5).

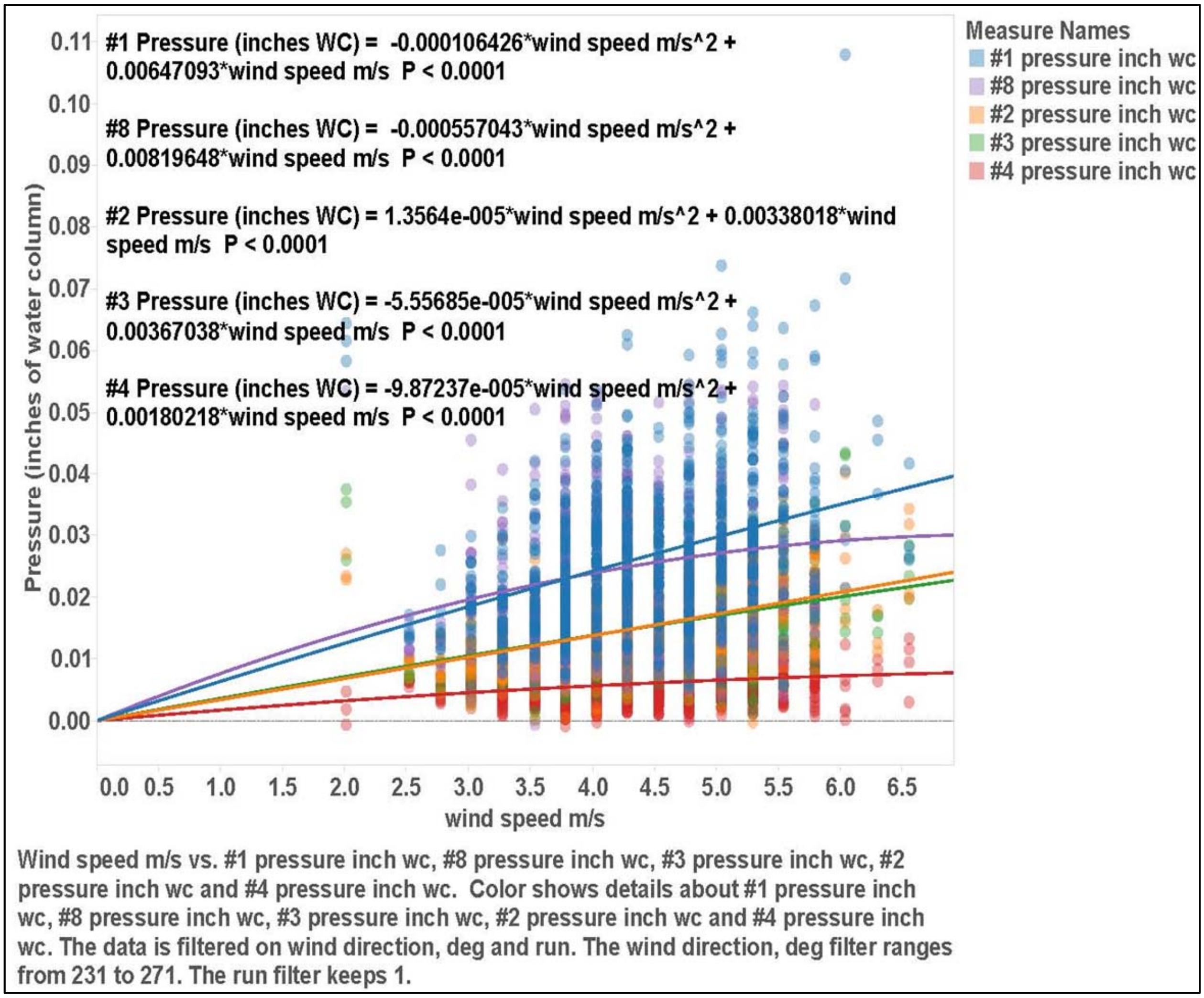


Figure 5.2.5.: Pressure readings (in wc) for sensors #1 2, 3, 4, and 8 for third field test (Scenario 1)

Data Filter 2

The second filter does not use the anemometer data and uses all pressure data except for P26 which was selectively filtered when it exceeded its rated maximum. All the data was filtered for wind direction to limit direction 231° to 271°. (see Figure 5.2.6.)

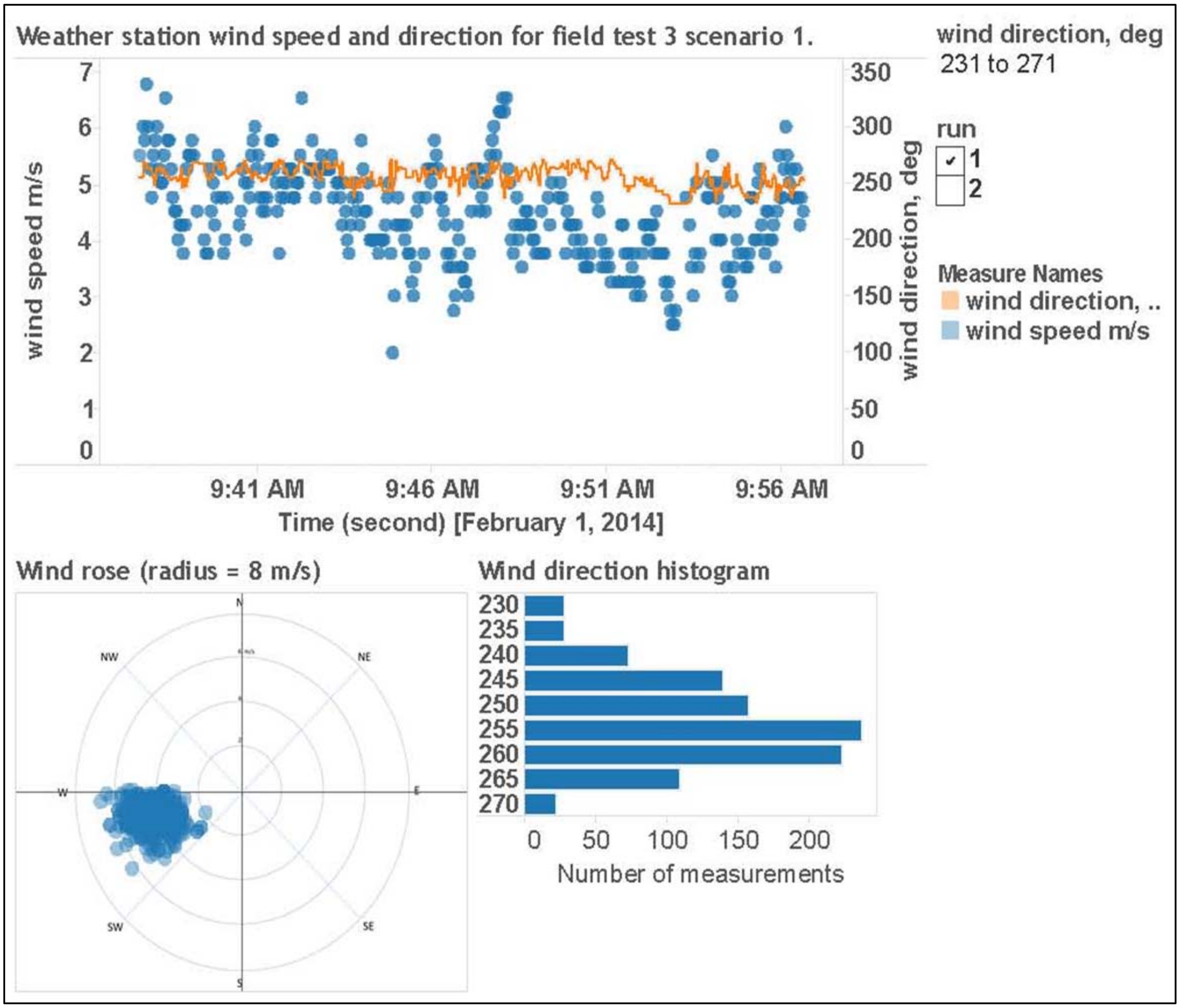
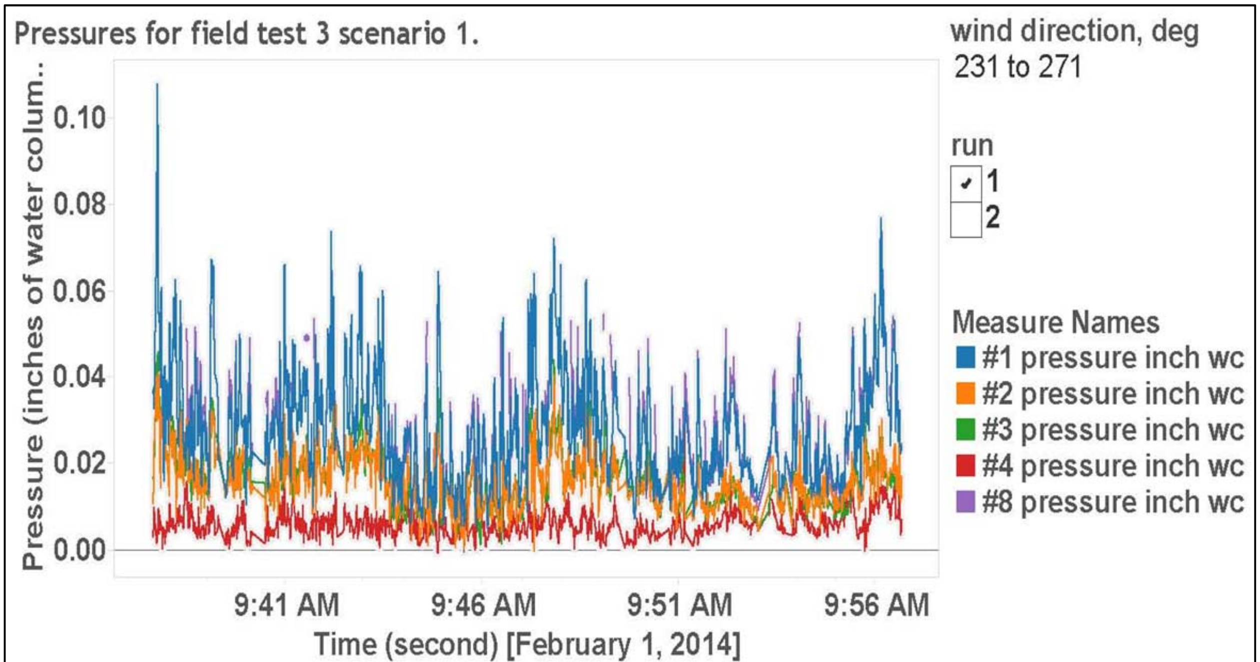


Figure 5.2.6.: Wind speeds and direction mapped for third field test (Scenario 1)

Pressure sensors #1 (Setra) and #8 (P26) were placed in the same location and experienced similar average pressures, 0.02840 (n=1,007 seconds) and 0.02444 inches of water column (n=556), respectively. Other average pressures ranged from 0.00617 to 0.01609 inches of water column (see Figure 5.2.7).



Average pressures

#1 pressure inch wc	0.02840
#2 pressure inch wc	0.01596
#3 pressure inch wc	0.01609
#4 pressure inch wc	0.00617
#8 pressure inch wc	0.02444

Number in sample

Count of #1 pressure inch wc	1,007.0
Count of #2 pressure inch wc	1,007.0
Count of #3 pressure inch wc	1,007.0
Count of #4 pressure inch wc	1,007.0
Count of #8 pressure inch wc	556.0

Figure 5.2.7: Pressures (in wc) mapped for third field test (Scenario 1)

The relationships between air pressures and weather station wind speeds are depicted in Fig. 5.2.8.

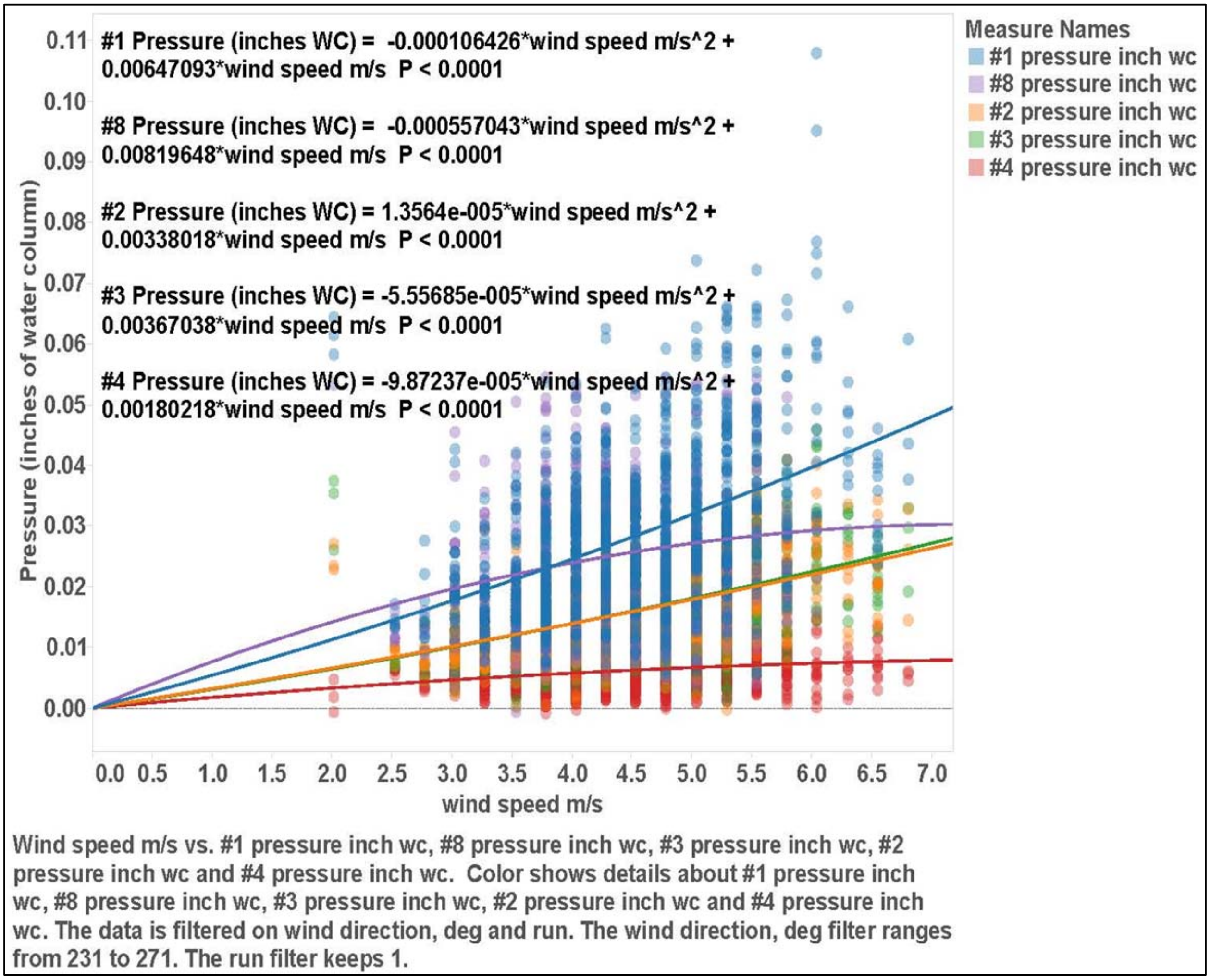


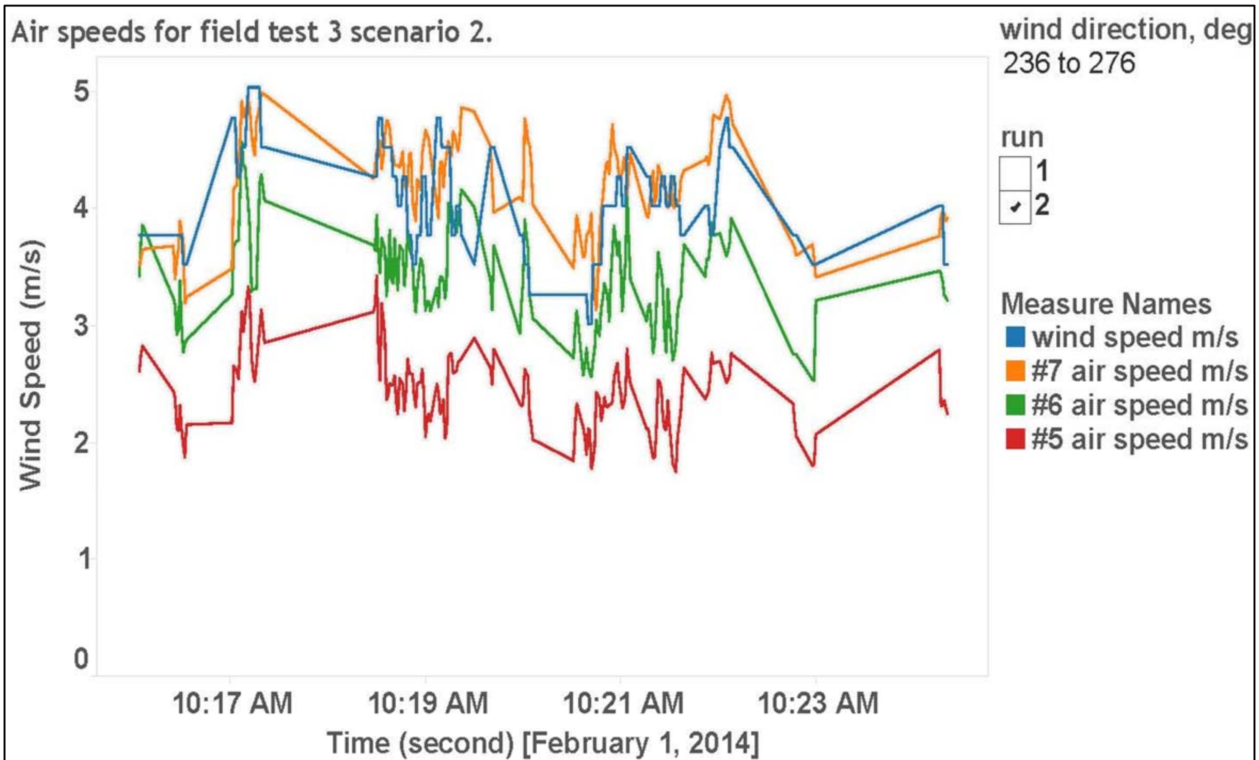
Figure 5.2.8: Pressures (in wc) compared to weather station wind speed readings (m/s)

5.2.1 Data Analysis of Field Test Series 3 – Scenario 2

Data Filter 1

The first filter eliminated all data when the anemometers exceeded their maximum rated velocity of 5 m/s. The P26 pressure sensor was selectively filtered when it exceeded its rated maximum. And then all the data was filtered for wind direction to limit direction 236^o to 276^o.

Weather station wind speed averaged 4.071 m/s and the anemometers ranged from 2.438 to 4.248 m/s (n=177 seconds) (see Figure 5.2.9).



Average air speeds

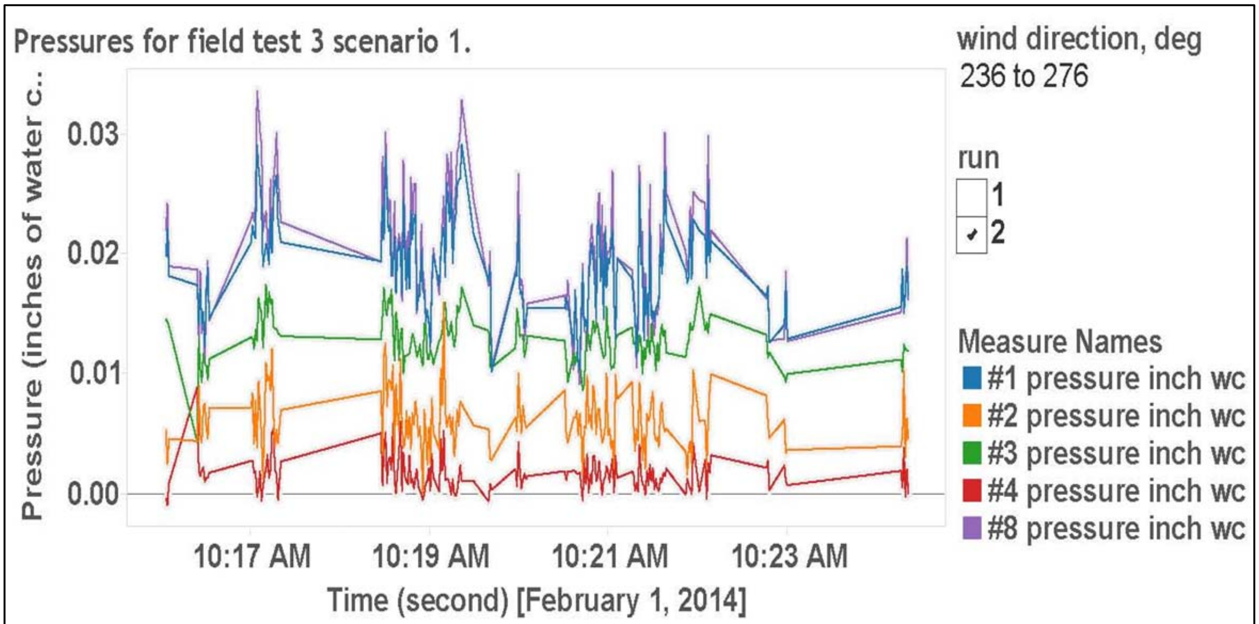
#5 air speed m/s	2.438
#6 air speed m/s	3.407
#7 air speed m/s	4.248
wind speed m/s	4.071

Number in sample

Count of #5 air speed m/s	177.0
Count of #6 air speed m/s	177.0
Count of #7 air speed m/s	177.0
Count of wind speed m/s	177.0

Figure 5.2.9.: Air speeds (m/s) for third field test (Scenario 2)

Pressure sensors #1 (a Setra) and #8 (P26) were placed in the same location and experienced similar average pressures, 0.01896 and 0.02003 inches of water column, respectively (n=177 seconds). Other average pressures ranged from 0.00597 to 0.01516 inches of water column (see Figure 5.2.10).



Average pressures

#1 pressure inch wc	0.01896
#2 pressure inch wc	0.00613
#3 pressure inch wc	0.01282
#4 pressure inch wc	0.00161
#8 pressure inch wc	0.02006

Number in sample

Count of #1 pressure..	177.0
Count of #2 pressure..	177.0
Count of #3 pressure..	177.0
Count of #4 pressure..	177.0
Count of #8 pressure..	177.0

Figure 5.2.10.: Pressure readings (inch of wc) for third field test (Scenario 2)

Within the wind direction filter range, most of the wind came from the 235 to 240 direction and predominant speeds were 3 to 5 m/s (see Figure 5.2.11).

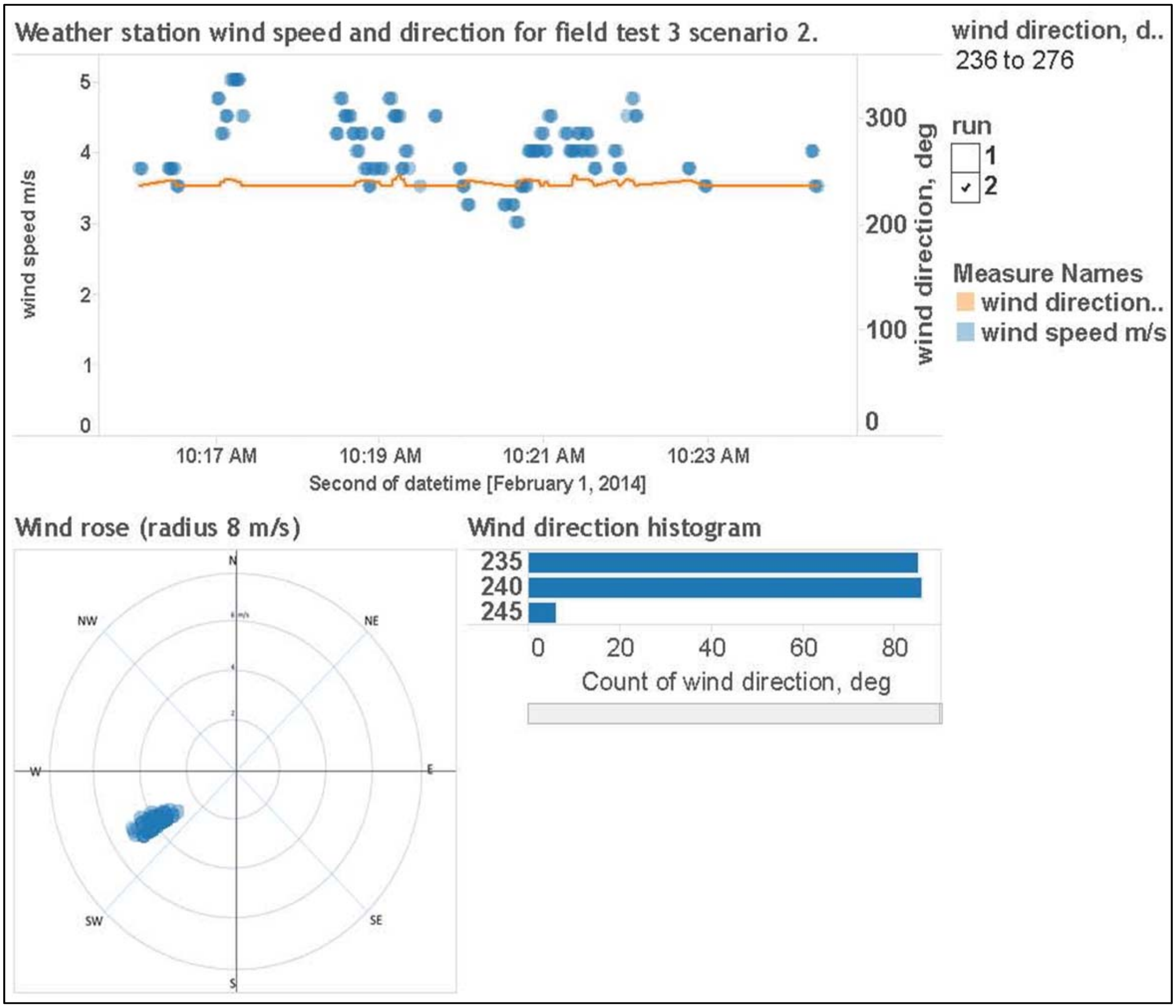


Figure 5.2.11. Wind speeds and direction mapped for third field test (Scenario 2)

The relationship between anemometer air speeds and weather station wind speed was linear and depicted in Figure 5.2.12.

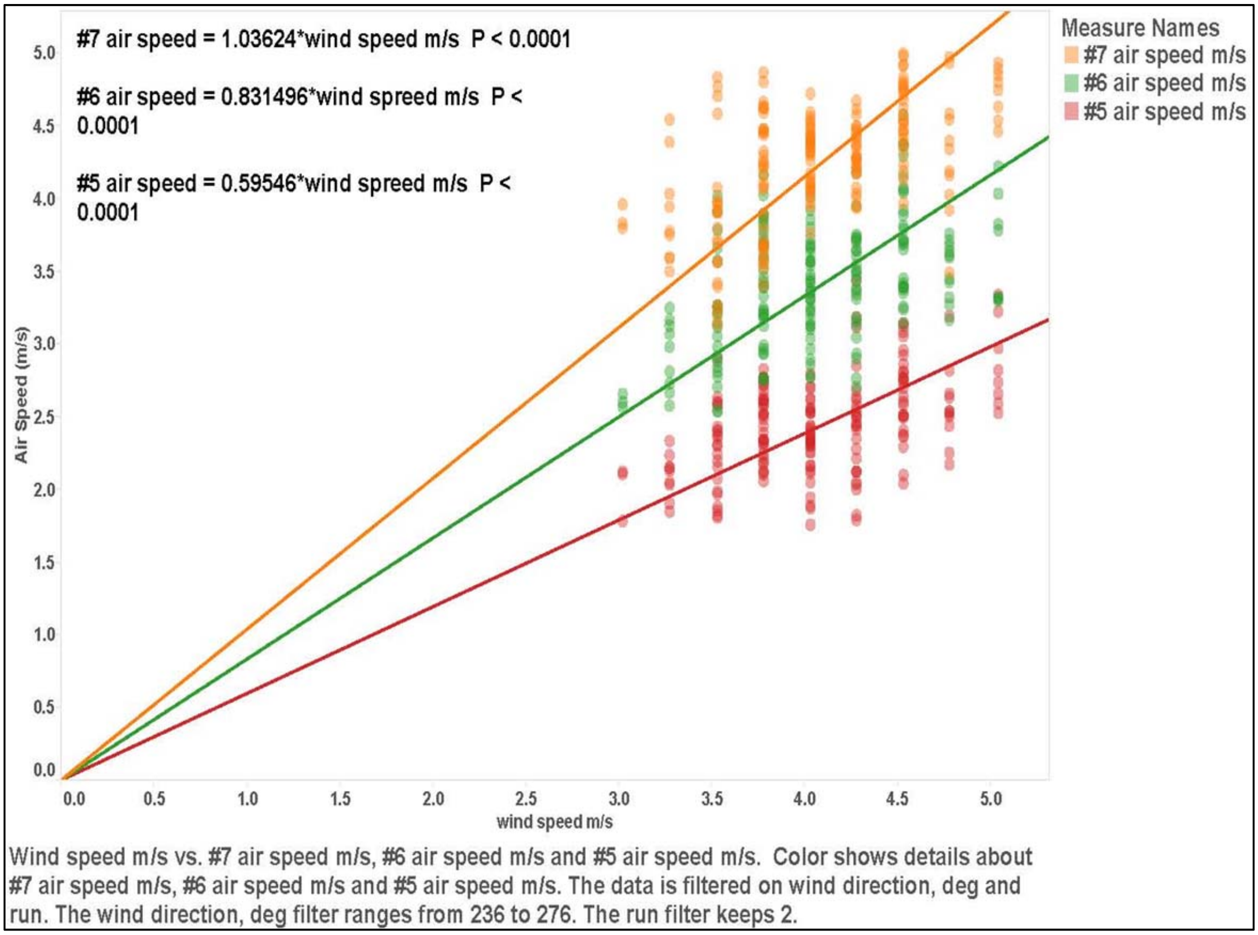
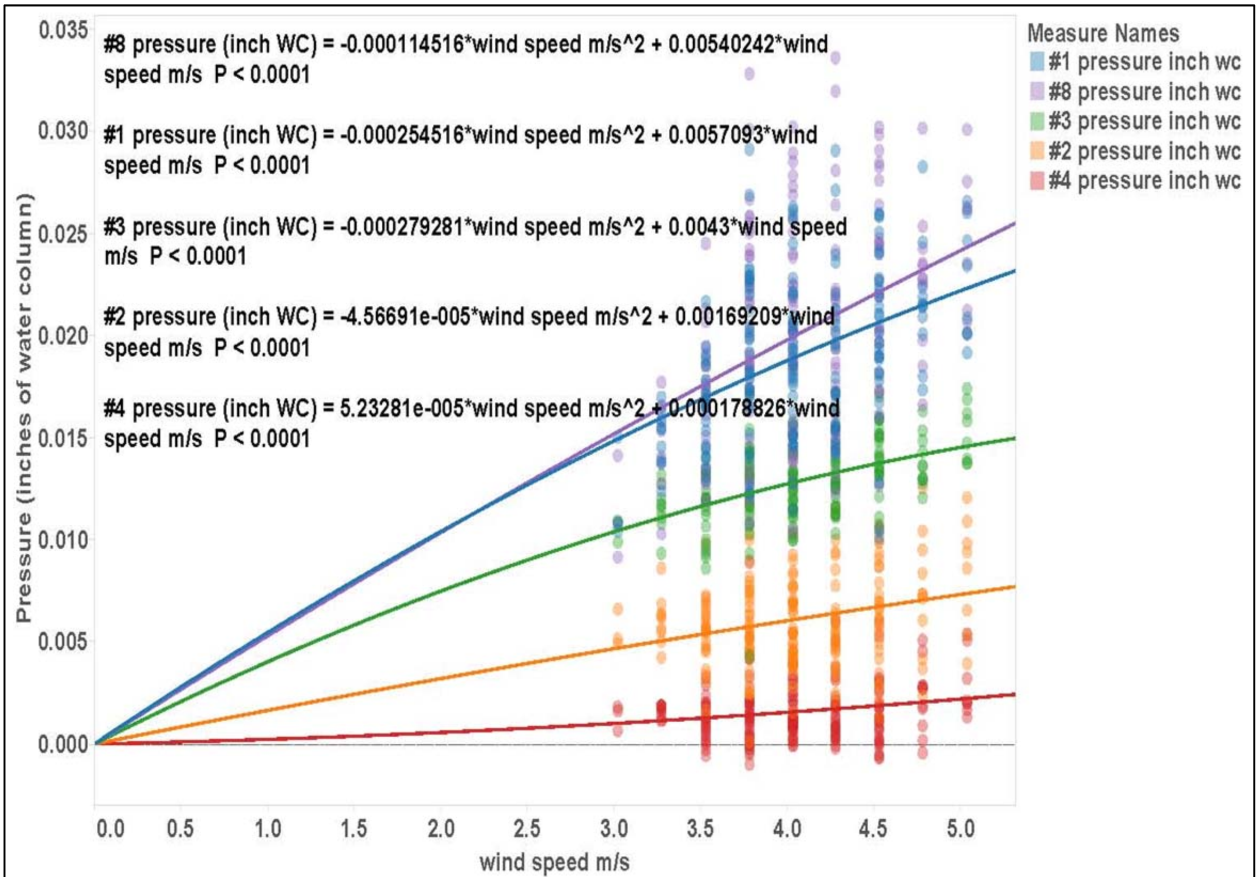


Figure 5.2.12. Wind speeds (m/s) for sensors #5, 6, and 7

The relationship between air pressures and weather station wind speeds is depicted in Fig. 5.2.13.



Wind speed m/s vs. #1 pressure inch wc, #8 pressure inch wc, #3 pressure inch wc, #2 pressure inch wc and #4 pressure inch wc. Color shows details about #1 pressure inch wc, #8 pressure inch wc, #3 pressure inch wc, #2 pressure inch wc and #4 pressure inch wc. The data is filtered on wind direction, deg and run. The wind direction, deg filter ranges from 236 to 276. The run filter keeps 2.

Figure 5.2.13: Pressure readings (in wc) for sensors #1 2, 3, 4, and 8

Data Filter 2

The second data filter does not use the anemometer data and uses all pressure data except for P26 which was selectively filtered if it exceeded its rated maximum (which it did not in this case). All the data was filtered for wind direction to limit direction 231^o to 271^o.

The Weather station wind speed averaged 4.03 m/s but ranged from 3.02 to 5.04 m/s. The predominant direction was in the 235^o to 240^o range (see Figure 5.2.14).

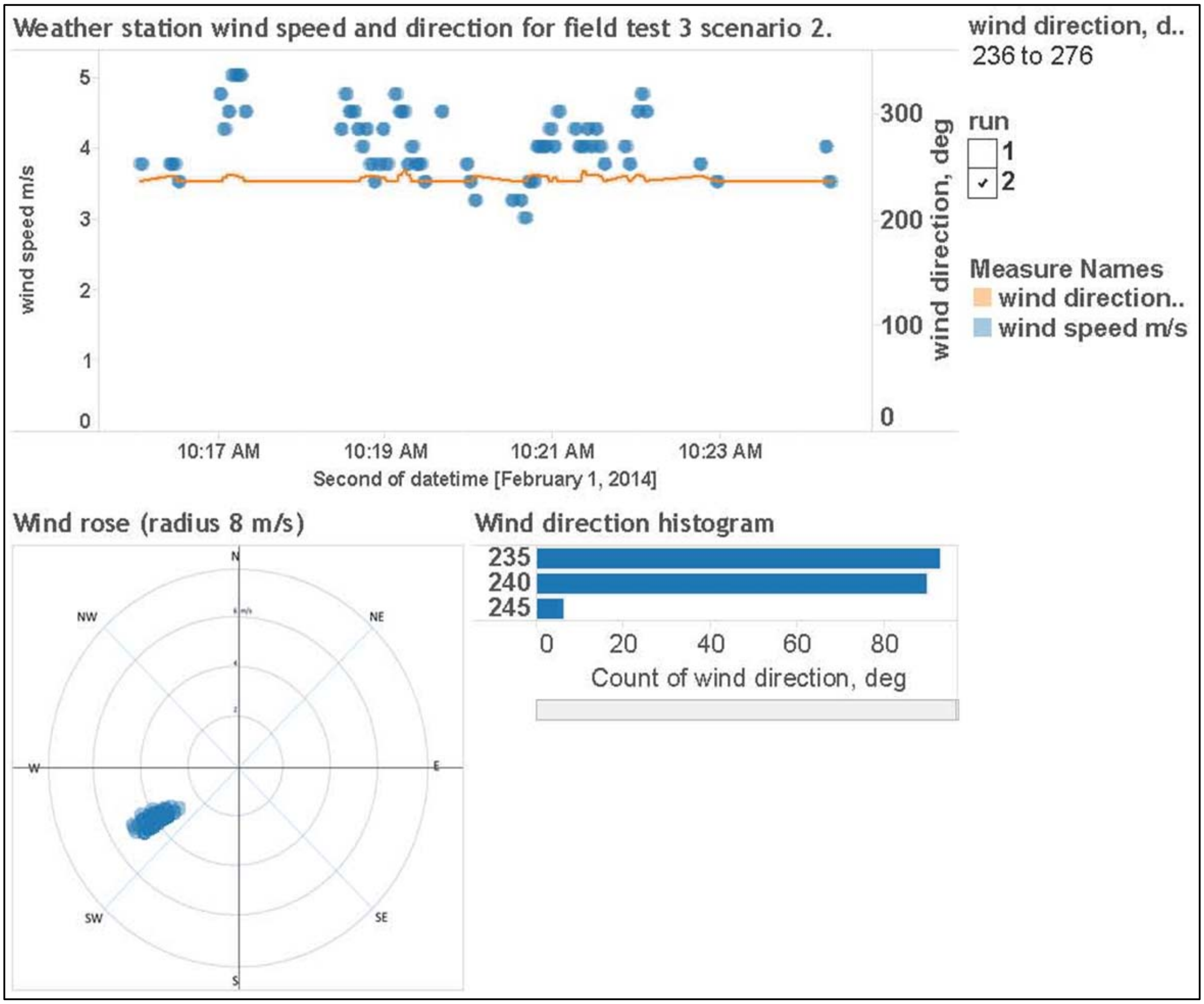
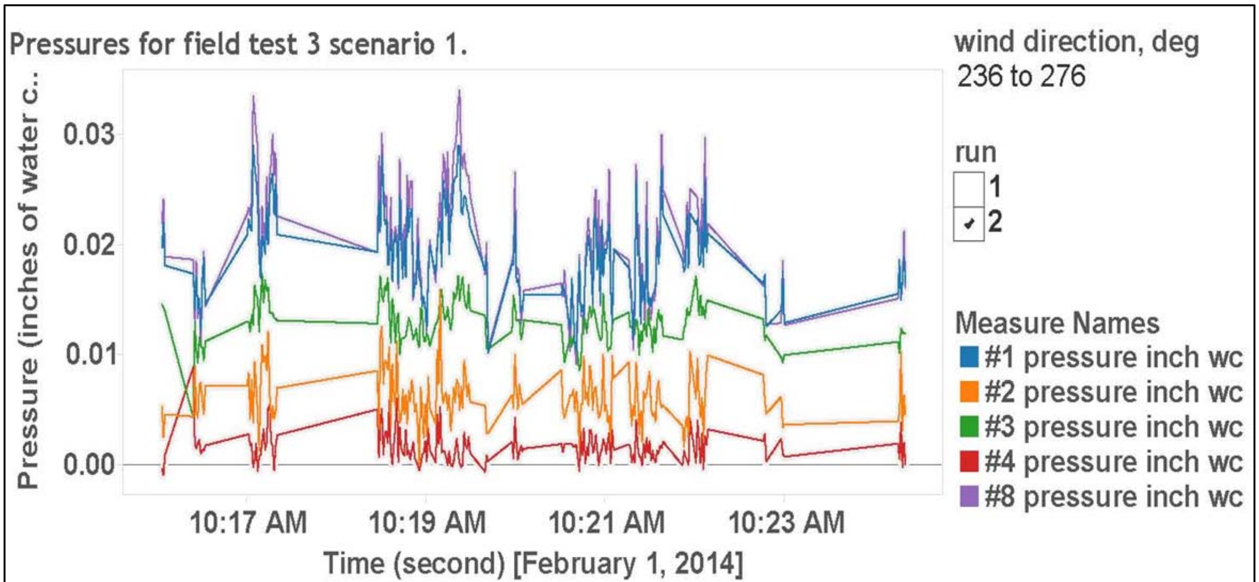


Figure 5.2.14: Wind speeds and direction mapped for third field test (Scenario 2)

Pressure sensors #1 (a Setra) and #8 (P26) were placed in the same location and experienced similar average pressures, 0.01920 (n=189 seconds) and 0.02042 inches of water column (n=189), respectively. Other average pressures ranged from 0.00160 to 0.01297 inches of water column (see Figure 5.2.15).



Average pressures

#1 pressure inch wc	0.01920
#2 pressure inch wc	0.00617
#3 pressure inch wc	0.01297
#4 pressure inch wc	0.00160
#8 pressure inch wc	0.02042

Number in sample

Count of #1 pressure..	189.0
Count of #2 pressure..	189.0
Count of #3 pressure..	189.0
Count of #4 pressure..	189.0
Count of #8 pressure..	189.0

Figure 5.2.15: Pressure readings (in wc) for third field test (Scenario 2)

The relationship between air pressures and weather station wind speeds is depicted in Fig. 5.2.16.

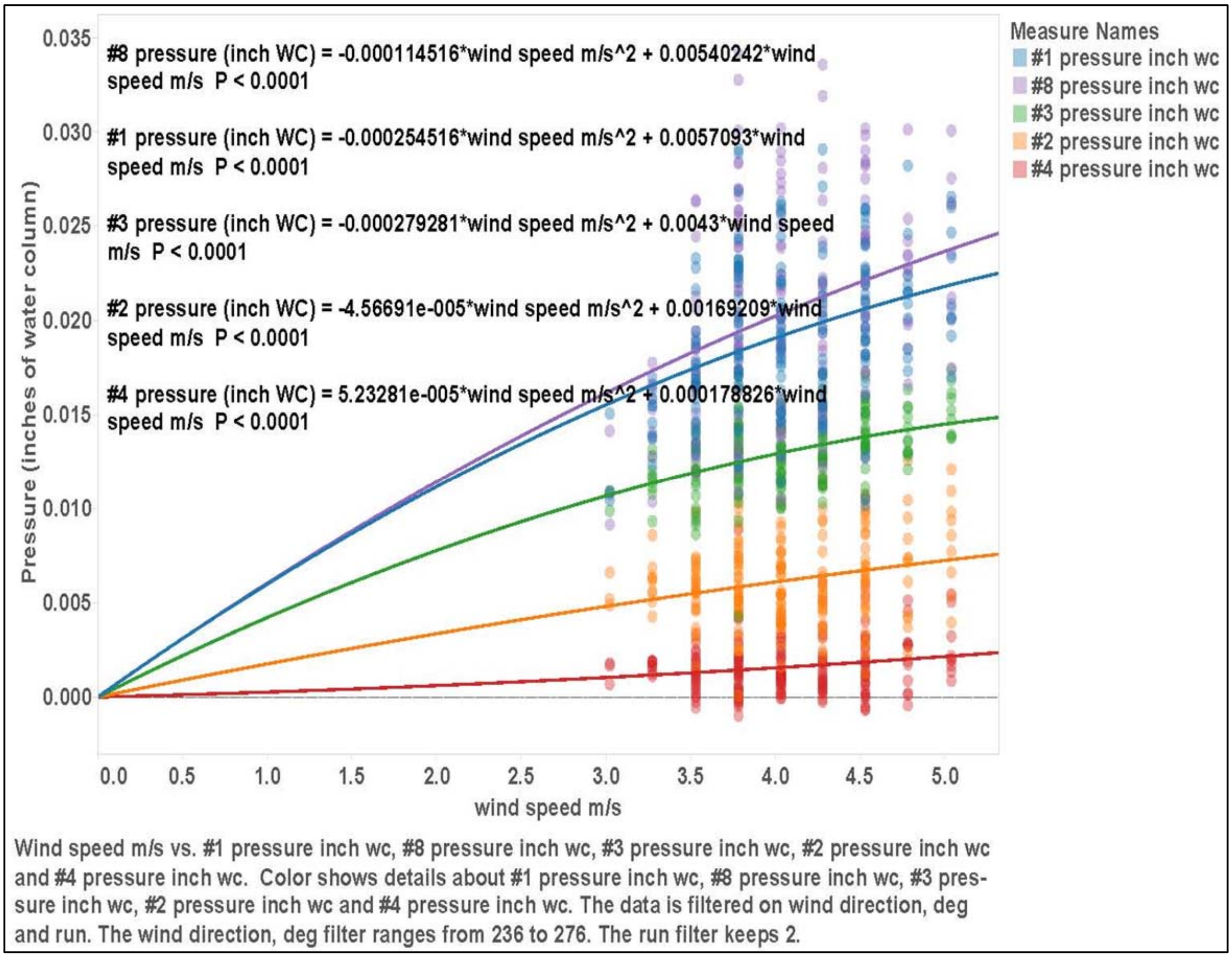


Figure 5.2.16. Pressure readings (in wc) for sensors #1 2, 3, 4, and 8

5.3 Lessons Learned:

- It would be beneficial to configure the SignalExpress software to carry out the 1-second averaging. It can also be configured to scale the data, but having the raw readings seems a more secure way of storing the data and avoids a potential loss of data quality due to a mistake in configuration.
- The vertical data structure allows for linking the table to a sensor information table that would have more complete information on the sensor. This format provided some obstacles for filtering data, so there is still work to be done on the scripting for filters.
- Data needs to have a precision of 5 decimal points because the units of inches of water column are so small.
- Future analyses may filter for wind direction if the wind shifted during the test.
- There appears to be an approximate 8-second difference in timing of gusts between the weather station and the anemometers. This is presumably due to a momentum effect of the cup-type sensor on the weather station. A more precise wind measurement may be beneficial for future studies.

SECTION 6: COMPARISON OF PREDICTED CFD AND ACTUAL FIELD DATA FOR TEST STRUCTURE

This section describes the process of comparing the actual field data with CFD simulations using the same wind conditions as encountered during the field tests. Since the wind conditions in the initial CFD simulations (which were used to select the appropriate placements of the wind sensors and pressure tubing terminal units) a new set of CFD simulations had to be carried out. This section shows the developed process of validating CFD simulations with the actual field measurements.

6.1 Repeating CFD Simulation Using the Actual Wind Conditions at the Test Site

The CFD simulations carried out for the comparison with actual field data used more refined computational domain setting than the initial CFD simulation. The geometry of the test structure remained the same in both CFD simulation runs.

6.1.1 Domain Size

The size of the computational domain was chosen based on the best practice recommendation of COST (Franke, 2007, reference list in the literature review for external CFD, project report 1) for buildings in urban environment conditions. However, for the purpose of the shakedown tests with a car to test the capability of the CFD application on dealing with high accuracy and large numbers of volume cells, the size of lateral extension D, inflow region extension L1, wake region extension L2, the top region extension were set as follows H (Table 6.1.1) where H = 5’-4”(1.65m) is the height of the car (Fig. 6.1.1.1a, Fig.6.1.1.1b and Fig. 6.1.1.2).

Extension of the domain	Minimum Recommendation	Actual size used
Lateral extension D	5H = 8.25	15H ≈ 24m
Inflow region extension L1	5H = 8.25	15H ≈ 24m
Wake region extension L2	15H = 24.75	40H ≈ 65m
Top region H	5H = 8.25	15H ≈ 13m

Table 6.1.1: The heights of the anemometers and the pressure terminal tubes for measurement

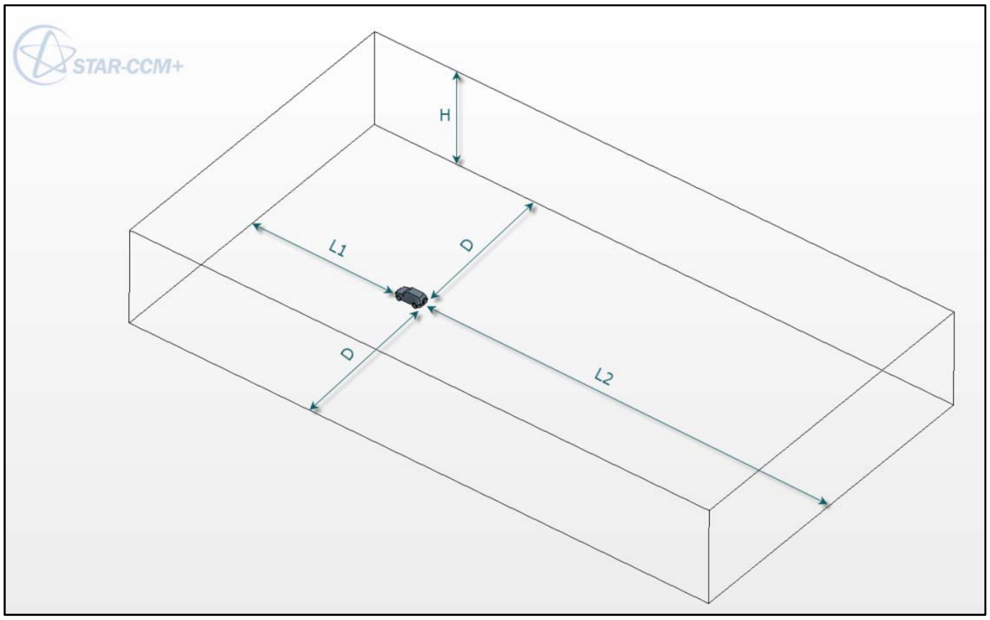


Figure 6.1.1.1a: The size of the computational domain for the car parallel to the prevailing wind test scenario

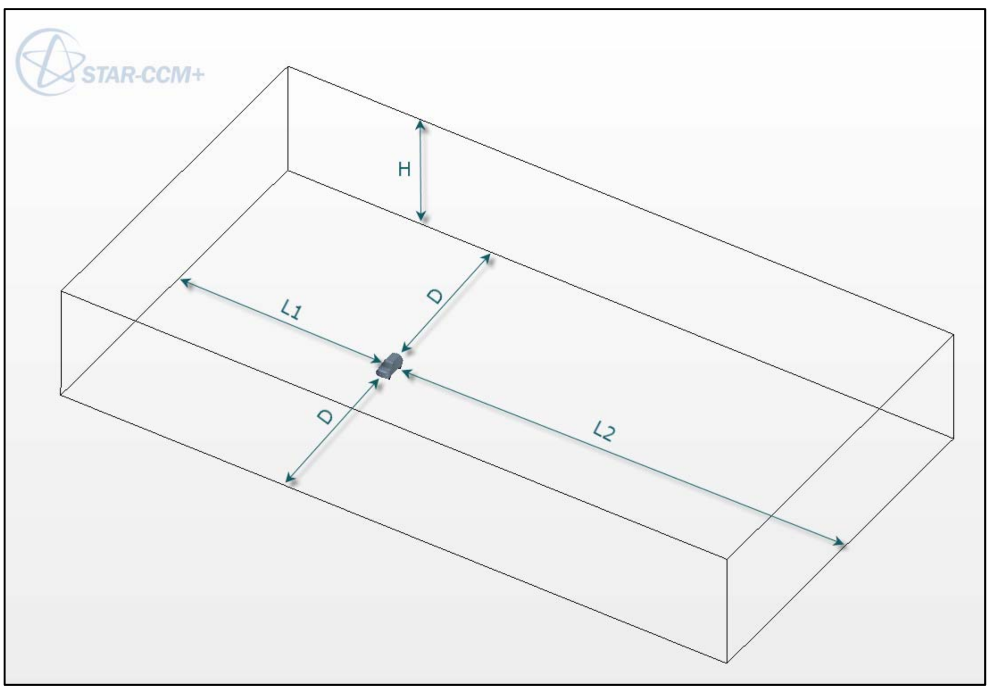


Figure 6.1.1.1b: The size of the computational domain for the car perpendicular to the prevailing wind test scenario

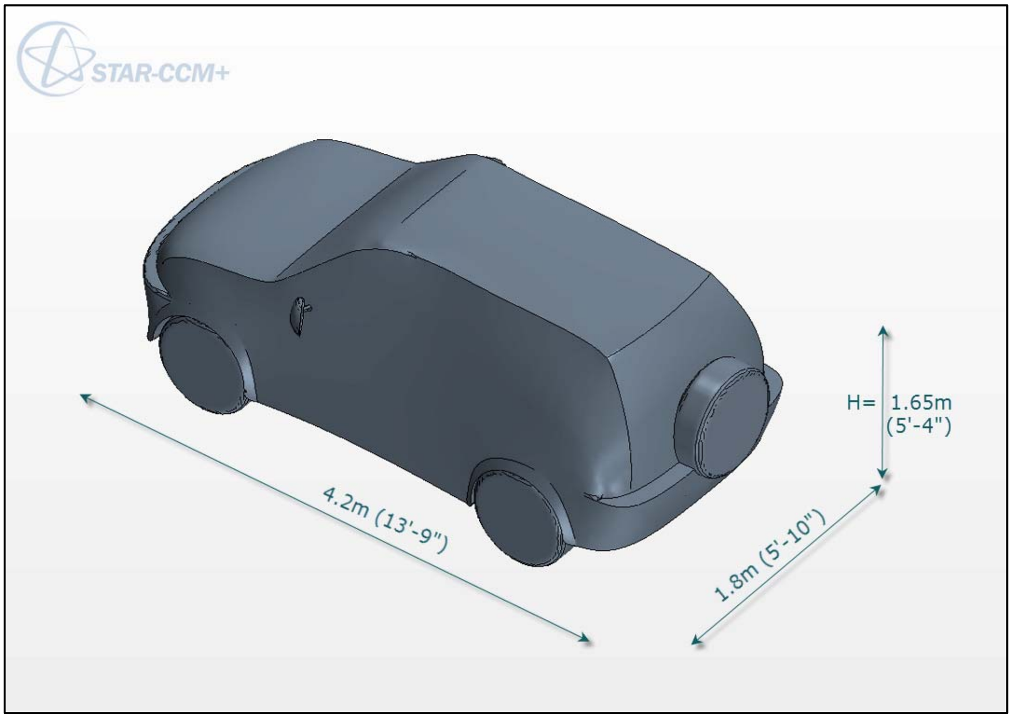


Figure 6.1.1.2: The dimension of the test structure (RAV-SUV) car which was used for the shakedown tests

6.1.2 Volume Meshing

- STAR-CCM+ provides several meshers as well as control volume cell types for meshing. For building structure related meshing, trimmed cell mesher was used to produce high-quality grid as convenient alignment with the Cartesian coordinate system. Since the 3D CAD model was modeled from Autodesk Inventor, then imported into STAR-CCM+, use of surface wrapper functionality of STAR-CCM+ was a convenient tool to create a continuous surface mesh. Near-wall prism layers were applied for the cars' surfaces as well as for the domain's ground surface. Four meshers were chosen including Surface Remesher, Surface Wrapper, Trimmer and Prism Layer Mesher as shown in the Figure 6.1.2.1 as follows:

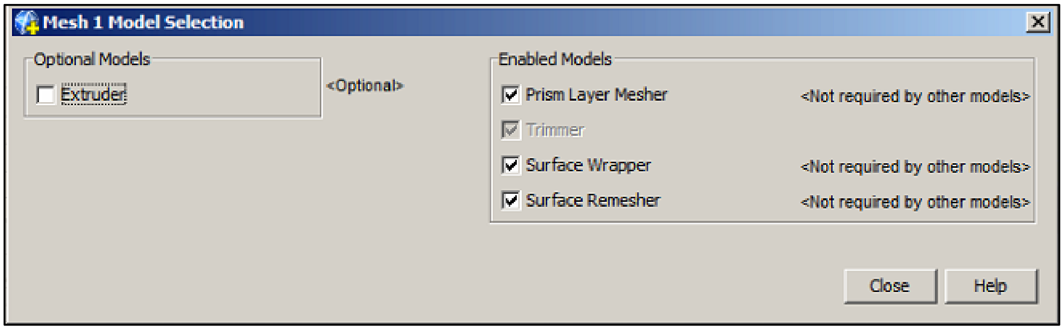


Figure 6.1.2.1: Selected meshers for meshing

- To ensure the meshing high resolution around the car but reducing the number of volume cells, the minimum size of the volume cells was set as small as 1mm (0.001 m) to capture the car's detailed surfaces while the maximum of the volume cells was 4m to set for the air boundary layer. The global meshing settings for the meshers is shown in the Table 6.1.2.1 as follows:

-

Parameters	Values
Reference Base Size	1.0 m
Maximum Cell Size	4 m (400%)
Number of Prism Layers	3
Prism Layer Thickness	0.02 m (2%)
Surface Growth Rate	1.3
Relative Minimum Surface Size	1.0 m (100%)
Relative Target Size	5.0 m (500%)
Template Growth Rate	Very Slow
Wrapper Scale Factor	80%

Table 6.1.2.1: Global setting for meshing

- The domain's ground surface was locally set with following settings (Table 6.1.2.2):

Parameters	Values
Number of Prism Layers	3
Prism Layer Thickness	0.4m (40%)

Table 6.1.2.2: Local setting for the ground

- All car's surfaces was also locally set with the following settings (Table 6.1.2.3)

Parameters	Values
Relative Minimum Size	0.02m (2%)
Relative Target Size	0.1m (10%)
Number of Prism Layers	3
Prism Layer Thickness	0.005m (0.5%)

Table 6.1.2.3: Local setting for the car

The visualization of the meshing of the computational domain and the car is shown in Figure 6.1.2.3 and Figure 6.1.2.4 . The different cell sizes can be observed close to the test structure (RAV-SUV) and more distant at the domain boundaries.

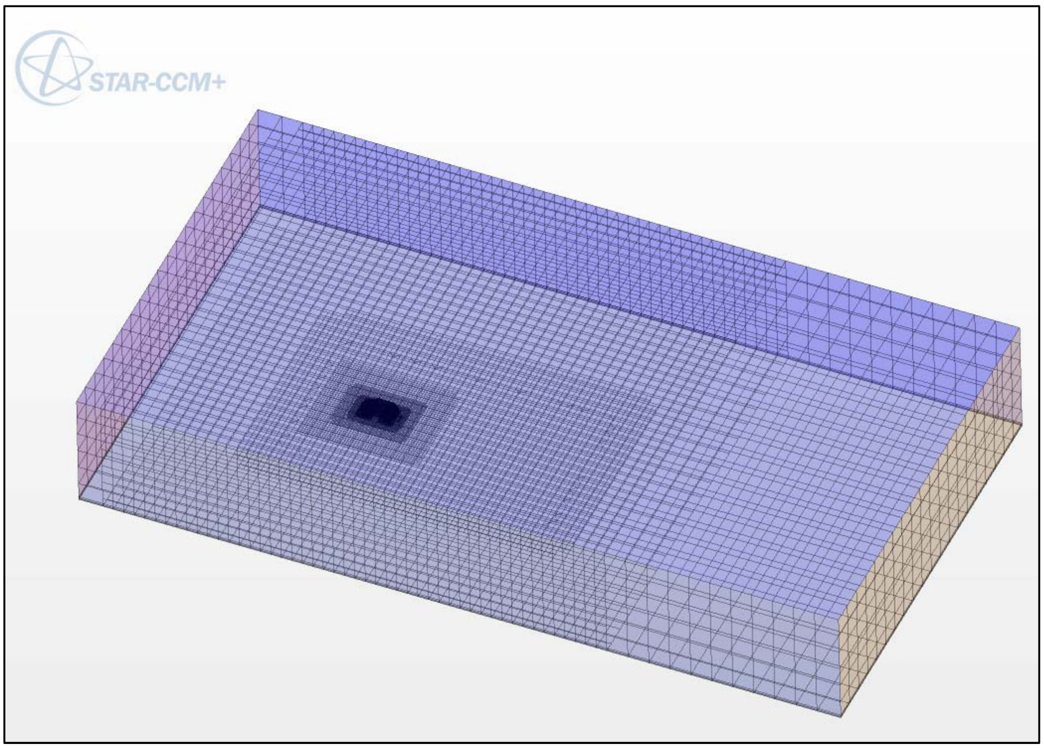


Figure 6.1.2.3: Meshing of computational domain and the car.

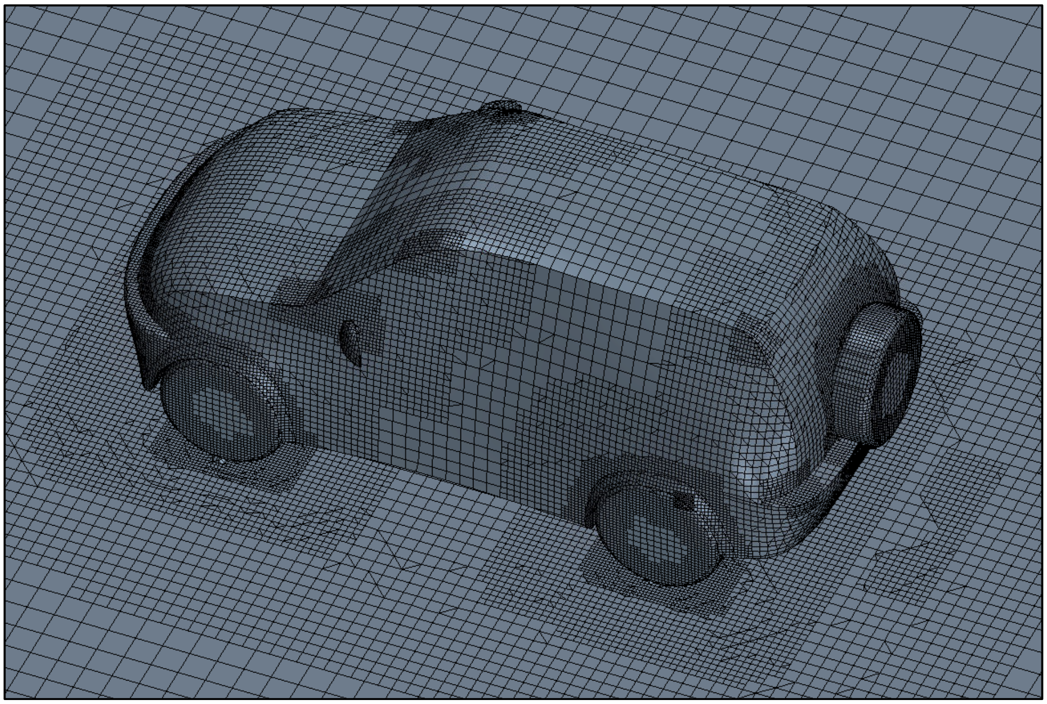


Figure 6.1.2.4: Detailed surface meshing of the car.

6.1.3 Volume Mesh Quality Check

Checking the quality of the volume cells of meshing is essential for the accuracy of the simulation. Therefore, a quick cell diagnosis was conducted after the meshing was completed. Two criteria were used for checking the quality of the volume mesh, these two criteria are face validity and the volume change.

The first criterion is the face validity - "an area-weighted measure of the correctness of the face normal vectors relative to their attached cell centroid" (Fig. 6.1.3.1). The face validity ranges from 1.0 for good cells (face normal points outwards) to 0.5 for bad cells (face normal points inwards toward the cell centroid) (STAR-CCM+ Manual).

The second criterion is the volume change metric as "the ratio of the volume of a cell to that of its largest neighbor." Illustrated in the Figure 6.1.3.1. A value of 1.0 indicates that the cell has a volume equal to or higher than its neighbors and a volume change of 1e-05 or below indicates bad cells having a large jump in volume from these cells to their neighbors and should be investigated or fixed.

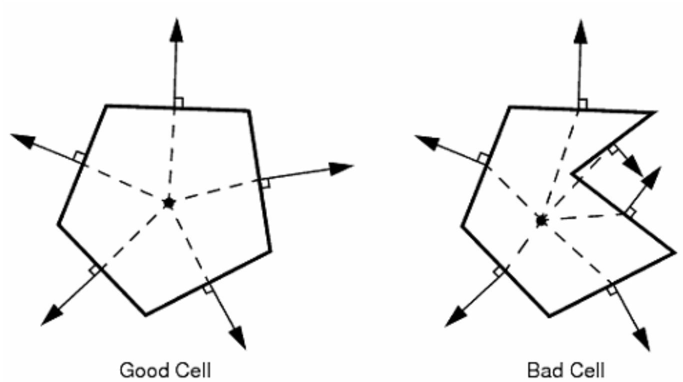


Figure 6.1.3.1 Example of good and bad cell based on cell validity criterion (STAR-CCM+ Manual).

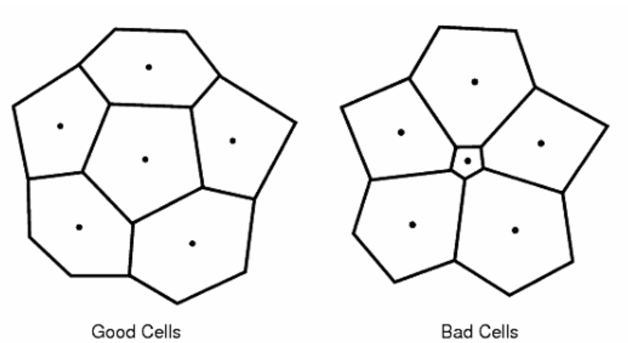


Figure 6.1.3.1: Example of good and bad cell based on volume change criterion (STAR-CCM+ Manual).

The result of the cell validity and volume change check of the model was shown as follows (Table 6.1.3.1 and Table 6.1.3.2):

Cell validity		**Number of cells**	**Percentage**
	<= 1e-6	0	0.000%
1e-6	1e-5	0	0.000%
1e-5	1e-4	0	0.000%
1e-4	1e-3	28	0.004%
1e-3	1e-2	664	0.089%
1e-2	1e-1	16,738	2.241%
1e-1	1.0	729,422	97.67%
Total number of volume cells		746,852	

Table 6.1.3.1: Result of the cell validity check

Volume change		**Number of cells**	**Percentage**
	<= 0.5	0	0%
0.5	0.6	0	0%
0.6	0.7	0	0%
0.7	0.8	0	0%
0.8	0.9	0	0%
0.9	1.0	0	0%
1.0		746,852	100%

Table 6.1.3.1: Result of the volume change check.

6.1.4 Physics Settings

The simulation used steady state analysis. In the CFD analysis constant velocity and direction wind data for approach wind profile is defines. Since the CFD results were compared with actual field measurements a representative wind velocity and direction was used as CFD input parameters, which resembled the statistical description of the data obtained in the field. A RANS-based Realizable k-ε turbulence model was chosen. Since the height of domain is 13m which is quite small in comparison to the recommended height (200 m) of the air boundary layer which in within that range, the air density can be treated as constant (COST, Franke 2007). Other physics selected for this simulation included two-layer all y+ wall treatment, segregated flow (Fig. 6.1.4).

6.1.5 Boundary Conditions

Boundary conditions of the computational domain include the air boundary layers (inlet boundary, outlet boundary, lateral boundaries), the ground and car surfaces. Inlet boundary was used as velocity inlet. The vertical wind profile for the inlet were used is the log-law equation of wind velocity U(z), turbulence kinetic energy k(z) and turbulence dissipation rate ε(z) varying with the height as follows:

$$U(z) = \frac{U^*_{ABL}}{k} ln\left(\frac{z - z_{ground} + z_0}{z_0}\right)$$

$$k(z) = \frac{U^{*2}_{ABL}}{\sqrt{C_\mu}}$$

$$\varepsilon(z) = \frac{U^{*3}_{ABL}}{k(z + z_0)}$$

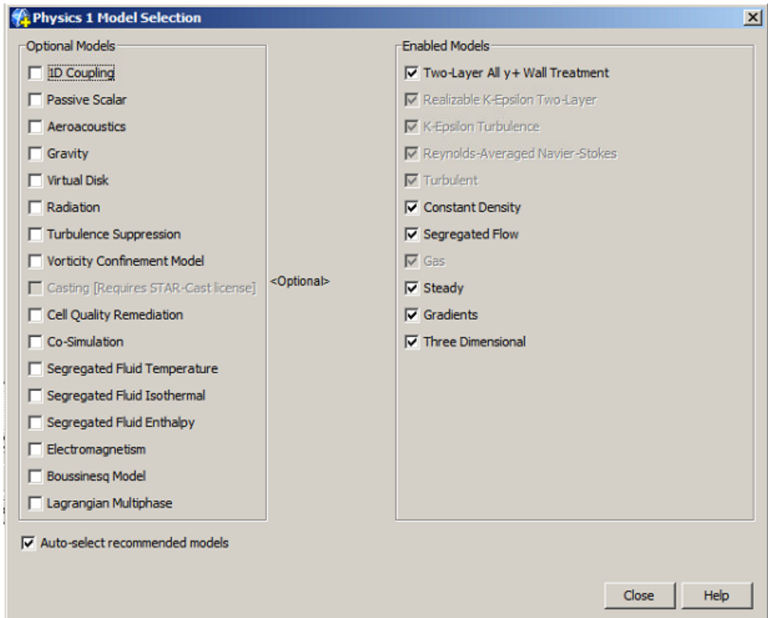


Figure 6.1.4: Data setting in STAR-CCM+ - Physics models selected for the simulation

Where k is the Karman constant (=0.42), C_μ is the model constant (0.09), z_0 is the roughness parameter and U^*_{ABL} is the atmospheric boundary layer friction velocity can be calculated as:

$$U^*_{ABL} = \frac{kU_r}{\ln((z_r + z_0)/z_0)}$$

Therefore,

$$U(z) = U_r\, ln\left(\frac{z - z_{ground} + z_0}{z}\right) / \ln\left(\frac{z_r + z_0}{z}\right)$$

Where z is the height, z_{ground} is the ground elevation, z_o is the aerodynamic roughness length (Table 6.1.5), U_r is the reference velocity at reference height z_r.

Class	*Short terrain description*	z_0 *(m)*
1	Open sea, fetch at least 5 km	0.000 2
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, $x/H > 20$	0.10
5	High crops; scattered obstacles, $15 < x/H < 20$	0.25
6	Parkland, bushes; numerous obstacles, $x/H \approx 10$	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City centre with high- and low-rise buildings	≥2

Note: Here *x* is a typical upwind obstacle distance and *H* is the height of the corresponding major obstacles. For more detailed and updated terrain class descriptions see Davenport and others (2000) (see also Part II, Chapter 11, Table 11.2).

Table 6.1.5: Aerodynamic roughness length z_o based on terrain classification from Davenport (1960) (Source: MO Guide to Meteorological Instruments and Methods of Observation WMO-No. 8 page I.5-12)

The inlet boundary condition was set as pressure inlet with static pressure assigned as 0 Pascal. The lateral boundaries and the top boundary were assigned as symmetry plane. The ground and the car surfaces were assigned as wall type. The Blended Wall Function was used as near-wall function using the default values of function coefficient E (9.0) and the Von Karman constant Kappa (0.42).

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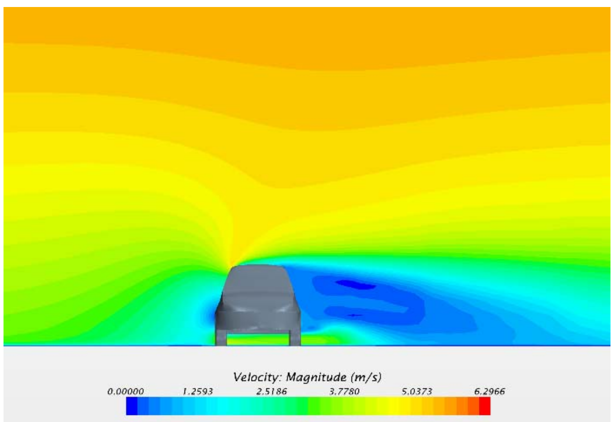
6.2 Comparing CFD Results with Actual data:

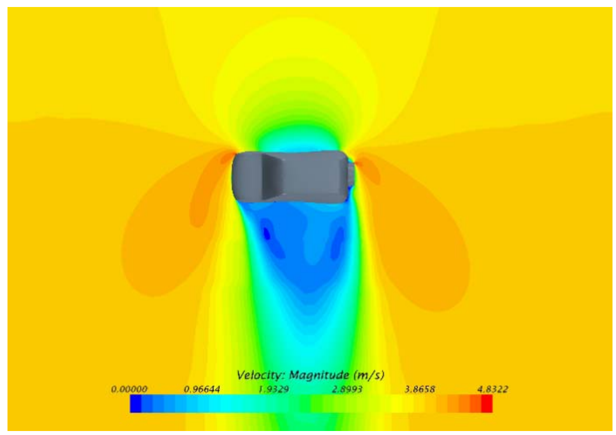
This section presents the comparison of CFD simulations carried out with the wind conditions at the test site and the actual field data.

6.2.1 CFD Result Visualization to be used for Field Data Comparison

Each scenario was set to run for maximum iteration up to 1000. No other convergence criteria settings were set for the solver, but it was expected that the residuals for continuity, momentum, turbulence kinetic energy (TKE) and turbulence dissipation rate (TDR) should be below 1e-4. Two examples of velocity and pressure maps are shown in Fig. 6.2.1.1 and Fig. 6.2.1.2. More other post-processing of CFD results is shown in the Appendix E.3.

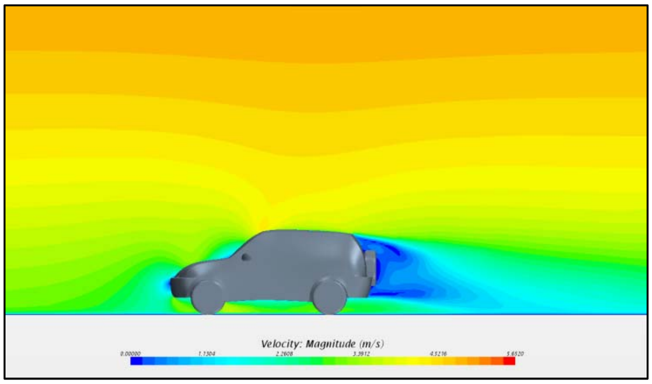


Side view

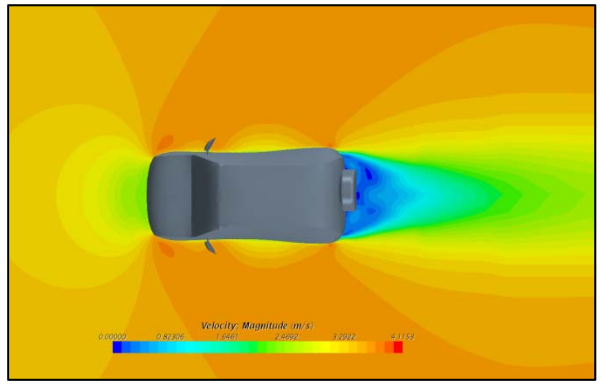


Plan view

Figure 6.2.1.1: **Scenario 1:** Velocity map at cross section and Pressure map at 3 feet height elevation plane (Scenario 1: approach wind perpendicular to the longitudinal axis of the car)



Side view



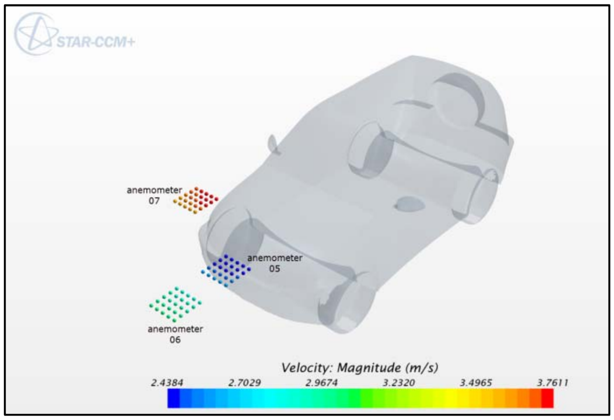
Plan view

Figure 6.6.1.2: **Scenario 2:** Velocity map at cross section and Pressure map at 3 feet height elevation plane (Scenario 2: approach wind parallel to the longitudinal axis of the car)

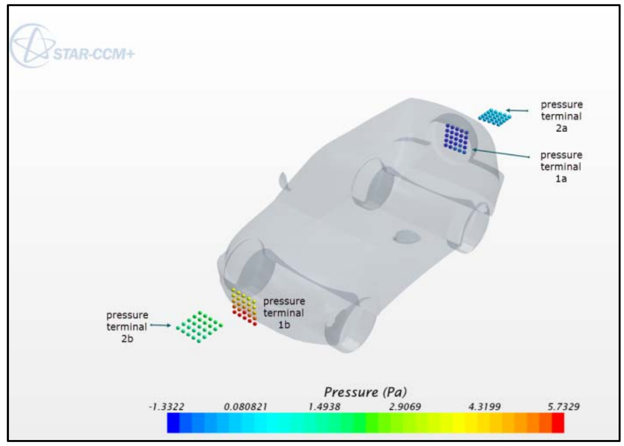
6.2.2 CFD Results at Locations Corresponding to Field Data Measurements

In order to compare the actual field measurement to the CFD results, data from the CFD results were extracted at cell locations which exactly match the locations where measurement were taken. It was decided that rather than using a specific CFD cell (or data point), a small-grid probe with a dimension of 1 x 1 feet would yield more representative CFD data. Thus in order to account for the size and the configuration of the differential pressure terminals as well as the tolerance during the field test, the extracted data from the CFD data for a given sensor were averaged from cells located on the 1’ by 1’ grid.

In STAR-CCM+, representation grid-type probes of 1’ by 1’ (5x5 cell resolution) were created to the height where the sensors were in place for measurement during the field tests (see Figures 6.2.1.1 through 6.2.2.2). There are 25 cells for each 1’ by 1’ representation grid-type probe.



Small-grid probe to represent velocity data calculated in the CFD simulations



Small-grid probe to represent pressure data calculated in the CFD simulations

Figure 6.2.2.2: Presentation grid-type probes 1'x1' used to extract the wind velocities and wind-driven differential pressure (run 2: the approach wind parallel to the longitudinal axis of the car)

6.3 Conclusions of Comparison

The wind velocities, wind-driven differential pressures from the field tests and extracted CFD results were compared for validation. The comparison for two runs which are relevant to two field test's scenarios is shown in the Appendix F. For both scenarios, comparisons suggest a quite good correlation between field measurement and CFD prediction for wind velocity. There is, however, difference in differential pressure (Table 6.3.1 and Table 6.3.2).

Sensor ID	Unit	Measurement	CFD	Difference (%)
Anemometer 5	m/s	1.296	1.312	1.27%
Anemometer 6	m/s	2.728	2.772	1.61%
Anemometer 7	m/s	3.756	4.015	6.90%
Differential Pressure (1b vs.1a)	Pa	6.56938	5.781207	-12.00%
	in w.c.	0.02640	0.023233	
Differential Pressure (2b vs.2a)	Pa	3.77241	2.134643	**-43.41%**
	in w.c.	0.01516	0.008578	

Table 6.3.1: Field measurement and CFD result comparison of run 1 (approach wind perpendicular to longitudinal axis of the car).

Sensor ID	Unit	Measurement	CFD	Difference (%)
Anemometer 5	m/s	2.438	2.456	0.75%
Anemometer 6	m/s	3.407	2.904	**-14.77%**
Anemometer 7	m/s	4.248	3.700	**-12.91%**
Differential Pressure (1b vs.1a)	Pa	4.71800	5.78120	**22.53%**
	in w.c.	0.01896	0.02323	
Differential Pressure (2b vs.2a)	Pa	1.52539	2.13464	**39.94%**
	in w.c.	0.00613	0.00858	

Table 6.3.2: Field measurement and CFD result comparison of run 2 (approach wind parallel to longitudinal axis of the car).

The discrepancy between measurement and CFD results in differential pressure required the research team to consider the follows issues for subsequent project work:

- Apply appropriate filtering of data for given wind direction so that turbulence-related approach wind phenomena can be eliminated.
- Review of the settings of the CFD models such as roughness length, the wall-function coefficients, and the configuration of the pressure probes for extracting data.

REFERENCES

For the sake of brevity the references are noted throughout the text rather than given in form of a reference list.

LIST OF APPENDICES:

There are six appendices presented which provide additional information about the project work performed:

Appendix A – Selection of Test Site and Test Structure

Project communication that describes candidate test sites and the selection of the final shakedown test site and test structure.

Appendix B – Instrumentation

Specification and other supporting information about the instrumentation used in the shakedown testing.

Appendix C – Field Tests

Provides descriptions and Photo documentation of the three days of Shakedown testing.

Appendix D - Data Analysis and Data Reduction

Provides a comprehensive description of the methods and procedures used in the data analysis and data reduction.

Appendix E – Initial CFD Simulations

1. Description of CAD process to build the 3D-model of the test structure (RAV-SUV)

2. Description of the initial CFD simulation runs that were used to identify suitable locations for the placement of the anemometers and pressure tubing terminals

Appendix F – Final CFD Simulations and Comparison of CFD and Actual Field Measurements

Documentation of the results of the final CFD simulations that were used for the comparison with the actual field data.

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Appendix A – Selection of Test Site and Test Structure

Project communication that describe candidate test sites and the selection of the final shakedown test site and test structure.

HNEI – ERDL CFD research project

PROPOSED WORK PLAN

Task 7.a.3: Develop and calibrate a data verification process for external CFD simulations

Proposed work plan for this project phase:

Time allocated for this Phase: November 10, through December 6, 2013:

The main objectives of the shake-down tests in this project phase 7.a.3 are as follows:

- Calibrating wind velocity and/or pressure instrumentation in the lab environment and deploy instruments in field to obtain scoping data for the shake-down testing
- Deploy a simple wind obstruction in the field to obtain measurements of wind movement around the object, expressed as velocity and pressure patterns.
- Compare of the result of measured field data of velocity and/or pressures with CFD analysis and fine tune CFD model or repeated field test runs

The objectives are realized by the following project tasks

(A) Acquire working knowledge in setting up and calibrating instrumentation for velocity and pressure measurements and prepare instrumentation and data acquisition systems for field deployment.

In preparation of the actual velocity and/or pressure measurements of external wind movement around the selected building in the UHM (still TBD) the instrumentation and data acquisition systems needs to be prepared, calibrated and be readied for field deployment.

Velocity sensors are available to conduct the first set of measurements. There are three types of anemometers available:

1. Weather station with wind data for wind velocity and direction
2. Eight to nine anemometer senor to measure unidirectional wind velocity

The date acquisition hardware is available for the velocity sensors and an instrumentation array network will be created to log the data.

Pressure transducers are not yet available. It is presently examined whether or not a differential pressure transducer can be obtained for a short time from local sources in order to verify the pressure differentials that can be measured in the tests

For the field test simple stands will be build. The simple stands will be fabricated in the ARCH shop and will serve to attach the velocity and pressure transducers. Figure 1 shows a possible construction of the instrumentation stands; in case recycled material can be used for the stands the design will be changed

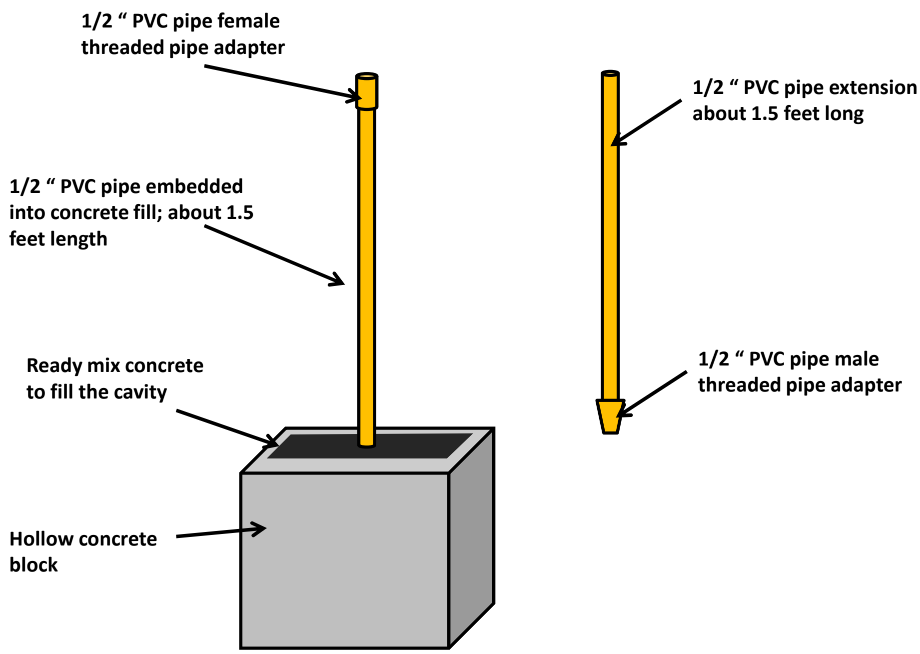


Figure 1: Simple instrument stands to be built for the shake-down test in the field

(B) Identify a suitable test location where wind movement is appropriate for initial test data of velocity and pressures around a simple (and smaller) object.

An earlier plan was to carry out the wind measurements of the shake-down tests around a simple object in close vicinity of the School of Architecture. The original plans for the scoping test measurement included to create an obstruction to wind movement by assembling a temporary rectangular object of about 10x10 feet with a height of about 6 feet. The temporary object was to be built by wooden boxes and tables to acquire the targeted box-like structure.

Initial wind velocity scoping measurements were conducted at a site close to the School of Architecture building over two days on November 7th and 8th. (refer to Figure 3 for the location of the initial scoping test) The purpose of the scoping tests was to identify approximate average and peak wind velocity as well as direction in order to determine a baseline for typical wind movement at the site. The scoping tests revealed that the wind direction and speeds at the initial site are erratic with frequent changes in wind speed magnitude and wind direction. Data analysis of the wind record indicate that the predominate wind direction was essentially evenly distributed over a 90 degree direction range. The wind velocity also changed with significant amplitudes and short term variances. The reason for this fast changing wind regime is the creation of large scale eddies as the wind moves around the adjacent buildings and over the grassy area in front of the SoA building.

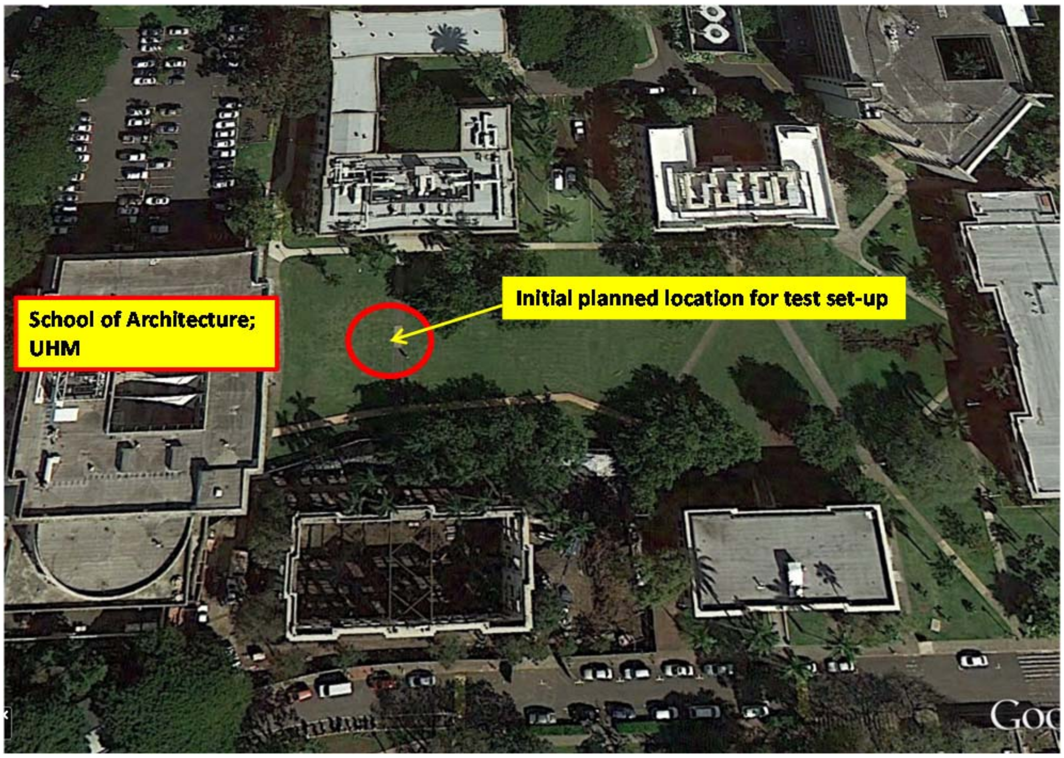


Figure 2: Site of the initial scoping test and initially planned site for the shake-down test in the field; this site proved not to be appropriate for the shale-down testing

Based on the initial scoping test the CFD determined that the initial site would not be suitable to carry out shake-down tests for velocity and pressure occurrence around the test structure. The CFD team therefore searched for a site that would combine the following two main criteria:

- Good exposure to wind, which means relative unobstructed wind approach and normally good wind conditions, with steady wind speeds and less eddies from adjacent strcutures.
- Ease of access to place a temporary structure surrounded by an array of instruments.

The CFD team has identified a site in Hawaii Kai that that is located on a dirt parking lot next to the ocean. The site has typically good exposure to wind. The site is shown in Figures 3 and 4 as the vicinity map and site map, respectively.

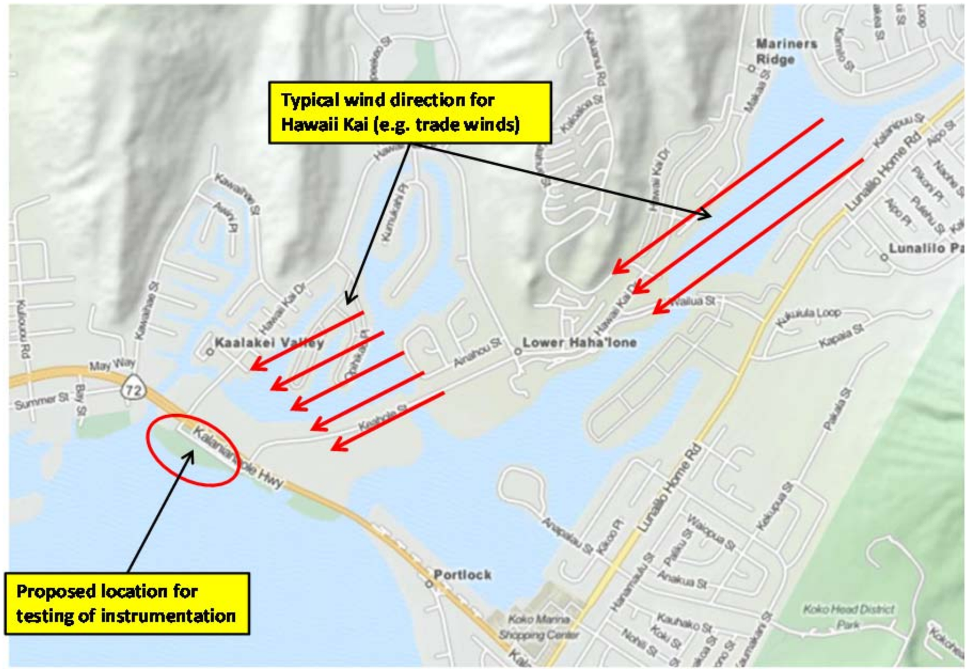


Figure 3: Selected site for the shake-down tests – Vicinity Map

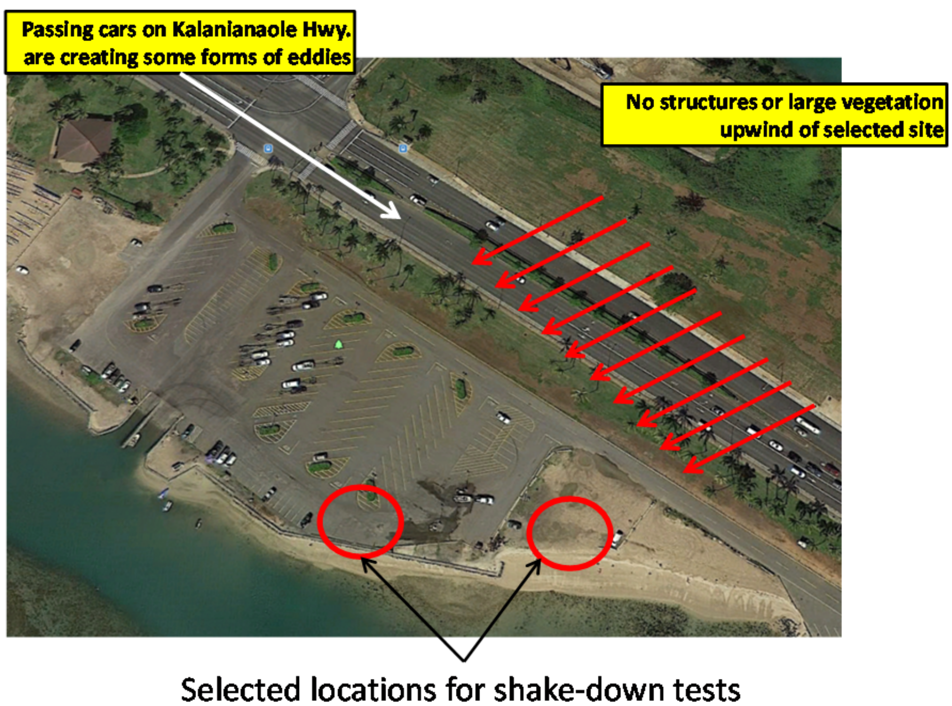


Figure 4: Selected site for the shake-down tests – detail map

(C) Selecting a suitable object to serve as obstruction to wind movement

The shake-down test will measure velocity and pressure patterns around an obstruction as wind is deflected by a sizable object. The object (subsequently referred to as the test specimen) should to be large enough to develop a discernible change in wind patterns and a resulting detectable velocity and pressure field in close proximity of the object.

While a large and fixed test specimen, such as a small building or container size structure, with simple geometry, would be the most appropriate, flexibility, ease and low cost of deployment the test specimen motivated the CFD team to select a vehicle as the test specimen. A moveable test specimen such as a larger car or better a truck has the great advantage of being installed (e.g. parked) in a short time without the requirement of long preparations or obtain authorizations. Figure 5 shows the two vehicles the CFD test team has identified as possible test specimen. The final selection of the vehicle will be contingent on available funds to rent a larger truck, such as suggested in Figure 5.

Candidate vehicles to be used in the shake-down tests

Option 1: - SUV
Advantage - Car available without cost, for one or multiple time
Disadvantage – lateral area is not large

Option 2: - mid size truck
Advantage – lateral area is larger than in option 1
Disadvantage – truck as to be rented, perhaps multiple times; it will not be sure that the truck with the same outside dimensions will be available

Figure 5: Candidate vehicles to be used as test specimen for the shake-down tests

(D) Creating the 3D-geometry and CFD meshing of the test specimen in the selected CFD program (STARR-CCM+) and run initial simulations using appropriate boundary conditions:

CFD simulations will be conducted using the selected vehicle. Initial CFD simulations will be conducted before the shake-down tests to identify the approximate flow field around the vehicle, in order to identify the appropriate placement of instruments around the test specimen (e.g. vehicle). Figure 6 shows an **anticipated wind velocity** around the test specimen. The markers in Figure 6 suggest locations of interest for which wind velocities data should be obtained in the shake-down tests.

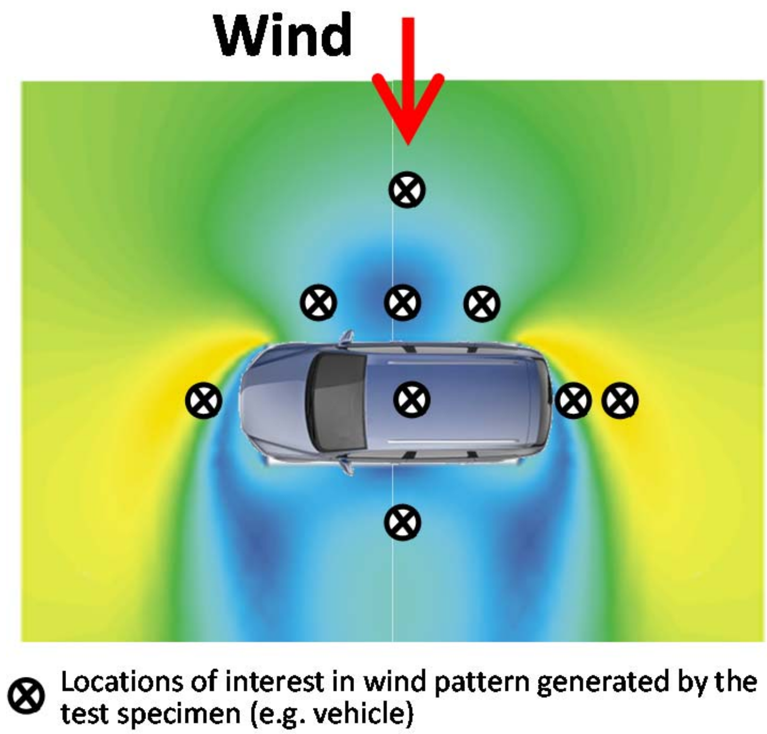


Figure 6: Anticipated locations of interest to obtain velocity data (Note: velocity pattern indicated is a generic pattern and does not reflect the CFD analysis for the test specimen)

(E) Obtain velocity and possibly also pressure measurements in field tests.

The field measurements will be conducted at short notice. After the instrumentation is ready to deploy suitable weather forecasts with sufficient wind will trigger the tests.

<u>Proposed instrumentation placement for wind velocity measurements around test specimen:</u>

The anticipated generic wind velocity pattern around the test specimen (refer to Figure 6.) would call for a deployment of available anemometer instrumentation as depicted in Figure 7. It is planned to carry out at least one day of testing in the field, where the team wants to obtain a comprehensive data set using two approach directions of the wind, relative to the test specimen. If needed the test will be conducted at multiple days

Proposed instrumentation placement for wind pressure measurements around test specimen:

Pressure measurements would be conducted by using one (1) differential pressure transducer and varying the location of test tubing (e.g. plastic tubing to connect the two tube terminus to the differential pressure transducer).

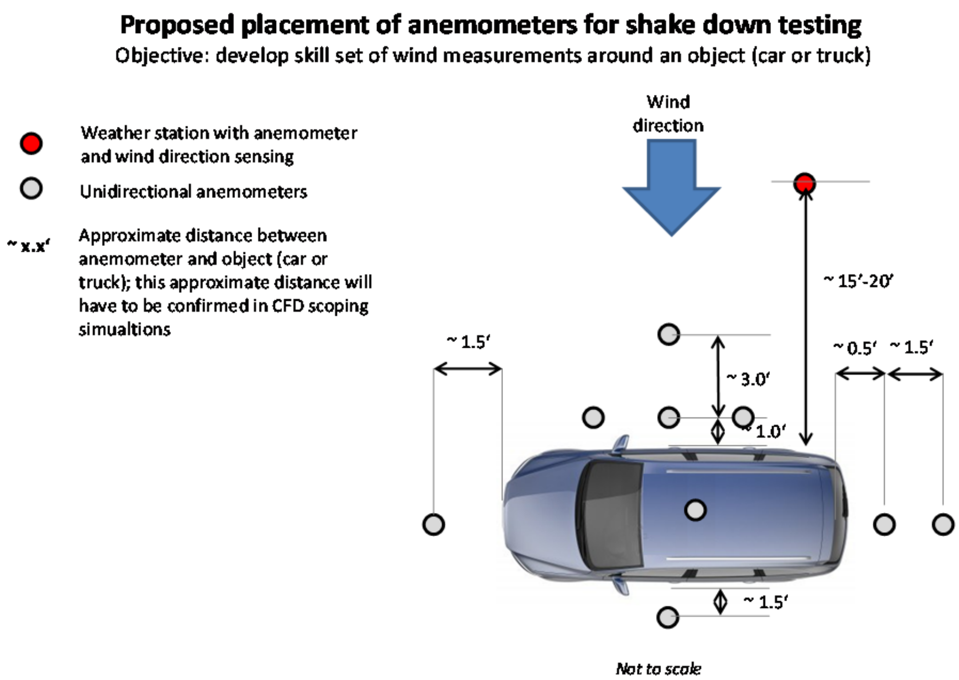


Figure 7: proposed placement of anemometers around the test specimen for shake-down testing

(F) Compare the wind velocity and pressures measured in the field with the results of the CFD simulations:

The data obtained in the field will be compared with results of CFD simulations using average wind velocities and approach directions identified during the field experiments.

(G) Fine tune the CFD model and repeat field test if required.

The CFD simulations will be fine-tuned using a test matrix of different turbulence models, mesh density and/or boundary conditions. If required the field test will be repeated.

(H) Create final report and submit to HNEI.

The completed shake-down tests and the results of the CFD simulations and comparison to field data will be described in a final report to HNEI.

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Appendix B – Instrumentation

Specification and other supporting information about the instrumentation used in the shakedown testing

Appendix B. Instrumentation

Equipment Specification Sheets are included in this appendix. Further information can be found at websites:

- National Instruments USB-6341
  - http://sine.ni.com/nips/cds/view/p/lang/en/nid/209069
- Onset HOBO U12 portable data loggers
  - http://www.onsetcomp.com/products/data-loggers/U12-data-loggers
- Setra Air Pressure Transducer Model 264
  - http://www.setra.com/products/pressure/low-differential-pressure-transducer-model-264/
- Halstrup Walcher P26 pressure transducer
  - http://www.iag.co.at/uploads/tx_iagproducts/pdf_handbuch/P26.en.pdf
- Degree Controls Accusense F900-0-5-1-9-2 anemometer with the XS blade
  - http://www.degreec.com/en/airflow-sensing-products/embedded-sensing-products/f900-airflow-sensors.html
- Onset HOBO U30 weather station
  - http://www.onsetcomp.com/products/data-loggers/u30-nrc

NI 6341/6343 Specifications

Français	Deutsch	日本語	한국어	简体中文

ni.com/manuals

Specifications listed below are typical at 25 °C unless otherwise noted. Refer to the *X Series User Manual* for more information about NI PCIe-6341/6343, NI PXIe-6341, and NI USB-6341/6343 devices.

Analog Input

Number of channels
- NI 6341 .... 8 differential or 16 single ended
- NI 6343 .... 16 differential or 32 single ended

ADC resolution .... 16 bits

DNL .... No missing codes guaranteed

INL .... Refer to the *AI Absolute Accuracy Table*

Sample rate
- Maximum .... 500 kS/s single channel, 500 kS/s multichannel (aggregate)
- Minimum .... No minimum
- Timing accuracy .... 50 ppm of sample rate
- Timing resolution .... 10 ns

Input coupling .... DC

Input range .... ±10 V, ±5 V, ±1 V, ±0.2 V

Maximum working voltage for analog inputs (signal + common mode) .... ±11 V of AI GND

CMRR (DC to 60 Hz) .... 100 dB

Input impedance
- Device powered on
  - AI+ to AI GND .... >10 GΩ in parallel with 100 pF
  - AI- to AI GND .... >10 GΩ in parallel with 100 pF
- Device powered off
  - AI+ to AI GND .... 1200 Ω
  - AI- to AI GND .... 1200 Ω

Input bias current .... ±100 pA

NATIONAL INSTRUMENTS™

Crosstalk (at 100 kHz)

Adjacent channels	-75 dB
Nonadjacent channels	-90 dB
Small signal bandwidth (-3 dB)	1.2 MHz
Input FIFO size	4,095 samples
Scan list memory	4,095 entries

Data transfers

NI PCIe/PXIe-6341/6343	DMA (scatter-gather), programmed I/O
NI USB-6341/6343	USB Signal Stream, programmed I/O

Overvoltage protection (AI <0..31>, AI SENSE, AI SENSE 2)

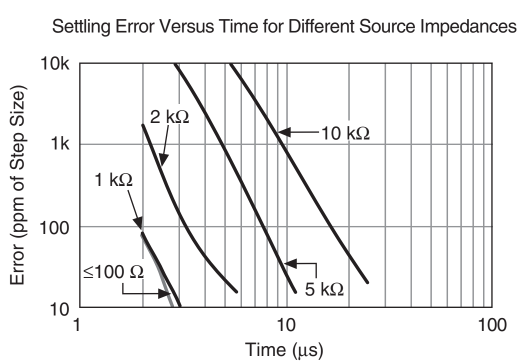
Device powered on	±25 V for up to two AI pins
Device powered off	±15 V for up to two AI pins
Input current during overvoltage condition	±20 mA max/AI pin

Settling Time for Multichannel Measurements

Accuracy, full scale step, all ranges

±90 ppm of step (±6 LSB)	2 µs convert interval
±30 ppm of step (±2 LSB)	3 µs convert interval
±15 ppm of step (±1 LSB)	5 µs convert interval
Analog triggers	None

Typical Performance Graph



Analog Output

Number of channels
- NI 6341 2
- NI 6343 4

DAC resolution .... 16 bits

DNL .... ±1 LSB

Monotonicity .... 16 bit guaranteed

Maximum update rate (simultaneous)
- 1 channel .... 900 kS/s
- 2 channels .... 840 kS/s per channel
- 3 channels .... 775 kS/s per channel
- 4 channels .... 719 kS/s per channel

Timing accuracy .... 50 ppm of sample rate

Timing resolution .... 10 ns

Output range .... ±10 V

Output coupling .... DC

Output impedance .... 0.2 Ω

Output current drive .... ±5 mA

Overdrive protection .... ±15 V

Overdrive current .... 15 mA

Power-on state .... ±20 mV

Power-on/off glitch
- NI PCIe/PXIe-6341/6343 .... 2 V for 500 ms
- NI USB-6341/6343 .... 1.5 V for 1.2 s[1]

Output FIFO size .... 8,191 samples shared among channels used

Data transfers
- NI PCIe/PXIe-6341/6343 .... DMA (scatter-gather), programmed I/O
- NI USB-6341/6343 .... USB Signal Stream, programmed I/O

AO waveform modes:
- Non-periodic waveform
- Periodic waveform regeneration mode from onboard FIFO
- Periodic waveform regeneration from host buffer including dynamic update

---

[1] Typical behavior. Time period may be longer due to host system USB performance. Time period will be longer during firmware updates.

Settling time, full scale step
15 ppm (1 LSB) .... 6 µs

Slew rate .... 15 V/µs

Glitch energy
- Magnitude .... 100 mV
- Duration .... 2.6 µs

Calibration (AI and AO)

Recommended warm-up time .... 15 minutes

Calibration interval .... 2 years

AI Absolute Accuracy Table

Nominal Range		Residual Gain Error (ppm of Reading)	Gain Tempco (ppm/°C)	Reference Tempco (ppm/°C)	Residual Offset Error (ppm of Range)	Offset Tempco (ppm of Range/°C)	INL Error (ppm of Range)	Random Noise, σ (μVrms)	Absolute Accuracy at Full Scale[1] (μV)
Positive Full Scale	Negative Full Scale								
10	-10	65	7.3	5	13	23	60	270	2190
5	-5	72	7.3	5	13	23	60	135	1130
1	-1	78	7.3	5	17	26	60	28	240
0.2	-0.2	105	7.3	5	27	39	60	9	60

$$AbsoluteAccuracy = Reading \cdot (GainError) + Range \cdot (OffsetError) + NoiseUncertainty$$

$$GainError = ResidualGainError + GainTempco \cdot (TempChangeFromLastInternalCal) + ReferenceTempco \cdot (TempChangeFromLastExternalCal)$$

$$OffsetError = ResidualOffsetError + OffsetTempco \cdot (TempChangeFromLastInternalCal) + INL\_Error$$

$$NoiseUncertainty = \frac{RandomNoise \cdot 3}{\sqrt{10{,}000}}$$

For a coverage factor of 3 σ and averaging 10,000 points.

[1] Absolute accuracy at full scale on the analog input channels is determined using the following assumptions:

TempChangeFromLastExternalCal = 10 °C
TempChangeFromLastInternalCal = 1 °C
number_of_readings = 10,000
CoverageFactor = 3 σ

For example, on the 10 V range, the absolute accuracy at full scale is as follows:

$GainError = 65\ ppm + 7.3\ ppm \cdot 1 + 5\ ppm \cdot 10$ $\quad$ $GainError = 122\ ppm$

$OffsetError = 13\ ppm + 23\ ppm \cdot 1 + 60\ ppm$ $\quad$ $OffsetError = 96\ ppm$

$$NoiseUncertainty = \frac{270\ \mu V \cdot 3}{\sqrt{10{,}000}} \qquad Noise\ Uncertainty = 8.1\ \mu V$$

$$AbsoluteAccuracy = 10\ V \cdot (GainError) + 10\ V \cdot (OffsetError) + NoiseUncertainty \qquad AbsoluteAccuracy = 2{,}190\ \mu V$$

Accuracies listed are valid for up to two years from the device external calibration.

AO Absolute Accuracy Table

Nominal Range		Residual Gain Error (ppm of Reading)	Gain Tempco (ppm/°C)	Reference Tempco (ppm/°C)	Residual Offset Error (ppm of Range)	Offset Tempco (ppm of Range/°C)	INL Error (ppm of Range)	Absolute Accuracy at Full Scale[1] (μV)
Positive Full Scale	Negative Full Scale							
10	-10	80	11.3	5	53	4.8	128	3,271

[1] Absolute Accuracy at full scale numbers is valid immediately following internal calibration and assumes the device is operating within 10 °C of the last external calibration.

Accuracies listed are valid for up to two years from the device external calibration.

AbsoluteAccuracy = OutputValue · (GainError) + Range · (OffsetError)

GainError = ResidualGainError + GainTempco · (TempChangeFromLastInternalCal) + ReferenceTempco · (TempChangeFromLastExternalCal)

OffsetError = ResidualOffsetError + OffsetTempco · (TempChangeFromLastInternalCal) + INL_Error

Digital I/O/PFI

Static Characteristics

Number of channels	
NI 6341	24 total, 8 (P0.<0..7>) 16 (PFI <0..7>/P1, PFI <8..15>/P2)
NI 6343	48 total, 32 (P0.<0..31>) 16 (PFI <0..7>/P1, PFI <8..15>/P2)
Ground reference	D GND
Direction control	Each terminal individually programmable as input or output
Pull-down resistor	50 kΩ typical, 20 kΩ minimum
Input voltage protection[1]	±20 V on up to two pins

Waveform Characteristics (Port 0 Only)

Terminals used	
NI 6341	Port 0 (P0.<0..7>)
NI 6343	Port 0 (P0.<0..31>)
Port/sample size	
NI 6341	Up to 8 bits
NI 6343	Up to 32 bits
Waveform generation (DO) FIFO	2,047 samples
Waveform acquisition (DI) FIFO	255 samples
DO or DI Sample Clock frequency	
NI PCIe/PXIe-6341/6343	0 to 1 MHz, system and bus activity dependent
NI USB-6341/6343	0 to 1 MHz, system and bus activity dependent
Data transfers	
NI PCIe/PXIe-6341/6343	DMA (scatter-gather), programmed I/O
NI USB-6341/6343	USB Signal Stream, programmed I/O
Digital line filter settings	160 ns, 10.24 µs, 5.12 ms, disable

[1] Stresses beyond those listed under *Input voltage protection* may cause permanent damage to the device.

PFI/Port 1/Port 2 Functionality

Functionality .... Static digital input, static digital output, timing input, timing output

Timing output sources....................................... Many AI, AO, counter, DI, DO timing signals

Debounce filter settings .... 90 ns, 5.12 µs, 2.56 ms, custom interval, disable; programmable high and low transitions; selectable per input

Recommended Operation Conditions

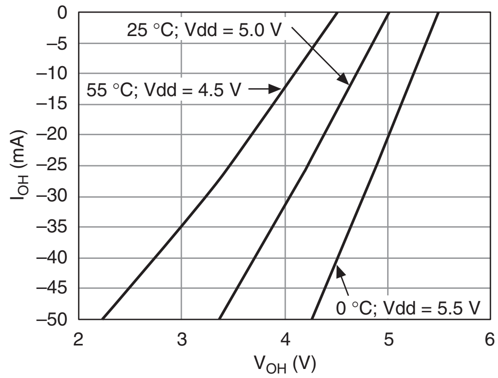
Level	Min	Max
Input high voltage (V_{IH})	2.2 V	5.25 V
Input low voltage (V_{IL})	0 V	0.8 V
Output high current (I_{OH})		
P0.<0..31>	—	-24 mA
PFI <0..15>/P1/P2	—	-16 mA
Output low current (I_{OL})		
P0.<0..31>	—	24 mA
PFI <0..15>/P1/P2	—	16 mA

Electrical Characteristics

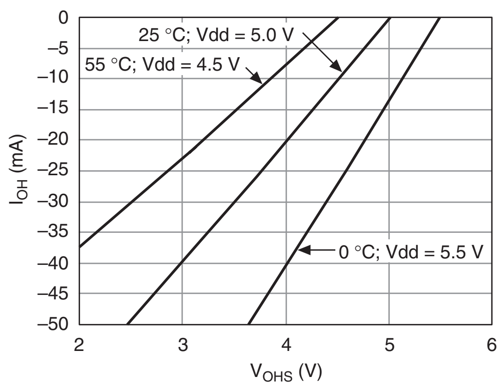
Level	Min	Max
Positive-going threshold (VT+)	—	2.2 V
Negative-going threshold (VT-)	0.8 V	—
Delta VT hysteresis (VT+ - VT-)	0.2 V	—
I_{IL} input low current (V_{in} = 0 V)	—	-10 µA
I_{IH} input high current (V_{in} = 5 V)	—	250 µA

Digital I/O Characteristics

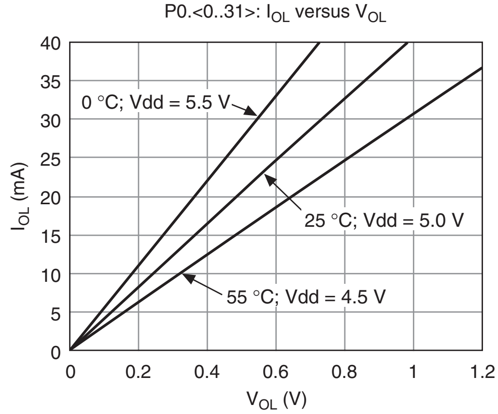
P0.<0..31>: I_{OH} versus V_{OH}



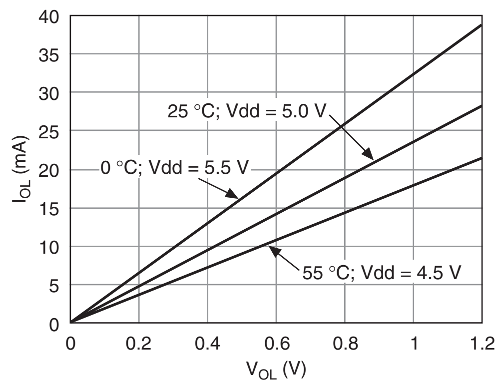
PFI <0..15>/P1/P2: I_{OH} versus V_{OH}



P0.<0..31>: I_{OL} versus V_{OL}



PFI <0..15>/P1/P2: I_{OL} versus V_{OL}



General-Purpose Counter/Timers

Number of counter/timers	4
Resolution	32 bits
Counter measurements	Edge counting, pulse, pulse width, semi-period, period, two-edge separation
Position measurements	X1, X2, X4 quadrature encoding with Channel Z reloading; two-pulse encoding
Output applications	Pulse, pulse train with dynamic updates, frequency division, equivalent time sampling
Internal base clocks	100 MHz, 20 MHz, 100 kHz
External base clock frequency	
NI PCIe/USB-6341/6343	0 MHz to 25 MHz
NI PXIe-6341	0 MHz to 25 MHz; 0 MHz to 100 MHz on PXIe-DSTAR<A,B>
Base clock accuracy	50 ppm
Inputs	Gate, Source, HW_Arm, Aux, A, B, Z, Up_Down, Sample Clock
Routing options for inputs	
NI PCIe-6341/6343	Any PFI, RTSI, many internal signals
NI PXIe-6341	Any PFI, PXIe-DSTAR<A,B>, PXI_TRIG, PXI_STAR, many internal signals
NI USB-6341/6343	Any PFI, many internal signals

FIFO .... 127 samples per counter

Data transfers

NI PCIe/PXIe-6341/6343 .... Dedicated scatter-gather DMA controller for each counter/timer, programmed I/O

NI USB-6341/6343 .... USB Signal Stream, programmed I/O

Frequency Generator

Number of channels 1

Base clocks .... 20 MHz, 10 MHz, 100 kHz

Divisors .... 1 to 16

Base clock accuracy .... 50 ppm

Output can be available on any PFI or RTSI terminal.

Phase-Locked Loop (PLL)

Number of PLLs 1

Reference clock locking frequencies

Reference Signal	Locking Input Frequency (MHz)		
	PCIe	PXIe	USB
PXIe-DSTAR<A,B>	—	10, 20, 100	—
PXI_STAR	—	10, 20	—
PXIe_CLK100	—	100	—
PXI_TRIG <0..7>	—	10, 20	—
RTSI <0..7>	10, 20	—	—
PFI <0..15>	10, 20	10, 20	10

Output of PLL .... 100 MHz Timebase; other signals derived from 100 MHz Timebase including 20 MHz and 100 kHz Timebases

External Digital Triggers

Source

NI PCIe-6341/6343 .... Any PFI, RTSI

NI PXIe-6341 .... Any PFI, PXIe-DSTAR<A,B>, PXI_TRIG, PXI_STAR

NI USB-6341/6343 .... Any PFI

Polarity	Software-selectable for most signals
Analog input function	Start Trigger, Reference Trigger, Pause Trigger, Sample Clock, Convert Clock, Sample Clock Timebase
Analog output function	Start Trigger, Pause Trigger, Sample Clock, Sample Clock Timebase
Counter/timer functions	Gate, Source, HW_Arm, Aux, A, B, Z, Up_Down, Sample Clock
Digital waveform generation (DO) function	Start Trigger, Pause Trigger, Sample Clock, Sample Clock Timebase
Digital waveform acquisition (DI) function	Start Trigger, Reference Trigger, Pause Trigger, Sample Clock, Sample Clock Timebase

Device-To-Device Trigger Bus

Input source	
NI PCIe-6341/6343	RTSI <0..7>[1]
NI PXIe-6341	PXI_TRIG <0..7>, PXI_STAR, PXIe-DSTAR<A,B>
NI USB-6341/6343	None
Output destination	
NI PCIe-6341/6343	RTSI <0..7>[2]
NI PXIe-6341	PXI_TRIG <0..7>, PXIe-DSTARC
NI USB-6341/6343	None
Output selections	10 MHz Clock, frequency generator output, many internal signals
Debounce filter settings	90 ns, 5.12 µs, 2.56 ms, custom interval, disable; programmable high and low transitions; selectable per input

[1] In other sections of this document, *RTSI* refers to RTSI <0..7> for NI PCIe-6341/6343 or PXI_TRIG <0..7> for NI PXIe-6341.

[2] In other sections of this document, *RTSI* refers to RTSI <0..7> for NI PCIe-6341/6343 or PXI_TRIG <0..7> for NI PXIe-6341.

Bus Interface

NI PCIe-6341/6343

- Form factor .... x1 PCI Express, specification v1.1 compliant
- Slot compatibility .... x1, x4, x8, and x16 PCI Express slots[1]
- DMA channels .... 8, analog input, analog output, digital input, digital output, counter/timer 0, counter/timer 1, counter/timer 2, counter/timer 3

NI PXIe-6341

- Form factor .... x1 PXI Express peripheral module, specification rev 1.0 compliant
- Slot compatibility .... x1 and x4 PXI Express or PXI Express hybrid slots
- DMA channels .... 8, analog input, analog output, digital input, digital output, counter/timer 0, counter/timer 1, counter/timer 2, counter/timer 3

All NI PXIe-6341 devices may be installed in PXI Express slots or PXI Express hybrid slots.

NI USB-6341/6343

- USB compatibility .... USB 2.0 Hi-Speed or full-speed[2]
- USB Signal Stream .... 8, can be used for analog input, analog output, digital input, digital output, counter/timer 0, counter/timer 1, counter/timer 2, counter/timer 3

Power Requirements

⚠ **Caution** The protection provided by the NI 6341/6343 can be impaired if it is used in a manner not described in the *X Series User Manual*.

NI PCIe-6341/6343

- Without disk drive power connector installed
  - +3.3 V .... 1.4 W
  - +12 V .... 8.6 W
- With disk drive power connector installed
  - +3.3 V .... 1.4 W
  - +12 V .... 3 W
  - +5 V .... 15 W

---

[1] Some motherboards reserve the x16 slot for graphics use. For PCI Express guidelines, refer to `ni.com/pciexpress`.

[2] Operating on a full-speed bus will result in lower performance and you might not be able to achieve maximum sampling/update rates.

NI PXIe-6341

+3.3 V .... 1.6 W

+12 V .... 19.8 W

Caution NI USB-6341/6343 devices *must* be powered with NI offered AC adapter or a National Electric Code (NEC) Class 2 DC source that meets the power requirements for the device and has appropriate safety certification marks for country of use.

NI USB-6341/6343

Power supply requirements....................... 11 to 30 VDC, 30 W, 2 positions 3.5 mm pitch pluggable screw terminal with screw locks similar to Phoenix Contact MC 1,5/2-STF-3,5 BK

Power input mating connector .... Phoenix Contact MC 1,5/2-GF-3,5 BK or equivalent

Current Limits

Caution Exceeding the current limits may cause unpredictable behavior by the device and/or PC/chassis.

NI PCIe-6341/6343

Without disk drive power connector installed

P0/PFI/P1/P2 and +5 V terminals combined........................... 1 A max

With disk drive power connector installed

+5 V terminal (connector 0).............. 1 A max[1]

+5 V terminal (connector 1).............. 1 A max[1]

P0/PFI/P1/P2 combined.................... 1 A max

NI PXIe-6341

+5 V terminal (connector 0)...................... 1 A max[1]

P0/PFI/P1/P2 and +5 V terminals combined.................................. 2 A max

NI USB-6341/6343

+5 V terminal .... 1 A max[1]

P0/PFI/P1/P2 and +5 V terminals combined.................................. 2 A max

---

[1] Has a self-resetting fuse that opens when current exceeds this specification.

Physical Requirements

Printed circuit board dimensions

NI PCIe-6341/6343 .... 9.9 × 16.8 cm (3.9 × 6.6 in.) (half-length)

NI PXIe-6341 .... Standard 3U PXI

Enclosure dimensions (includes connectors)

NI USB-6341/6343

Screw Terminal .... 26.4 × 17.3 × 3.6 cm (10.4 × 6.8 × 1.4 in.)

BNC .... 20.3 × 18.5 × 6.8 cm (8.0 × 7.3 × 2.7 in)

Weight

NI PCIe-6341 .... 104 g (3.6 oz)

NI PCIe-6343 .... 114 g (4.0 oz)

NI PXIe-6341 .... 157 g (5.5 oz)

NI USB-6341

Screw Terminal .... 1.406 kg (3 lb 1.6 oz)

BNC .... 1.520 kg (3 lb 5.6 oz)

NI USB-6343

Screw Terminal .... 1.445 kg (3 lb 3 oz)

BNC .... 1.803 kg (3 lb 15.6 oz)

I/O connector

NI PCIe/PXIe-6341 .... 1 68-pin VHDCI

NI PCIe/PXIe-6343 .... 2 68-pin VHDCI

NI USB-6341

Screw Terminal .... 64 screw terminals

BNC .... 20 BNCs and
30 screw terminals

NI USB-6343

Screw Terminal .... 128 screw terminals

BNC .... 30 BNCs and
60 screw terminals

NI PCIe/PXIe-6341/6343 mating connectors:

- 68-Pos Right Angle Single Stack PCB-Mount VHDCI (Receptacle), MOLEX 71430-0011
- 68-Pos Right Angle Dual Stack PCB-Mount VHDCI (Receptacle), MOLEX 74337-0016
- 68-Pos Offset IDC Cable Connector (Plug) (SHC68-*), MOLEX 71425-3001

NI PCIe-6341/6343
disk drive power connector .... Standard ATX peripheral connector
(not serial ATA)

NI USB-6341/6343 screw terminal wiring .... 16-24 AWG

If you need to clean the chassis, wipe it with a dry towel.

Maximum Working Voltage[1]

Channel to earth .... 11 V, Measurement Category I

Caution Do *not* use for measurements within Categories II, III, or IV.

Environmental

Operating temperature

NI PCIe-6341/6343 .... 0 to 50 °C

NI PXIe-6341 .... 0 to 55 °C

NI USB-6341/6343 .... 0 to 45 °C

Storage temperature .... -40 to 70 °C

Operating humidity .... 10 to 90% RH, noncondensing

Storage humidity .... 5 to 90% RH, noncondensing

Pollution Degree 2

Maximum altitude .... 2,000 m

Indoor use only

Shock and Vibration (NI PXIe-6341 Only)

Operational shock .... 30 g peak, half-sine, 11 ms pulse (Tested in accordance with IEC-60068-2-27. Test profile developed in accordance with MIL-PRF-28800F.)

Random vibration

Operating .... 5 to 500 Hz, 0.3 g_{rms}

Nonoperating .... 5 to 500 Hz, 2.4 g_{rms} (Tested in accordance with IEC-60068-2-64. Nonoperating test profile exceeds the requirements of MIL-PRF-28800F, Class 3.)

[1] *Maximum working voltage* refers to the signal voltage plus the common-mode voltage.

Safety

This product meets the requirements of the following standards of safety for electrical equipment for measurement, control, and laboratory use:

- IEC 61010-1, EN 61010-1
- UL 61010-1, CSA 61010-1

Note For UL and other safety certifications, refer to the product label or the *Online Product Certification* section.

Electromagnetic Compatibility

This product meets the requirements of the following EMC standards for electrical equipment for measurement, control, and laboratory use:

- EN 61326-1 (IEC 61326-1): Class A emissions; Basic immunity
- EN 55011 (CISPR 11): Group 1, Class A emissions
- AS/NZS CISPR 11: Group 1, Class A emissions
- FCC 47 CFR Part 15B: Class A emissions
- ICES-001: Class A emissions

Caution When operating this product, use shielded cables and accessories

Note For EMC declarations and certifications and additional information, refer to the *Online Product Certification* section.

CE Compliance CE

This product meets the essential requirements of applicable European Directives as follows:

- 2006/95/EC; Low-Voltage Directive (safety)
- 2004/108/EC; Electromagnetic Compatibility Directive (EMC)

Online Product Certification

To obtain product certifications and the Declaration of Conformity (DoC) for this product, visit `ni.com/certification`, search by model number or product line, and click the appropriate link in the Certification column.

Environmental Management

NI is committed to designing and manufacturing products in an environmentally responsible manner. NI recognizes that eliminating certain hazardous substances from our products is beneficial to the environment and to NI customers.

For additional environmental information, refer to the *Minimize Our Environmental Impact* Web page at `ni.com/environment`. This page contains the environmental regulations and directives with which NI complies, as well as other environmental information not included in this document.

Waste Electrical and Electronic Equipment (WEEE)

EU Customers At the end of the product life cycle, all products *must* be sent to a WEEE recycling center. For more information about WEEE recycling centers, National Instruments WEEE initiatives, and compliance with WEEE Directive 2002/96/EC on Waste Electrical and Electronic Equipment, visit `ni.com/environment/weee.htm`.

电子信息产品污染控制管理办法 （中国 RoHS）

中国客户 National Instruments 符合中国电子信息产品中限制使用某些有害物质指令 (RoHS)。关于 National Instruments 中国 RoHS 合规性信息，请登录 `ni.com/environment/rohs_china`。(For information about China RoHS compliance, go to `ni.com/environment/rohs_china`.)

Contact Information

National Instruments corporate headquarters
11500 North Mopac Expressway, Austin, Texas, 78759-3504
512 795 8248
`ni.com/niglobal`

Figure 1. NI PCIe/PXIe-6341 Pinout

AI 0 (AI 0+)	68	34	AI 8 (AI 0–)
AI GND	67	33	AI 1 (AI 1+)
AI 9 (AI 1–)	66	32	AI GND
AI 2 (AI 2+)	65	31	AI 10 (AI 2–)
AI GND	64	30	AI 3 (AI 3+)
AI 11 (AI 3–)	63	29	AI GND
AI SENSE	62	28	AI 4 (AI 4+)
AI 12 (AI 4–)	61	27	AI GND
AI 5 (AI 5+)	60	26	AI 13 (AI 5–)
AI GND	59	25	AI 6 (AI 6+)
AI 14 (AI 6–)	58	24	AI GND
AI 7 (AI 7+)	57	23	AI 15 (AI 7–)
AI GND	56	22	AO 0
AO GND	55	21	AO 1
AO GND	54	20	NC
D GND	53	19	P0.4
P0.0	52	18	D GND
P0.5	51	17	P0.1
D GND	50	16	P0.6
P0.2	49	15	D GND
P0.7	48	14	+5 V
P0.3	47	13	D GND
PFI 11/P2.3	46	12	D GND
PFI 10/P2.2	45	11	PFI 0/P1.0
D GND	44	10	PFI 1/P1.1
PFI 2/P1.2	43	9	D GND
PFI 3/P1.3	42	8	+5 V
PFI 4/P1.4	41	7	D GND
PFI 13/P2.5	40	6	PFI 5/P1.5
PFI 15/P2.7	39	5	PFI 6/P1.6
PFI 7/P1.7	38	4	D GND
PFI 8/P2.0	37	3	PFI 9/P2.1
D GND	36	2	PFI 12/P2.4
D GND	35	1	PFI 14/P2.6

NC = No Connect

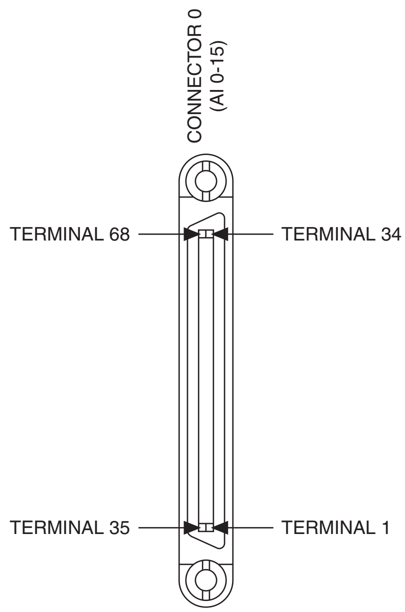
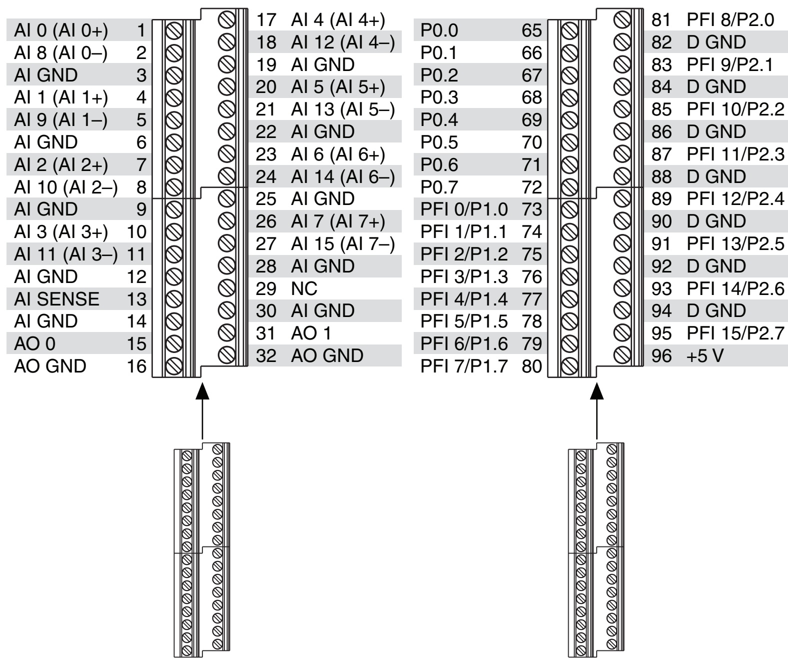


Figure 2. NI USB-6341 Screw Terminal Pinout



NC = No Connect

Figure 3. NI USB-6341 BNC Front Panel and Pinout

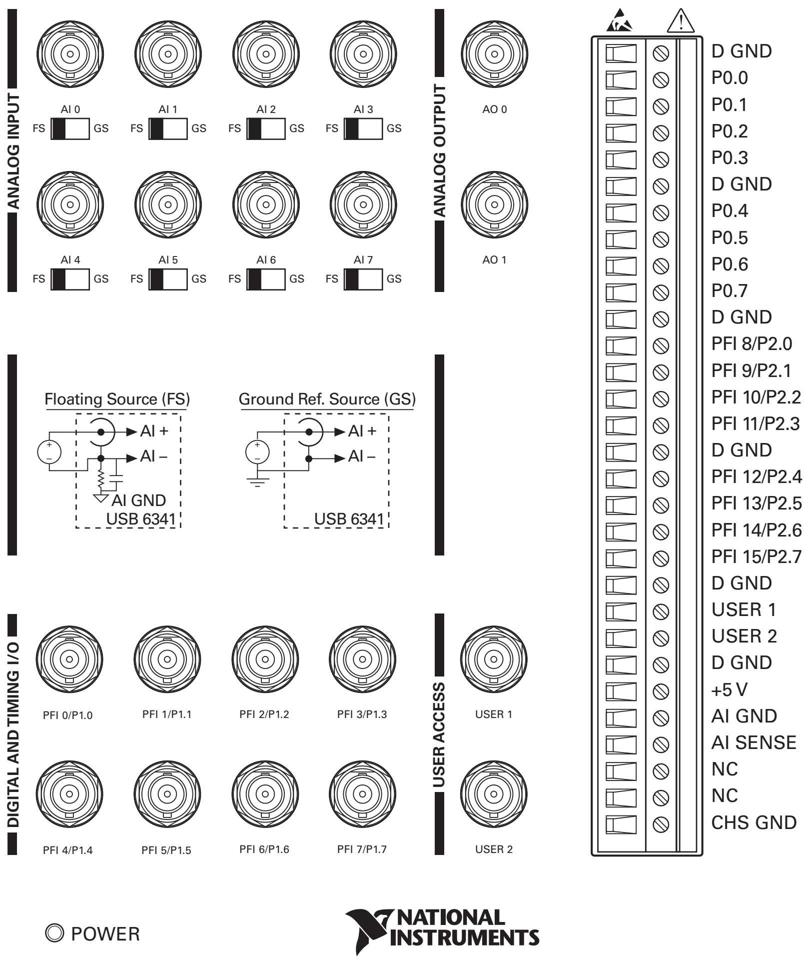
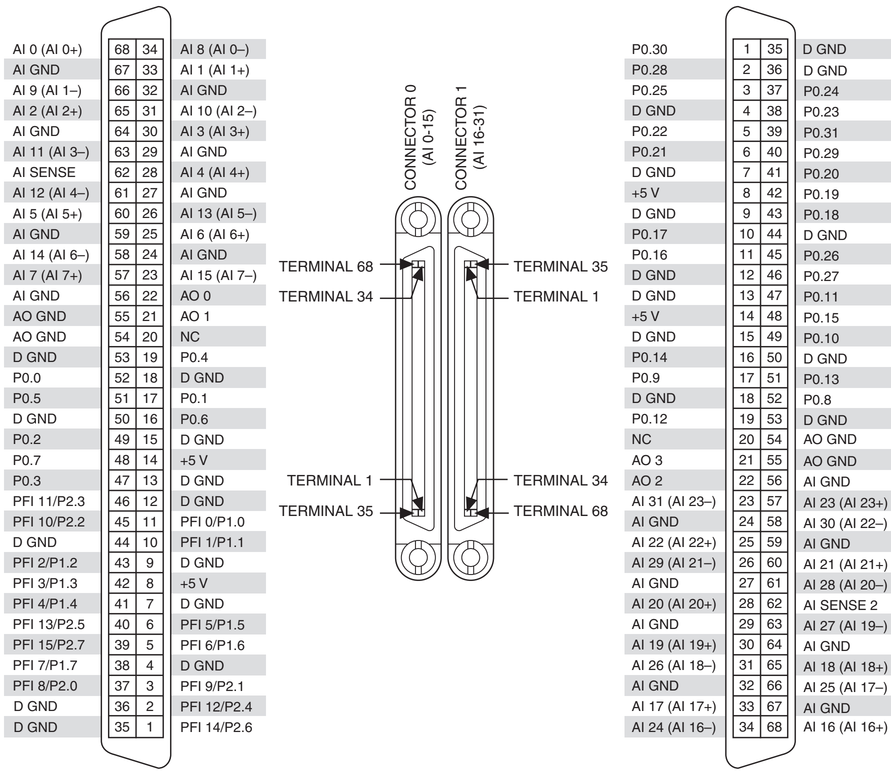
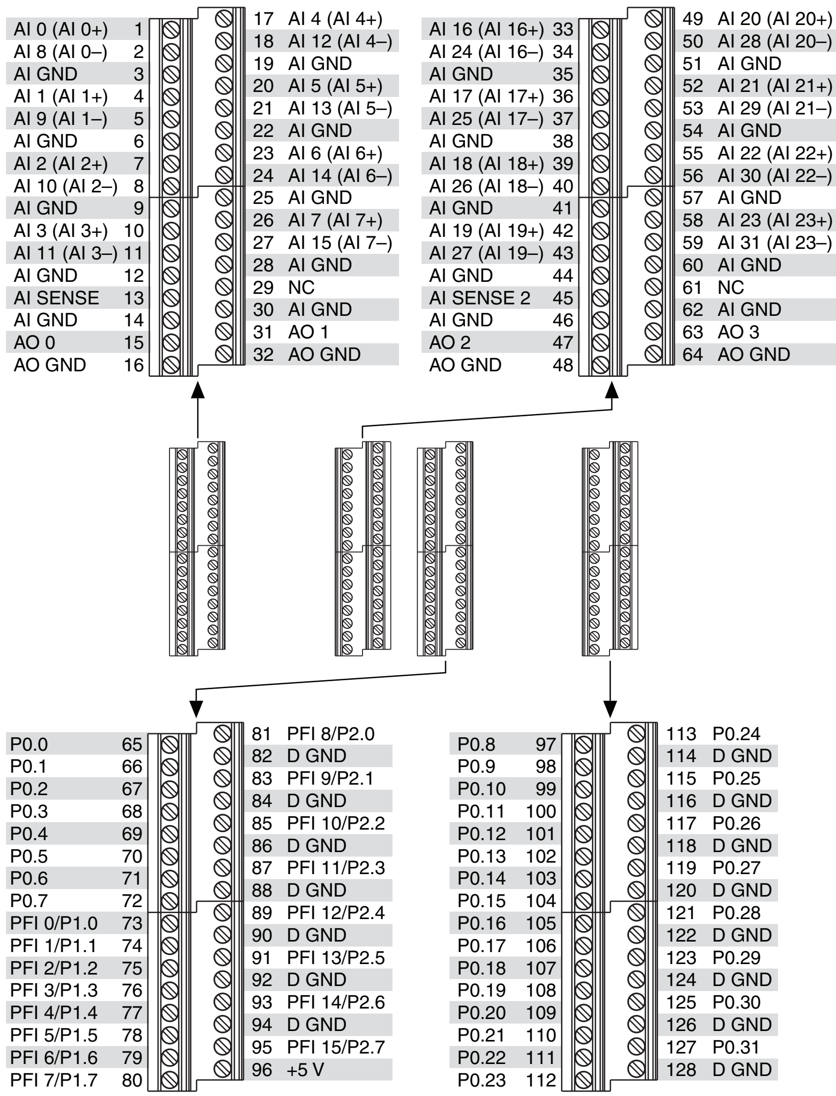


Figure 4. NI PCIe-6343 Pinout



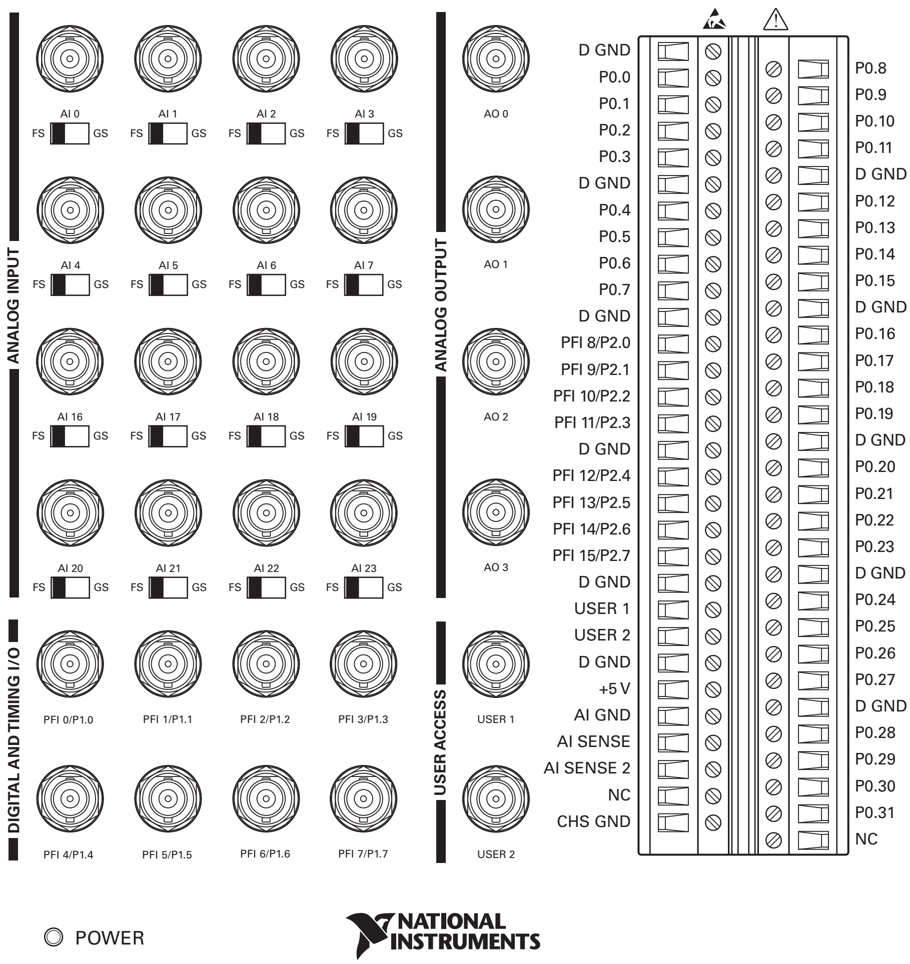
NC = No Connect   NC = No Connect

Figure 5. NI USB-6343 Screw Terminal Pinout



NC = No Connect

Figure 6. NI USB-6343 BNC Front Panel and Pinout



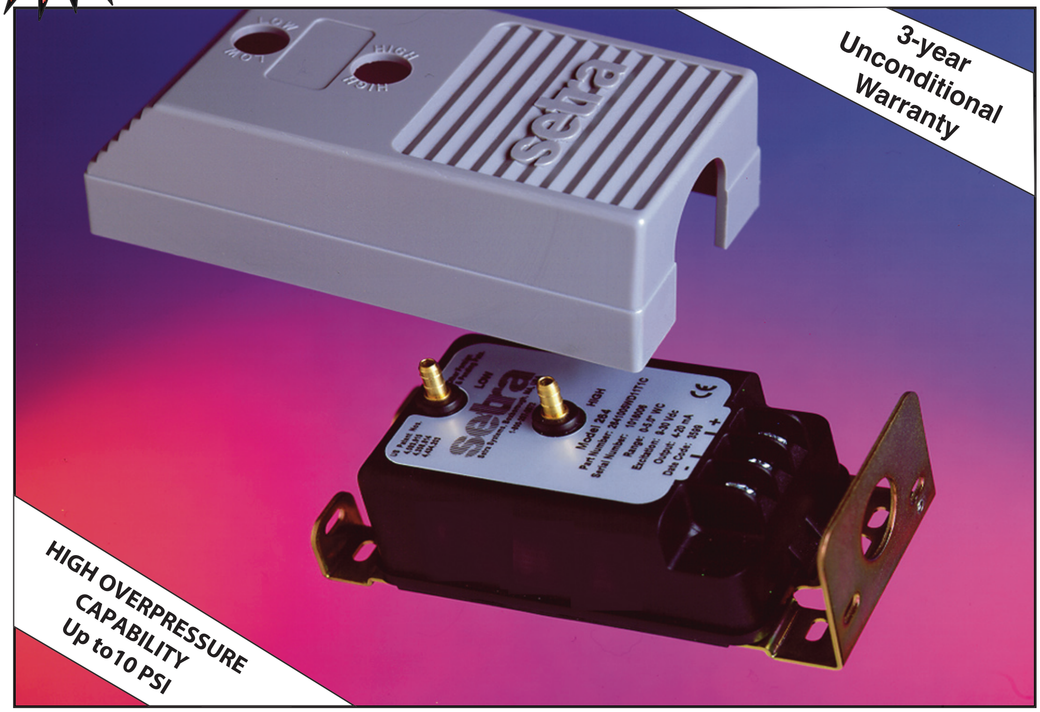
370786D-01 Jan13

GUARANTEED
3 DAY
SHIPMENT
FOR STANDARD PARTS
(less than 10 pieces)

Model 264

Very Low Differential Pressure Transducer

Unidirectional Ranges: 0 - 0.1 to 0 - 100 in. W.C.
Bidirectional Ranges: 0 - ±0.5 to 0 - ±50 in. W.C.
Air or Non-Conducting Gas



Setra Systems 264 pressure transducers sense differential or gauge (static) pressure and convert this pressure difference to a proportional electrical output for either unidirectional or bidirectional pressure ranges. The 264 Series is offered with a high level analog 0 to 5 VDC or 4 to 20 mA output.

Used in Building Energy Management Systems, these transducers are capable of measuring pressures and flows with the accuracy necessary for proper building pressurization and air flow control.

The 264 Series transducers are available for air pressure ranges as low as 0.1 in. W.C. full scale to 100 in. W.C. full scale. Static standard accuracy is ±1.0% full scale in normal ambient temperature environments, but higher accuracies are available. The units are temperature compensated to 0.033% FS/°F thermal error over the temperature range of 0°F to +150°F.

The Model 264 utilizes an improved all stainless steel micro-tig welded sensor. The tensioned stainless steel diaphragm and insulated stainless steel electrode, positioned close to the diaphragm, form a variable capacitor. Positive pressure moves the diaphragm toward the electrode, increasing the capacitance. A decrease in pressure moves the diaphragm away from the electrode, decreasing the capacitance. The change in capacitance is detected and converted to a linear DC electrical signal by Setra's unique electronic circuit.

The tensioned sensor allows up to 10 PSI overpressure (range dependent) with no damage to the unit. In addition, the parts that make up the sensor have thermally matched coefficients, which promote improved temperature performance and excellent long term stability.

NOTE: Setra quality standards are based on ANSI-Z540-1.
The calibration of this product is NIST traceable.

U.S. Patent nos. 4093915; 4358814; 4434203; 6019002; 6014800.
Other Patents Pending.

Applications

- Heating, Ventilating and Air Conditioning (HVAC)
- Energy Management Systems
- Variable Air Volume and Fan Control (VAV)
- Environmental Pollution Control
- Lab and Fume Hood Control
- Oven Pressurization and Furnace Draft Controls

Features

- Up to 10 PSI Overpressure (Range Dependent)
- Installation Time Minimized with Snap Track Mounting and Easy- To-Access Pressure Ports and Electrical Connections
- 0 to 5 VDC or 2-wire 4 to 20 mA Analog Outputs Are Compatible with Energy Management Systems
- Reverse Wiring Protection
- Internal Regulation Permits Use with Unregulated DC Power Supplies
- Fire Retardent Case (UL 94 V-0 Approved)
- Meets CE Conformance Standards

When it comes to a product to rely on - choose the Model 264. When it comes to a company to trust - choose Setra.

ISO 9001: 2000 Certified

Visit Setra Online:
http://www.setra.com

800-257-3872

159 Swanson Rd., Boxborough, MA 01719/Telephone: 978-263-1400/Fax: 978-264-0292

Model 264 Specifications

Performance Data

	Standard	Optional	
Accuracy* RSS(at constant temp)	±1.0% FS	±0.4% FS	±0.25% FS
Non-Linearity, BFSL	±0.96% FS	±0.38% FS	±0.22% FS
Hysteresis	0.10% FS	0.10% FS	0.10% FS
Non-Repeatability	0.05% FS	0.05% FS	0.05%FS

Thermal Effects**	
Compensated Range °F(°C)	0 to +150 (-18 to +65)
Zero/Span Shift %FS/°F(°C)	0.033 (0.06)
Maximum Line Pressure	10 psi
Overpressure	Up to 10 psi (Range Dependent)
Long Term Stability	0.5% FS/1 YR

Position Effect	Range	Zero Offset (%FS/G)
(Unit is factory calibrated at 0g effect in the vertical position.)	To 0.5 in. WC	0.60
	To 1.0 in. WC	0.50
	To 2.5 in. WC	0.22
	To 5 in. WC	0.14

* RSS of Non-Linearity, Hysteresis, and Non-Repeatability.
**Units calibrated at nominal 70°F. Maximum thermal error computed from this datum.

Environmental Data

Temperature	
Operating* °F (°C)	0 to +175 (-18 to +79)
Storage °F (°C)	-65 to +250 (-54 to +121)

*Operating temperature limits of the electronics only. Pressure media temperatures may be considerably higher.

Physical Description

Case	Fire-Retardant Glass Filled Polyester (UL 94 V-0 Approved)
Mounting	Four screw holes on removable zinc plated steel base (designed for 2.75" snap track)
Electrical Connection	Screw Terminal Strip
Pressure Fittings	3/16" O.D. barbed brass pressure fitting for 1/4" push-on tubing
Zero and Span Adjustments	Accessible on top of case
Weight (approx.)	10 ounces

Pressure Media

Typically air or similar non-conducting gases.

Specifications subject to change without notice.

Electrical Data (Voltage)

Circuit	3-Wire (Com, Exc, Out)
Excitation	9 to 30 VDC
Output*	0 to 5 VDC**
Bidirectional output at zero pressure:	2.5 VDC**
Output Impedance	100 ohms

*Calibrated into a 50K ohm load, operable into a 5000 ohm load or greater.
**Zero output factory set to within ±50mV (±25 mV for optional accuracies).
**Span (Full Scale) output factory set to within ±50mV. (±25 mV for optional accuracies).

Electrical Data (Current)

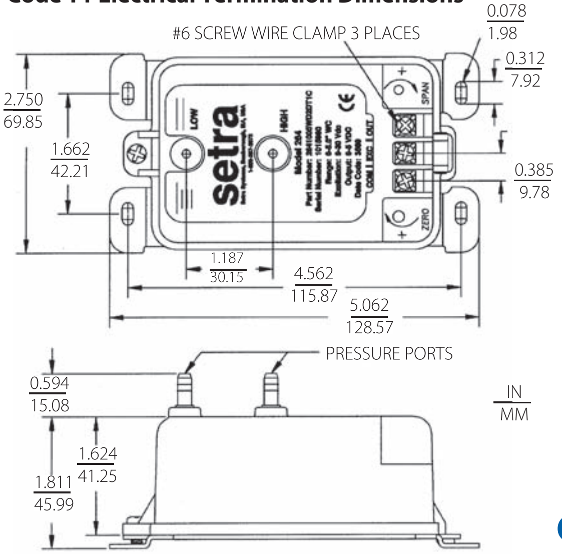
Circuit	2-Wire
Output*	4 to 20mA**
Bidirectional output at zero pressure:	12mA**
External Load	0 to 800 ohms

Minimum supply voltage (VDC) = 9+ 0.02 x (Resistance of receiver plus line).
Maximum supply voltage (VDC) = 30+ 0.004 x (Resistance of receiver plus line).

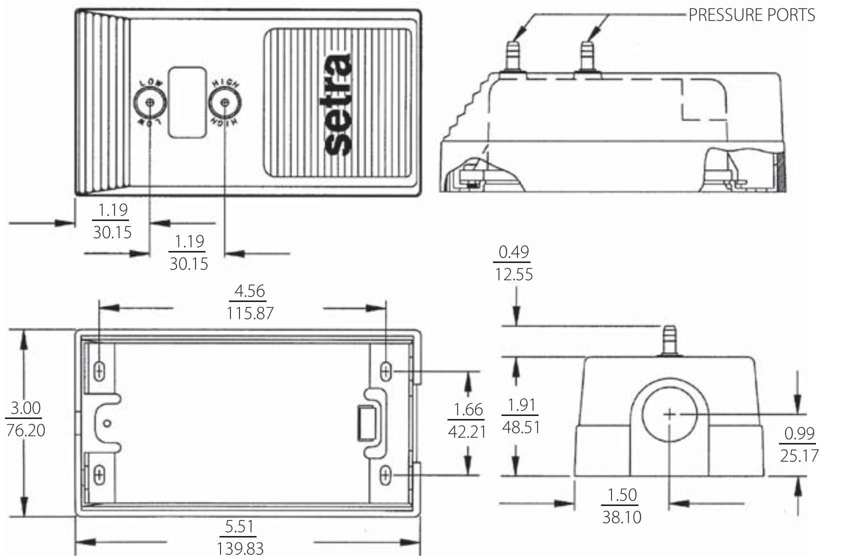
*Calibrated at factory with a 24 VDC loop supply voltage and a 250 ohm load.
**Zero output factory set to within ±0.16mA (±0.08 mA for optional accuracies).
**Span (Full Scale) output factory set to wtihin ±0.16mA (±0.08 mA for optional accuracies).

Outline Drawings

Code T1 Electrical Termination Dimensions



Optional 1/2" Conduit Electrical Enclosure Dimensions



SSP264 Rev.G 01/24/08

ORDERING INFORMATION

Code all blocks in table.

Example: Part No. 26412R5WD11T1C for a 264 Transducer 0 to 2.5 in. WC Range, 4 to 20 mA Output, Terminal Strip Electrical Connection, and ±1% Accuracy.

2 6 4 1 – [ ][ ][ ][ ][ ] – [ ][ ] – [ ][ ] – [ ]

Model	Ranges: Differential	Ranges: Bidirectional	Output	Elec. Termination	Accuracy
2641 = 264	0R1WD = 0 to 0.1 in. WC	R05WB = ±0.05 in. WC	11 = 4-20 mA	Standard	Standard
	R25WD = 0 to 0.25 in. WC	0R1WB = ±0.1 in. WC	2D = 0 to 5 VDC	T1 = Terminal Strip	C = ±1% FS
	0R5WD = 0 to 0.5 in. WC	R25WB = ±0.25 in. WC		Optional	Optional (w/Cal. Cert.)
	001WD = 0 to 1 in. WC	0R5WB = ±0.5 in. WC		A1 = 1/2" Conduit Enclosure	E = ±0.4% FS
	2R5WD = 0 to 2.5 in. WC	001WB = ±1 in. WC			F = ±0.25% FS
	003WD = 0 to 3 in. WC	1R5WB = ±1.5 in. WC			G = ±1% FS
	005WD = 0 to 5 in. WC	2R5WB = ±2.5 in. WC			
	010WD = 0 to 10 in. WC	005WB = ±5 in. WC			
	015WD = 0 to 15 in. WC	7R5WB = ±7.5 in. WC			
	025WD = 0 to 25 in. WC	010WB = ±10 in. WC			
	050WD = 0 to 50 in. WC	025WB = ±25 in. WC			
	100WD = 0 to 100 in. WC	050WB = ±50 in. WC			

Please contact factory for versions not shown.

159 Swanson Road, Boxborough, MA 01719/Tel: 978-263-1400
Toll Free: 800-257-3872; Fax: 978-264-0292; email: sales@setra.com

Differential pressure transmitter

P 26

Intelligent differential pressure transmitter with scalable range

Special features

- range and display scalable
- switching contacts with adjustable switching thresholds
- NEW: Now optionally with air consumption counter
- output characteristics can be configured (root-extraction / linear)
- automatic zero-point calibration prevents zero-point drift
- unit conversion (e.g. mmH_2O, mmHg, etc.)
- integrated valve provides a high level of overpressure protection
- Manual or external activation of zero adjustment
- available with interface USB (optional)
- also for top-hat rail mounting
- multilingual menu (English, German, Italian, French)
- ± measuring ranges

Technical data

measurement ranges (others available upon request)	10/50/100/250/500 Pa 1/2.5/5/10/20/50/100 kPa free scalable from 10..100% within a range
margin of error (0.3 Pa margin of error for reference)	0.5% + 0.3 Pa of scaled range (40...100% of end value)
deflection drift / temperature	0.03 %/K (+10 °C...+50 °C)
zero point drift / temperature	± 0 % (cyclical zero-point correction)
overload capacity	600 kPa for measurement ranges ≥ 2.5 kPa 200x for measurement ranges < 2.5 kPa
medium	air, all non-aggressive gases
max. line pressure	600 kPa for measurement ranges ≥ 2.5 kPa 200x for measurement ranges < 2.5 kPa
sensor response time	25 ms
time constants	25 ms ... 60 s (adjustable)
operating temperature	+10 °C ... +50 °C
storage temperature	-10 °C ... +70 °C
power consumption	approx. 6 VA
weight	approx. 0.75 kg
cable glands	3 x M 16
pressure ports	for hose NW 6 mm, others available upon request
protection class	IP 65, USB IP 40
testing	CE, CSA, GOST

output*	A	power supply	B
0 ... 10 V ($R_L \geq 2$ kΩ)	1	24 V AC/DC	24ACDC
0...20 mA ($R_L \leq 500$ Ω)	0	24 VAC with galvanic separation	24AC
4...20 mA ($R_L \leq 500$ Ω)	4	230/115 VAC	230/115
± 5 V ($R_L \geq 2$ kΩ)	5		

* output singal selectable

measurement range	C	margin of error	D
measurement range e.g., 0 – 10 Pa, mbar, mmHg, etc.		standard	S
		±0.2 % of end value, but min. 0.3 Pa (from ≥ 150 Pa)	2

LCD	E	contact points	F
none	0	none	0
LCD and buttons for configuration	LC	2 switching relays max. 230 VAC, 6 A	2
		2 relais, with air counter functionality	Z

interface / external zero-point calibration	G
none	0
USB, datacable included in delivery	US
external zero-point calibration	EX

Order key

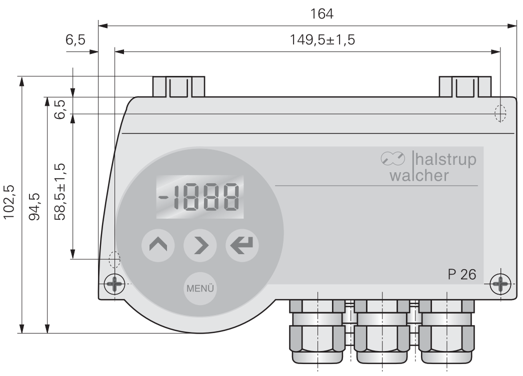
	A	B	C	D	E	F	G
P 26	-	-	-	-	-	-	

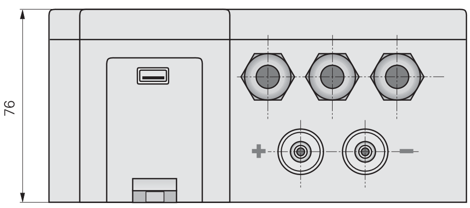
accessories	
☐ DAkkS-DKD calibration certificate, German	9601.-0003
☐ DAkkS-DKD calibration certificate, English	9601.-0004
☐ factory calibration certificate	9601.-0002

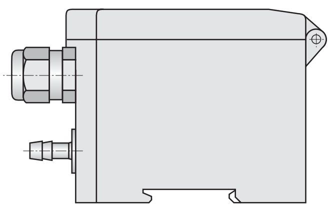
P 26

Dimension drawing

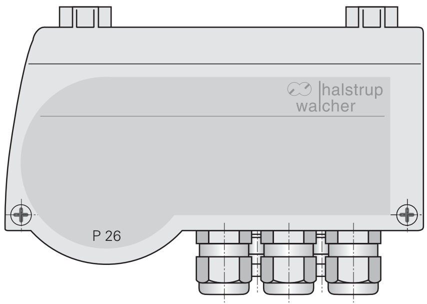
P 26 with LCD



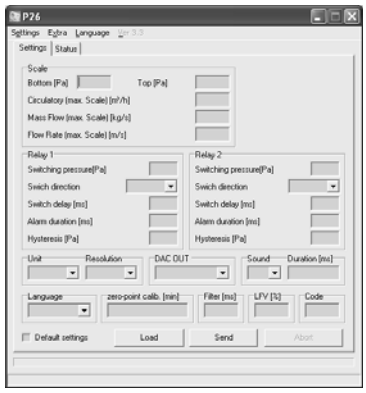




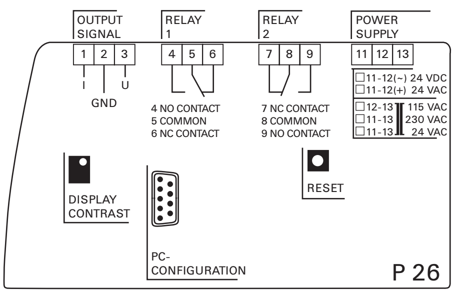
no LCD

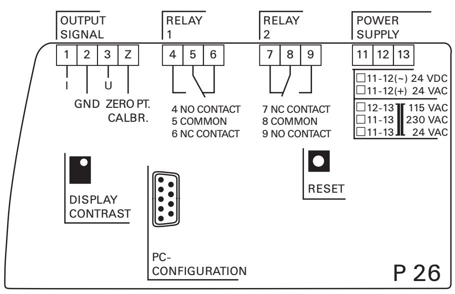


P 26 Configuration software



Connection diagram





degree C

CAMBRIDGE ACCUSENSE

F900 Series
Air Velocity and
Air Temperature Sensors

applications

- HVAC
- Industrial Processes
- Automotive
- Air filtration Systems
- Electronics Enclosures, and
- Critical Containment Areas
- Biological Safety Cabinets
- Fume Hoods
- Clean Rooms

features

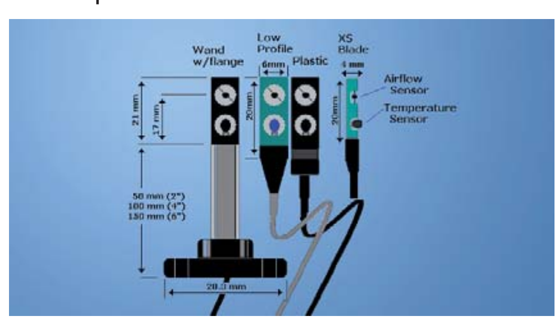
- Measures air & inert gas velocity and temperature
- Standard flow ranges between 0.15-10 m/s (approximately 30-2000 fpm)
- Temperature measurements from 0-70°C
- Digital UART Interface
- Linear 0-4 VDC airflow output from 0 to full-scale
- Wide voltage supply: 7-13VDC
- Temperature-compensated from 15-35°C
- Ideal for ducted or open airflow applications
- Available in multiple sensor heads
- Wide acceptance angle (±30°)

about

The F900 Airflow Sensor is designed to measure the velocity and temperature of airflows in applications such as HVAC, industrial processes, automotive, air filtration systems, electronics enclosures, and critical containment areas such as biological safety cabinets, fume hoods, and clean rooms.

With standard airflow sensing ranges from 0.15-2 m/s (30-400 fpm) to 0.15-10 m/s (30-2000 fpm), the Series F900 offers unparalleled price to performance, compact size, reliability with resistance to mechanical shock and vibration.

The F900 series has a linear 0-4V output and a digital 5v UART output depending on the model. The F900 is easy to install and operate. An adjustable mounting bracket is included with the sensor. In addition, the F900 can be ordered with any of the AccuSense remote sensing head options.



F900 Series Air Velocity and Air Temperature Sensors

airflow measurement

Air Velocity

Temperature compensation range: 15-35°C (60-95°F):
Accuracy: ±5% of reading or ±0.05m/s (10fpm)
±10% of reading or ±0.05m/s (10fpm)
Repeatability: ±1% of reading

Temperature Compensation Range: The F900 is a thermal airflow sensor; it is sensitive to changes in air density and indicates velocity with reference to a set of standard conditions (25°C (77°F), 760mmHg (101.325kPa), and 0%RH). The F900 has been designed so that when used over the stated temperature compensation range, the sensor indicates very close to actual air velocity and minimal compensation is only required to account for changes in barometric pressure or altitude. Changes in relative humidity have a minimal impact and can usually be ignored.

[1] Above 0.5m/s (100fpm), ±1.5°C (2.7°F) below 0.5m/s (100fpm).

Airflow Temperature

Measurement range: 0-70°C (32-158°F)
Measurement Accuracy[1]: ±1°C (1.8°F)
Resolution: ±0.1°C

temperature measurement

Range 0-70°C (50-140°F)	Available on 5v UART output only
Accuracy ±1°C above 1 m/s (196 fpm) ±1.5°C below 1 m/s (196 fpm)	Resolution is ±0.1°C

electrical specifications

Supply Voltage 7-13 VDC	Warm-up Time <5 seconds
Supply Current 40-75 mA	Operating Temperature 0 – 70°C (32-158°F)
Response Time 1.5 seconds	Storage Temperature –10 to 100°C
Output is linearized 0-4.0 vdc, which equals 0 to full scale of calibrated range (airflow only).	

mechanical specifications

Dimensions	100 mm long X 12 mm diameter for standard unit, 91 mm X 12 mm for long tube with remote sensor heads
Vibration	Up to 25 G's
Acceptance Angles	Standard, rod w/flange, plastic heads are ±30°, low-profile is ±45°, XS blade is ±60° from perpendicular

connection specifications

Pin 1 Black	Supply Return
Pin 2 Red	Supply 7-13 VDC
Pin 3 White	Analog Airflow Output (0-4Vout) for calibrated range, up to 4.095V beyond calibrated range.
Pin 4 Orange	Digital serial output - 19200 BPS, 5v UART level, 8 bit, 1 stop bit
Pin 5 Yellow	Digital serial input – 19200 BPS, 5v UART levels, 8 bit, 1 stop bit -
Connector	Molex#22-01-2057 or equivalent

part number scheme

F900 - V - A - B - S - L

V =
Velocity Range
N = 0.15 - 2 m/s
O = 0.15 – 5 m/s
P = 0.15 - 10 m/s

A =
Accuracy Specification
5 = Greater of 5% of reading or ±0.05 m/s or 1% full-scale
10 = Greater of 10% of reading or ±0.05 m/s or 1% full-scale

B =
Body Type
0 = Standard (Default) – short tube
1 = Long tube (for remote sensor heads)

S =
Sensor Head Type (for B =1 ONLY)
0 = Plastic
1 = Low Profile
2 = 50 mm (2") SS wand /w flange
4 = 100 mm (4") SS wand /w flange
6 = 150mm (6") SS wand /w flange
9 = XS Blade

L =
Sensor Cable Length (for B =1 ONLY)
2 = 2 m

User Manual available at www.degreeC.com

degreeC DEGREE CONTROLS,INC.
Engineered Airflow. Intelligent Cooling.
www.degreec.com • sales@degreec.com
18 Meadowbrook Drive, Milford, NH 03055 • TEL: 603-672-8900 or 1-877-DEGREEC • FAX: 603-672-9565

Onset Hobo U30 Specifications

Taken from Onset Website

- Normal operating range: -20°C to 40°C (-4°F to 104°F)
- Extended operating range: -40 to 60°C (-40 to 140°F) - see "Rechargeable Battery service Life" for impact of operations in Extended Operating Range.
- Sensor Inputs: 5 standard; option to expand to 10
- Smart Sensor Compatibility: Compatible with most Onset smart sensors, except for the S-BPA, S-TMA and S-THA
- Data Channels: Maximum of 15 (some sensors use more than one data channel)
- Alarm Output Relay: Can be configured to be activated, deactivated or pulsed on user-defined sensor alarms. The relay can be configured as normally open or normally closed, and is rated for 30 V and 1 amp max.
- Expansion Slot: One expansion slot is available for factory-installed expansion port.
- Local Communication: Full Speed USB via USB mini-B connector
- Size: 17.8 H x 11.7 D x 19.3 W cm (7.0 H x 4 .6 D x 7.6 W inches)
- Weight: 2 kg (4 lbs 10 oz)
- Materials: Outer Enclosure: ABS blend with stainless steel hinge pins and bronze inserts
- Inner Enclosure: Polycarbonate with bronze inserts
- U-Bolts: Steel with zinc dichromate finish
- Gaskets: Silicone rubber
- Cable entry channel: EPDM rubber
- Cable entry bars: Aluminum with ABS plastic thumb screws
- Data Storage Memory: Nonvolatile flash data storage, 512K bytes local storage
- Memory Modes: Stop when full, wrap around when full
- Operational Indicators: Up to six (depending upon options) status lights provide basic diagnostics
- Logging Interval: 1 second to 18 hours, user-specified interval
- Battery Type: 4 Volt, 4.5 AHr or 10 AHr, Rechargeable sealed lead-acid
- Rechargeable Battery Service Life: Typical 3–5 years depending upon conditions of use. Operation within the extended operating range (but outside the normal range) will reduce battery service life.
- Time Accuracy: 0 to 2 seconds for the first data point and ±5 seconds per week at 25°C (77°F)
- Environmental Rating: Weatherproof enclosure, tested to NEMA 6. (Requires proper installation of cable channel system)
- Mounting: 3.8 cm (1.5 inch) mast or wall mount
- Enclosure Access: Hinged door secured by two latches with eyelets for securing with user-supplied padlocks
- Sensor Network Cable Length: 100 m (328 ft) maximum
- External Power: External power is required. The system optionally accepts the following Onset solar panels:
- SOLAR-1.2W
- SOLAR-3W
- SOLAR-6W
- Alternatively it accepts an AC power adapter:
- AC-U30

- Optional Analog Sensor Port Specifications
- Input Channels: Two, single-ended
- Field Wiring: Two- or three-wire via screw terminals on detachable connector, 16–24 AWG.
- Replacement detachable connectors: Part of spares kit, Part No. A-FS-CVIA-7P-1
- Input Range: User-configurable: 0–20 mA DC, 0-2.5 VDC, 0-5 VDC, 0-10 VDC, or 0–20 VDC
- Minimum / Maximum Input Voltage: 0 / 24 VDC
- Minimum / Maximum Input Current: 0 / 24 mA DC
- Minimum Current Source Impedance: > 20 KΩ
- Accuracy: ± 0.25% of FSR from 50mV to FSV
- ADC Resolution 12 bits
- Excitation Power: Switched 12 VDC, up to 50 mA; user-selectable warm-up from 5msec to 2 minutes

Wind Speed Smart Sensor (S-WSA-M003)

The Wind Speed smart sensor is designed to work with HOBO® Station loggers. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive user setup.

Inside this Package

- Wind Speed smart sensor with mounting rod

Specifications

Measurement Range	0 to 45 m/sec (0 to 100 mph)
Accuracy	±1.1 m/sec (2.4 mph) or ±4% of reading, whichever is greater
Resolution	0.38 m/sec (0.8 mph)
Service Life	> 5 year life typical, factory replaceable mechanism
Distance Constant	3 m (9.8 ft)
Starting Threshold	≤ 1 m/sec (2.2 mph)
Maximum Wind Speed Survival	54 m/sec (120 mph)
Measurements	Wind speed: Average wind speed over logging interval Gust: Highest 3-second gust during the logging interval See *Measurement Operation* for more information.
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Environmental Rating	Sensor and Cable Jacket: Weatherproof
Housing	Three cup polycarbonate anemometer: Modified Teflon® bearings and hardened beryllium shaft with ice shedding design
Dimensions	41 x 16 cm (16 x 6.5 in.) including 1.27 cm (0.5 in) diameter mounting rod; 5.5 cm (2.1 in.) drip overhang
Weight	300 g (10 oz)
Bits per Sample	8 for each channel, 16 total
Number of Data Channels*	2
Measurement Averaging Option	No
Cable Length Available	3.5 m (11.5 ft)
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft)
Part Number	S-WSA-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Weather Station can accommodate 15 data channels and up to 100 m (328 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Wind Direction Smart Sensor (S-WDA-M003)

The Wind Direction smart sensor is designed to work with HOBO® Stations. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO Station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the logger without the need for any programming or extensive setup.

Inside this Package

- Wind Direction smart sensor with mounting rod

Specifications

Measurement Range	0 to 355 degrees, 5 degree dead band
Accuracy	± 5 degrees
Resolution	1.4 degrees
Starting Threshold	1 m/s (2.2 mph)
Maximum Wind Speed Survival	60 m/s (134 mph)
Measurement Definition	Unit vector averaging used; vector components for each wind measurement are calculated every three seconds for duration of logging interval (see *Measurement Operation*)
Operating Temperature Range	-40°C to 70°C (-40°F to 158°F)
Environmental Rating	Weatherproof
Service Life	4 to 6 years typical depending upon environmental conditions
Housing	Injection-molded plastic housing and vane, static dissipating base, lead-free silicon bronze nose and aluminum mounting rod
Bearing Type	Two shielded stainless steel ball bearing
Turning Radius	Approximately 13.5 cm (5.25 in.)
Dimensions	46 x 20 cm (18 x 8.5 in.) including 1.27 cm (0.5 in) diameter mounting rod; 2.5 mm (0.1 in.) drip overhang
Weight	370 g (13 oz)
Bits per Sample	8
Number of Data Channels*	1
Measurement Averaging Option	Automatic averaging (see *Measurement Operation*)
Cable Length Available	3.5 m (11.5 ft)
Length of Smart Sensor Network Cable*	0.5 m (1.6 ft)
Part Number	S-WDA-M003
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

* A single HOBO Station logger can accommodate 15 data channels and up to 100 m (325 ft) of smart sensor cable (the digital communications portion of the sensor cables).

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Appendix C – Field Tests

Descriptions and Photo documentation of the three days of Shakedown testing

Appendix C: Field Tests

Sensor layout scenarios for First Field Test

December 12, 2013

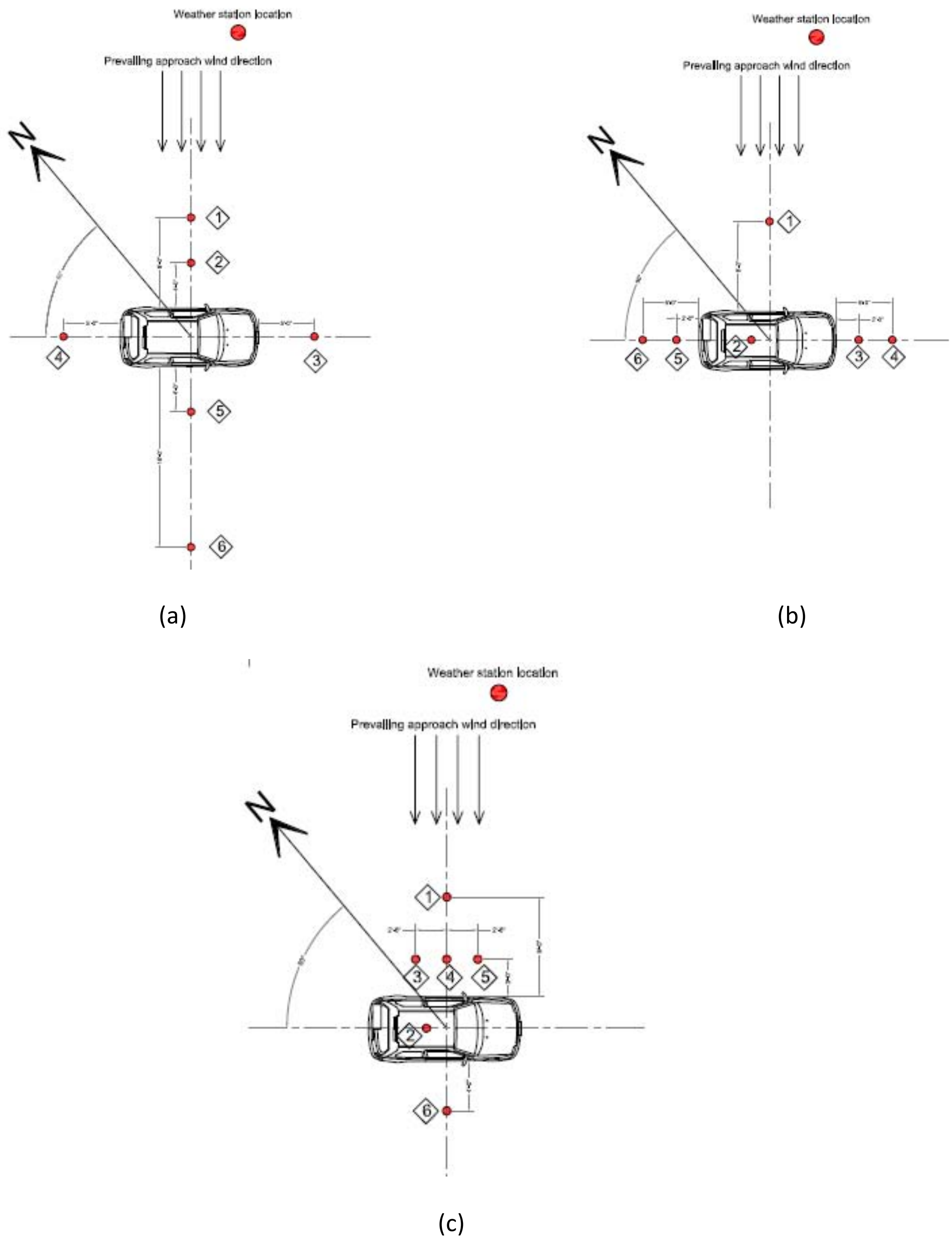
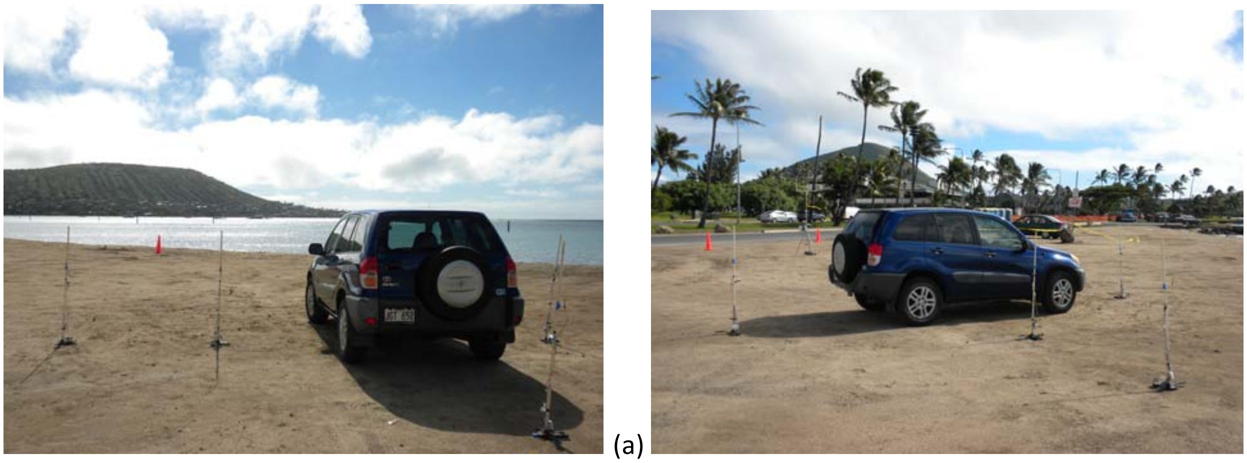
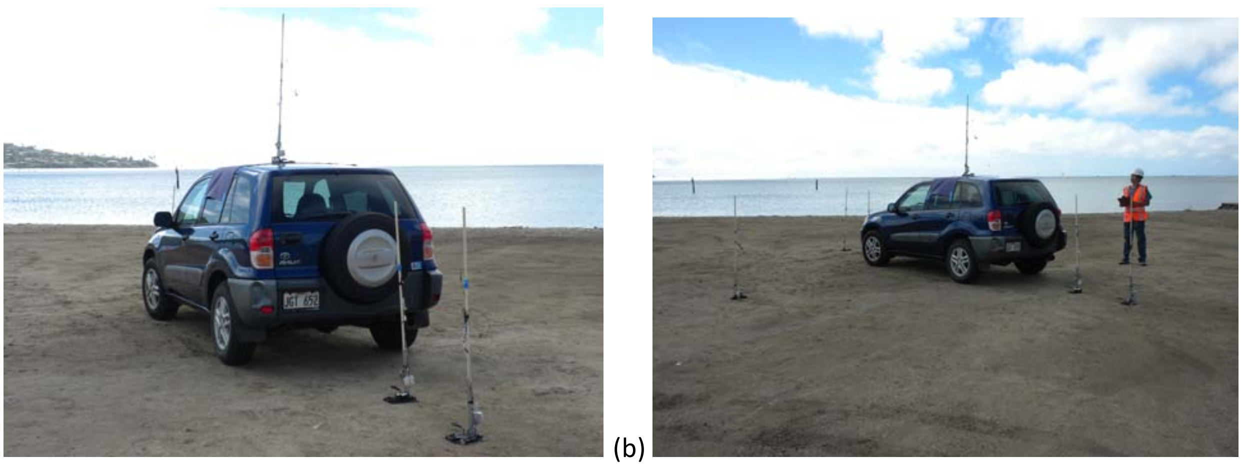


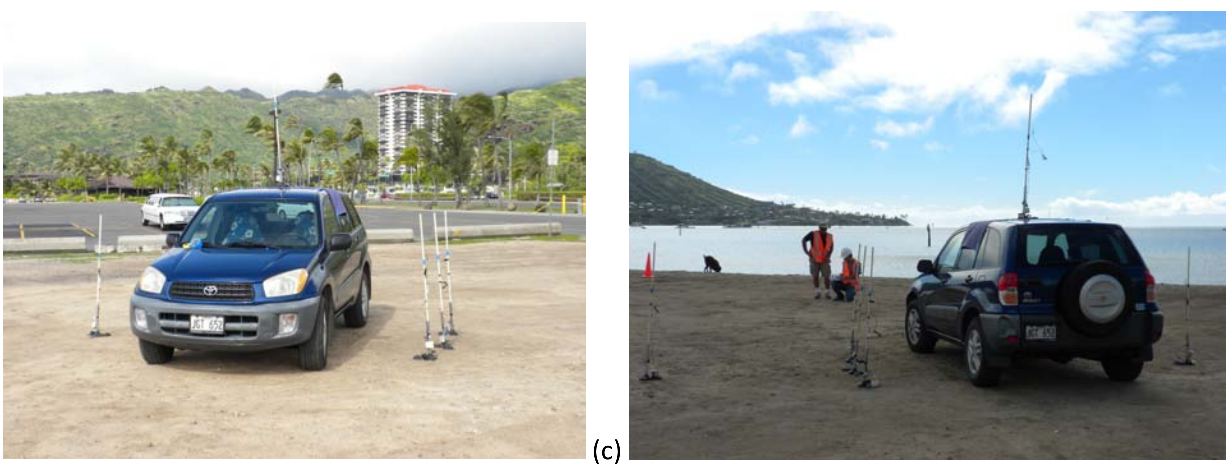
Figure 1. Scenarios of sensor layouts with wind perpendicular to the car for the first field test (See Fig. 2 for corresponding site photos)



(a)

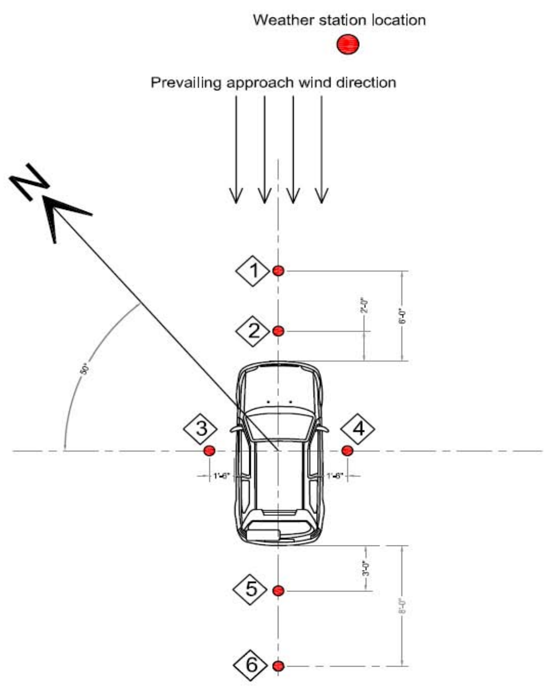


(b)

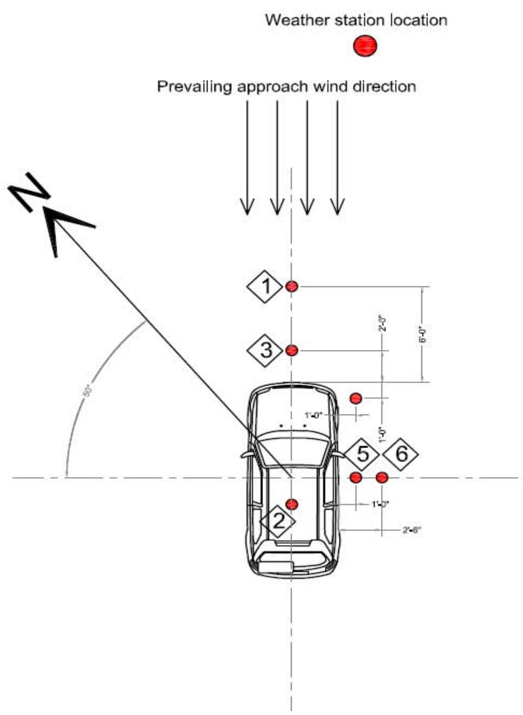


(c)

Figure 2. Scenario photos of sensor layouts with wind perpendicular to the car for the first field test
(See Fig. 1 for corresponding scenario diagrams)



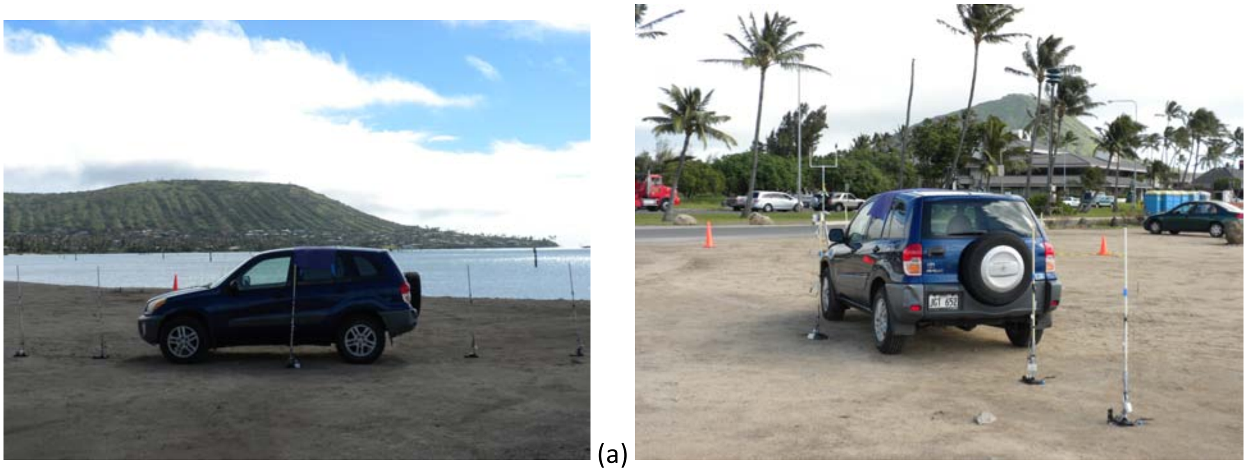
(a)



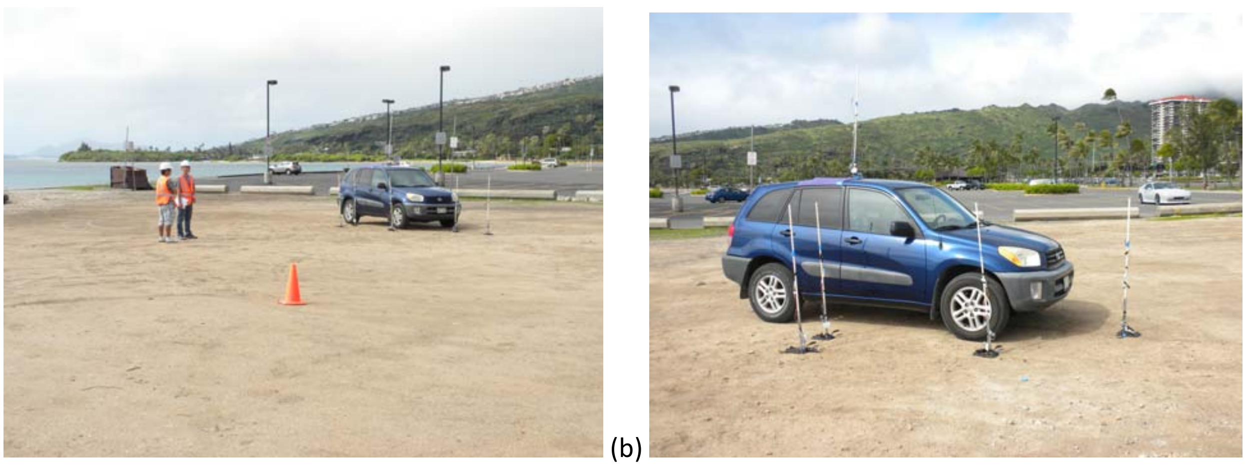
(b)

Figure 3. Scenarios of sensor layouts with wind parallel to the car for the first field test

(See Fig. 4 for corresponding site photos, Figs. 5-10 for instrumentation and field setup)



(a)



(b)

Figure 4. Scenario photos of sensor layouts with wind parallel to the car for the first field test (See Fig. 3 for corresponding scenario diagrams, Figs. 5-10 for instrumentation and field setup)

Figure 5. Calibrating and setting up the weather station (Hobo U30)

Figure 6. Setting up wind speed and direction sensors on the Hobo U30

Figure 7. Mapping and preparing the scenario layout of sensors

Figure 8. Anemometer (DegreeC F900) setup and labeling

Figure 9. Setting up and downloading data acquisition (1-second intervals) on the Hobo U30 logger

Figure 10. Setting up vehicle according to scenario layout (perpendicular or parallel to wind direction), and ensuring uninterrupted airflow through the site area, prior to data acquisition

Sensor layout scenarios for Second Field Test

January 10, 2014

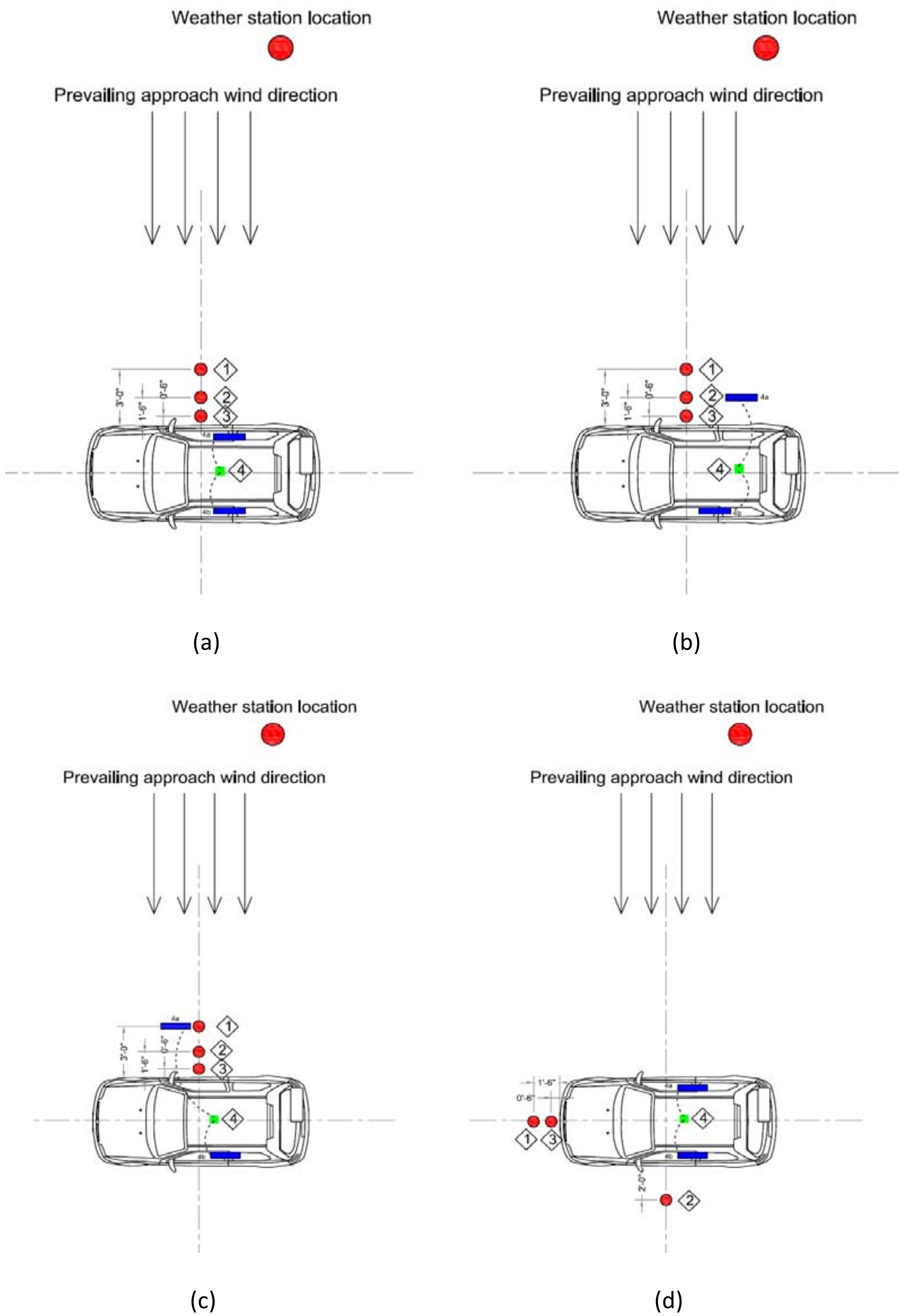
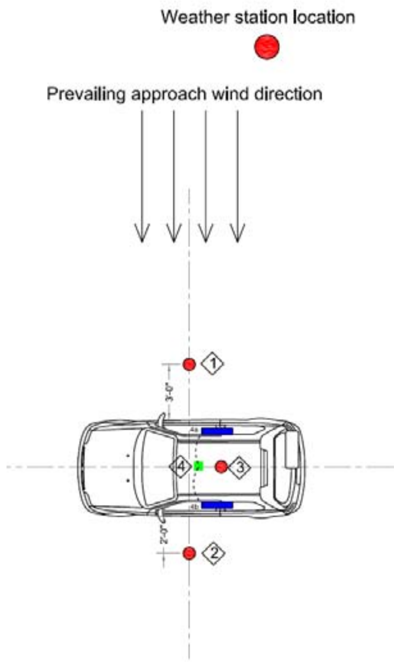
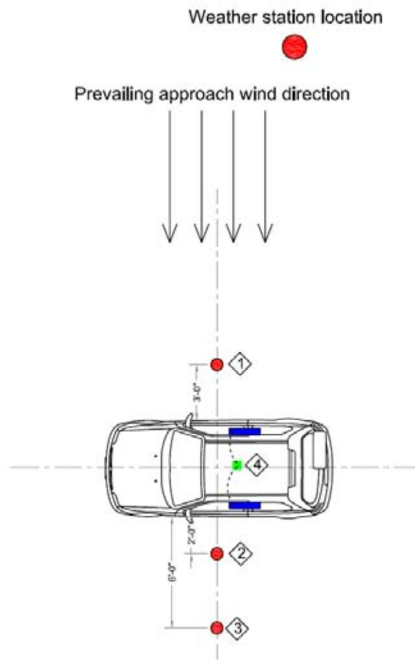


Figure 11. Scenarios of sensor layouts with wind perpendicular to the car for the second field test



(e)



(f)

Figure 11(contd). Scenarios of sensor layouts with wind perpendicular to the car for the second field test

(See Fig. 12 for corresponding site photos of instrumentation and setup of scenarios)

(a)

(b)

Figure 12. Site photos of sensor setup (wind perpendicular to the car) for the second field test

(c)

(d)

(e)

(f)

Figure 12 (contd). Site photos of sensor setup (wind perpendicular to the car) for the second field test

(See Fig. 11 for corresponding scenario diagrams of sensor setup)

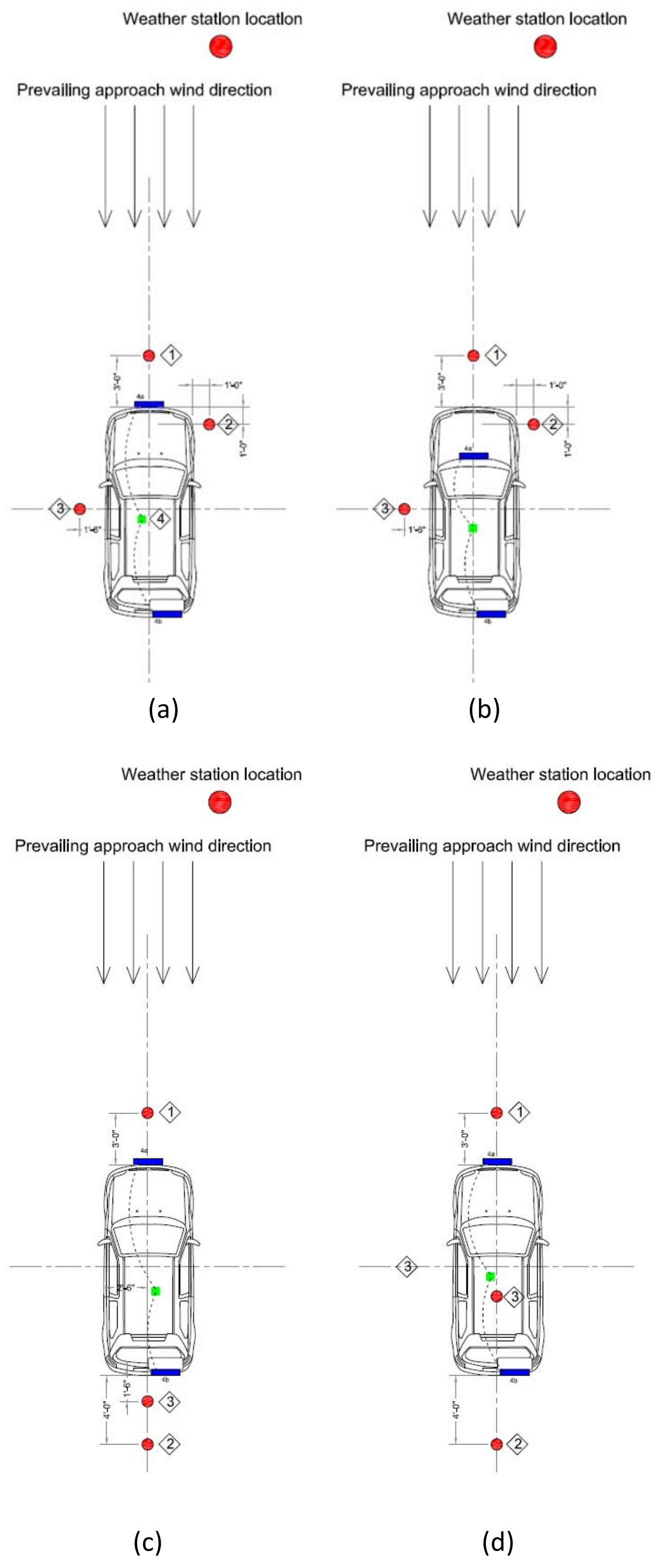


Figure 13. Scenarios of sensor layouts with wind parallel to the car for the second field test (See Fig. 14 for corresponding site photos, Figs. 15-20 for instrumentation and field setup)

(a)

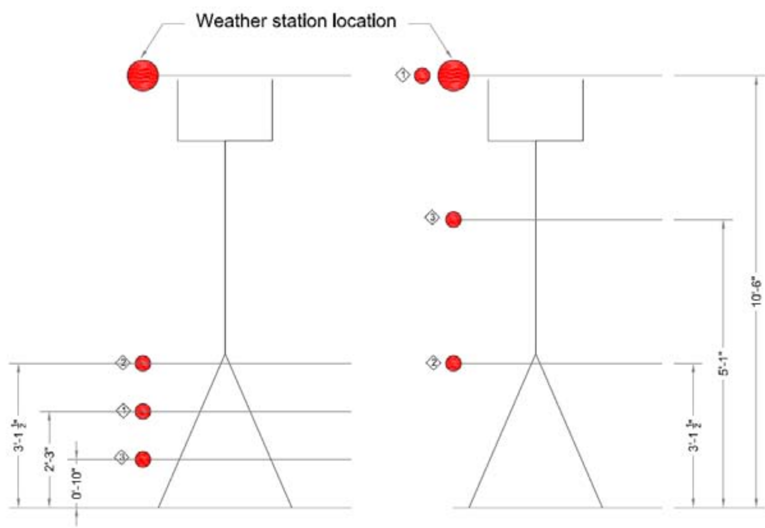
(b)

(c)

(d)

Figure 14. Site photos of sensor setup (wind parallel to the car) for the second field test

(See Fig. 13 for corresponding scenario diagrams, Figs. 15-20 for instrumentation and field setup)



(a) (b)

Figure 15. Sensor setup for measuring the approach wind velocity profile for the second field test (See Figs. 16-20 for corresponding site photos and layout)

Figure 16. Measuring heights for setup of anemometers (F900 DegreeC sensors) for wind velocity profile

Figure 17. Calibrating airflow sensors (F900 anemometers) to compare wind speed profiles

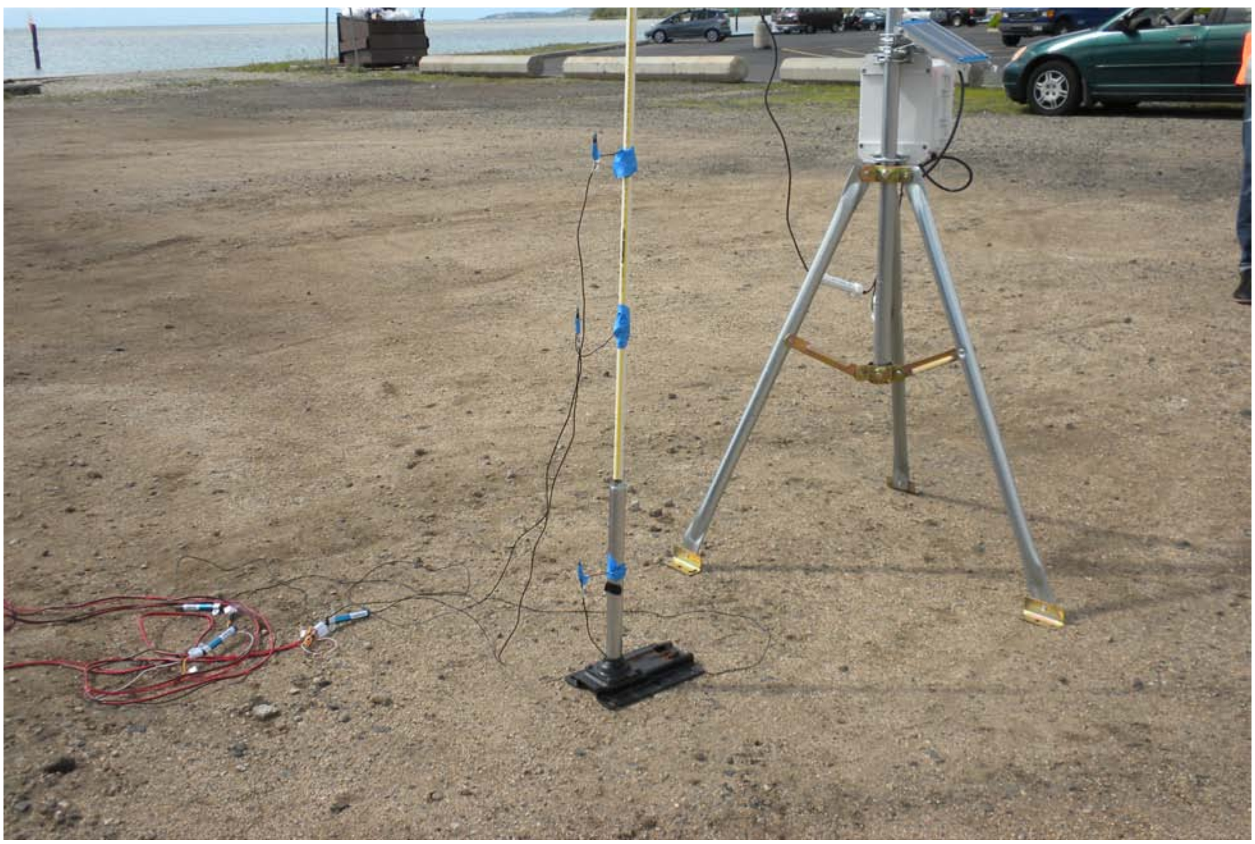


Figure 18. Setup of F900 anemometers and weather station to match scenario layout in Fig. 15 (a)

Figure 19. Setup of (F900) anemometers and (U30) weather station to match scenario in Fig. 15 (b)

Figure 20. Setup of (F900) anemometers and (U30) weather station to match scenario in Fig. 15 (b)

ERDL HNEI

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

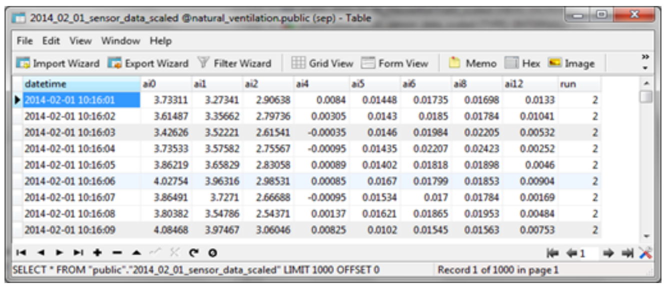
Appendix D - Data Analysis and Data Reduction

A comprehensive description of the methods and procedures used in the data analysis and data reduction

APPENDIX D
Data Analysis and Data Reduction

Steps taken to pre-process data from the third field test:

a. Raw Voltage and Current data came in two separate files
b. First iteration (Fig. 1):
    i. Combine both voltage and current data into one csv file
    ii. Every five entries were averaged and assigned the endpoint time
    iii. Regression equations were used to change the units from volts and amps to meters per second and inch water column.
    iv. Values had a 5 decimal point precision
    v. The shape of the csv had 10 columns, starting with the timestamp then continued to the right with values of each of the 8 sensors, followed by the run number.


2014_02_01_sensor_data_scaled @natural_ventilation.public (sep) - Table

File Edit View Window Help

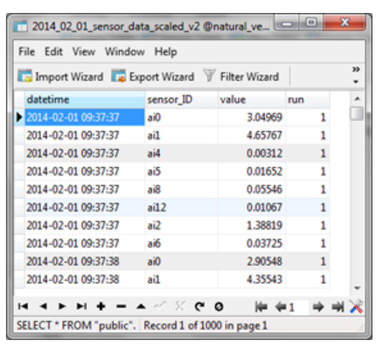
Import Wizard Export Wizard Filter Wizard Grid View Form View Memo Hex Image

datetime	ai0	ai1	ai2	ai4	ai5	ai6	ai8	ai12	run
2014-02-01 10:16:01	3.73311	3.27341	2.90638	0.0084	0.01448	0.01735	0.01698	0.0133	2
2014-02-01 10:16:02	3.61487	3.35662	2.79736	0.00305	0.0143	0.0185	0.01784	0.01041	2
2014-02-01 10:16:03	3.42626	3.52221	2.61541	-0.00035	0.0146	0.01984	0.02205	0.00532	2
2014-02-01 10:16:04	3.73533	3.57582	2.75567	-0.00095	0.01435	0.02207	0.02423	0.00252	2
2014-02-01 10:16:05	3.86219	3.65829	2.83058	0.00089	0.01402	0.01818	0.01898	0.0046	2
2014-02-01 10:16:06	4.02754	3.96316	2.98531	0.00085	0.0167	0.01799	0.01853	0.00904	2
2014-02-01 10:16:07	3.86491	3.7271	2.66688	-0.00095	0.01534	0.017	0.01784	0.00169	2
2014-02-01 10:16:08	3.80382	3.54786	2.54371	0.00137	0.01621	0.01865	0.01953	0.00484	2
2014-02-01 10:16:09	4.08468	3.97467	3.06046	0.00825	0.0102	0.01545	0.01563	0.00753	2

SELECT * FROM "public"."2014_02_01_sensor_data_scaled" LIMIT 1000 OFFSET 0 Record 1 of 1000 in page 1

Figure 1 Horizontal structure of data from first iteration

c. Second iteration (Fig. 2):
    i. Combine both voltage and current data into one csv file
    ii. Every five entries were averaged and assigned the endpoint time
    iii. Regression equations were used to change the units from volts and amps to meters per second and inch water column.
    iv. Values were updated to have 5 decimal point precision
    v. The shape of the csv had 4 columns from left to right: starting with the timestamp, then sensor ID, then the value the sensor reported at the time of the timestamp, and finally the run number.


2014_02_01_sensor_data_scaled_v2 @natural_ve...

File Edit View Window Help

Import Wizard Export Wizard Filter Wizard

datetime	sensor_ID	value	run
2014-02-01 09:37:37	ai0	3.04969	1
2014-02-01 09:37:37	ai1	4.65767	1
2014-02-01 09:37:37	ai4	0.00312	1
2014-02-01 09:37:37	ai5	0.01652	1
2014-02-01 09:37:37	ai8	0.05546	1
2014-02-01 09:37:37	ai12	0.01067	1
2014-02-01 09:37:37	ai2	1.38819	1
2014-02-01 09:37:37	ai6	0.03725	1
2014-02-01 09:37:38	ai0	2.90548	1
2014-02-01 09:37:38	ai1	4.35543	1

SELECT * FROM "public". Record 1 of 1000 in page 1

Figure 2 Vertical Structure of data from second iteration

Python Code for Pre-Processing Iteration #1

```
#----------------------------------------------------------#
# file: iteration1.py                    #
# author: Christian A. Damo                  #
# date: 2013-02-01                        #
#----------------------------------------------------------#
#-------------------------#
#importing modules needed #
#-------------------------#
import csv
import sys
import subprocess
import datetime
import os
#----------------#
# Body of script #
#----------------#
#make a system call "dir" to see what files are in the folder and capture the output
if len(sys.argv) != 5:
	print "not enough arguments"
	print "at prompt, type the following:"
	print "python iteration1.py nameOfVoltageFile nameOfCurrentFile run#"
	quit()
output = subprocess.Popen(["dir"],stdout = subprocess.PIPE, stderr = subprocess.STDOUT, shell = True).communicate()[0]
#split the string by lines
output = output.split("\n")
fileNames = []
#for each line split it by the empty spaces
for line in output:
	line = line.split(" ")
	#for each element find the file name of the files in that folder with the
	#extension *.txt
	for element in line:
		if ".csv" in element and "~" not in element and "_clean" not in element and "output" not in element:
			#if you found a valid filename, put it in a list
			fileNames.append(element[:-1])
#make_sub_folder()
# for each file in the list of found files
fileNames = [sys.argv[1], sys.argv[2]]
print fileNames
#let the user know you're working on it
#print "Working on " + file_
#setup the csv reader and writer
inputFile0 = open(fileNames[0],"r")
inputFile1 = open(fileNames[1],"r")
reader0=csv.reader(inputFile0, delimiter = "\t")
reader1=csv.reader(inputFile1, delimiter = "\t")
newName = "meta-file.csv"
outputFile=open(newName, "wb")
writer = csv.writer(outputFile)
#skip first line
row0 = reader0.next()
```

```
row0 = reader0.next()
row1 = reader1.next()
row1 = reader1.next()
#build the csv header row
newRow=["timestamp"]
for element in row0:
	element = element.split("Dev1_")
	newRow.append(element[1])
for element in row1:
	element = element.split("Dev1_")
	newRow.append(element[1])
print newRow
#write csv header row to file
writer.writerow(newRow)
#skip next line
row0 = reader0.next()
row0 = reader0.next()
row1 = reader1.next()
row1 = reader1.next()
#get start time
origDatetime = row0[0]
origDatetime = origDatetime.split(".")
origDatetime = origDatetime[0]
origDatetime = origDatetime.split(" ")
origDate = origDatetime[0].split("/")
month = origDate[0]
day = origDate[1]
year = origDate[2]
origTime = origDatetime[1]
origTime = origTime.split(":")
hour = origTime[0]
minute = origTime[1]
second = origTime[2]
origDatetime = datetime.datetime(int(year), int(month), int(day), int(hour), int(minute), int(second))
#good up to here
#skip 3 lines
row0 = reader0.next()
row1 = reader1.next()
row0 = reader0.next()
row1 = reader1.next()
row0 = reader0.next()
row1 = reader1.next()
currTime = origDatetime
for row0 in reader0:
	row1 = reader1.next()
	ai0 = float(row0[0])*1.25
	ai1 = float(row0[1])*1.25
	ai4 = (float(row0[2])*.02)-.001
	ai5 = (float(row0[3])*.0199)-.0008
	ai8 = (float(row0[4])*0.009636)-.04818
	ai12 = (float(row0[5])*.02)-.001
	ai2 = float(row0[6])*1.25
	ai6 = ((float(row1[0])*1000)*.0062) - 0.0246
	newRow = [currTime, ai0, ai1,ai4,ai5,ai8,ai12,ai2,ai6]
```

```
		writer.writerow(newRow)
		currTime = currTime + datetime.timedelta(seconds=0.2)
#close the files
inputFile0.close()
inputFile1.close()
outputFile.close()
#This section does the averaging
#setup the csv reader and writer
inputFile = open("meta-file.csv","r")
reader = csv.reader(inputFile)
newName = sys.argv[3]
outputFile=open(newName, "wb")
writer = csv.writer(outputFile)
#pick up the row
row = reader.next()
row.append("run")
#write the header lines
writer.writerow(row)
col1 = []
col2 = []
col3 = []
col4 = []
col5 = []
col6 = []
col7 = []
col8 = []
count = 0
for row in reader:
	if count == 0:
		col1.append(float(row[1]))
		col2.append(float(row[2]))
		col3.append(float(row[3]))
		col4.append(float(row[4]))
		col5.append(float(row[5]))
		col6.append(float(row[6]))
		col7.append(float(row[7]))
		col8.append(float(row[8]))
		count = count + 1
	elif count == 4:
		col1.append(float(row[1]))
		col2.append(float(row[2]))
		col3.append(float(row[3]))
		col4.append(float(row[4]))
		col5.append(float(row[5]))
		col6.append(float(row[6]))
		col7.append(float(row[7]))
		col8.append(float(row[8]))
		currtime = row[0]
		currtime = currtime.split(".")
		currtime = currtime[0]
		currtime = datetime.datetime.strptime(currtime, '%Y-%m-%d %H:%M:%S')
		currtime = currtime + datetime.timedelta(seconds=1)
```

```
                    newRow = [currtime,round(sum(col1)/len(col1),5), round(sum(col2)/len(col2),5),
round(sum(col3)/len(col3),5), round(sum(col4)/len(col4),5), round(sum(col5)/len(col5),5), round(sum(col6)/len(col6),5),
round(sum(col7)/len(col7),5), round(sum(col8)/len(col8),5)]
                    if sys.argv[4] == "run1":
                              newRow.append(1)
                    elif sys.argv[4] == "run2":
                              newRow.append(2)
                    elif sys.argv[4] == "run3":
                              newRow.append(3)
                    writer.writerow(newRow)
                    col1 = []
                    col2 = []
                    col3 = []
                    col4 = []
                    col5 = []
                    col6 = []
                    col7 = []
                    col8 = []
                    count = 0
          else:
                    col1.append(float(row[1]))
                    col2.append(float(row[2]))
                    col3.append(float(row[3]))
                    col4.append(float(row[4]))
                    col5.append(float(row[5]))
                    col6.append(float(row[6]))
                    col7.append(float(row[7]))
                    col8.append(float(row[8]))
                    count = count + 1
                    inputFile.close()
outputFile.close()
os.remove("meta-file.csv")
```

Python Code for Pre-Processing Iteration #1

```
#----------------------------------------------------------#
# file: iteration2.py                                      #
# author: Christian A. Damo                                #
# date: 2013-02-05                                         #
#----------------------------------------------------------#
#-------------------------#
#importing modules needed #
#-------------------------#
import csv
import sys
import subprocess
import datetime
import os
#----------------#
# Body of script #
#----------------#
#make a system call "dir" to see what files are in the folder and capture the output
if len(sys.argv) != 5:
```

```
        print "not enough arguments"
        print "need the following command line input:"
        print "python iteration2.py VoltageDataFile CurrentDataFile run#"
        quit()
# for each file in the given in the parameters
fileNames = [sys.argv[1], sys.argv[2]]

print fileNames
#let the user know you're working on it
#print "Working on " + file_
#setup the csv reader and writer
inputFile0 = open(fileNames[0],"r")
inputFile1 = open(fileNames[1],"r")
reader0=csv.reader(inputFile0, delimiter = "\t")
reader1=csv.reader(inputFile1, delimiter = "\t")
newName = "meta-file.csv"
outputFile=open(newName, "wb")
writer = csv.writer(outputFile)
#skip first line
row0 = reader0.next()
row0 = reader0.next()
row1 = reader1.next()
row1 = reader1.next()
#build the csv header row
newRow=["timestamp"]
for element in row0:
        element = element.split("Dev1_")
        newRow.append(element[1])
for element in row1:
        element = element.split("Dev1_")
        newRow.append(element[1])
print newRow
#write csv header row to file
writer.writerow(newRow)
#skip next line
row0 = reader0.next()
row0 = reader0.next()
row1 = reader1.next()
row1 = reader1.next()
#get start time
origDatetime = row0[0]
origDatetime = origDatetime.split(".")
origDatetime = origDatetime[0]
origDatetime = origDatetime.split(" ")
origDate = origDatetime[0].split("/")
month = origDate[0]
day = origDate[1]
year = origDate[2]
origTime = origDatetime[1]
origTime = origTime.split(":")
hour = origTime[0]
minute = origTime[1]
second = origTime[2]
origDatetime = datetime.datetime(int(year), int(month), int(day), int(hour), int(minute), int(second))
```

```
#good up to here
#skip 3 lines
row0 = reader0.next()
row1 = reader1.next()
row0 = reader0.next()
row1 = reader1.next()
row0 = reader0.next()
row1 = reader1.next()
currTime = origDatetime
for row0 in reader0:
	row1 = reader1.next()
	ai0 = float(row0[0])*1.25
	ai1 = float(row0[1])*1.25
	ai4 = (float(row0[2])*.02)-.001
	ai5 = (float(row0[3])*.0199)-.0008
	ai8 = (float(row0[4])*0.009636)-.04818
	ai12 = (float(row0[5])*.02)-.001
	ai2 = float(row0[6])*1.25
	ai6 = ((float(row1[0])*1000)*.0062) - 0.0246
	newRow = [currTime, ai0, ai1,ai4,ai5,ai8,ai12,ai2,ai6]
	writer.writerow(newRow)
	currTime = currTime + datetime.timedelta(seconds=0.2)
#close the files
inputFile0.close()
inputFile1.close()
outputFile.close()
#This section does the averaging
#setup the csv reader and writer
inputFile = open("meta-file.csv","r")
reader = csv.reader(inputFile)
newName = "meta-file2.csv"
outputFile=open(newName, "wb")
writer = csv.writer(outputFile)
#pick up the row
row = reader.next()
row.append("run")
#write the header lines
writer.writerow(row)
col1 = []
col2 = []
col3 = []
col4 = []
col5 = []
col6 = []
col7 = []
col8 = []
count = 0
for row in reader:
	if count == 0:
		col1.append(float(row[1]))
		col2.append(float(row[2]))
		col3.append(float(row[3]))
		col4.append(float(row[4]))
		col5.append(float(row[5]))
```

```
			col6.append(float(row[6]))
			col7.append(float(row[7]))
			col8.append(float(row[8]))
			count = count + 1
		elif count == 4:
			col1.append(float(row[1]))
			col2.append(float(row[2]))
			col3.append(float(row[3]))
			col4.append(float(row[4]))
			col5.append(float(row[5]))
			col6.append(float(row[6]))
			col7.append(float(row[7]))
			col8.append(float(row[8]))
			currtime = row[0]
			currtime = currtime.split(".")
			currtime = currtime[0]
			currtime = datetime.datetime.strptime(currtime, '%Y-%m-%d %H:%M:%S')
			currtime = currtime + datetime.timedelta(seconds=1)
			newRow = [currtime,round(sum(col1)/len(col1),5), round(sum(col2)/len(col2),5),
round(sum(col3)/len(col3),5), round(sum(col4)/len(col4),5), round(sum(col5)/len(col5),5), round(sum(col6)/len(col6),5),
round(sum(col7)/len(col7),5), round(sum(col8)/len(col8),5)]
			if sys.argv[4] == "run1":
				newRow.append(1)
			elif sys.argv[4] == "run2":
				newRow.append(2)
			elif sys.argv[4] == "run3":
				newRow.append(3)
			writer.writerow(newRow)
			col1 = []
			col2 = []
			col3 = []
			col4 = []
			col5 = []
			col6 = []
			col7 = []
			col8 = []
			count = 0
		else:
			col1.append(float(row[1]))
			col2.append(float(row[2]))
			col3.append(float(row[3]))
			col4.append(float(row[4]))
			col5.append(float(row[5]))
			col6.append(float(row[6]))
			col7.append(float(row[7]))
			col8.append(float(row[8]))
			count = count + 1
inputFile.close()
outputFile.close()
os.remove("meta-file.csv")
#open metafile2 to reformat it the way Eileen wants it
#with the header = (timestamp, sensor_id, value)
inputFile = open("meta-file2.csv","r")
reader=csv.reader(inputFile)
```

```
newName = sys.argv[3]
outputFile=open(newName, "wb")
writer = csv.writer(outputFile)
#pick up the header line
row = reader.next()
sensor_ID = []
sensor_ID = row[1:]
#construct new header
newRow = ["datetime", "sensor_ID", "value", "run"]
writer.writerow(newRow)
#pcik up and process every other line the same way
for row in reader:
	#for each sensor in the row
	time = row[0]
	run = row[-1]
	row = row[1:-1]
	x = 0
	newRow = []
	while x < len(row):
		newRow.append(time)
		newRow.append(sensor_ID[x])
		newRow.append(row[x])
		newRow.append(run)
		#print the row
		writer.writerow(newRow)
		newRow = []
		x = x + 1
inputFile.close()
outputFile.close()
os.remove("meta-file2.csv")
```

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Appendix E – Initial CFD Simulations

1. Description of CAD process to build the 3D-model of the test structure (RAV-SUV)
2. Description of the initial CFD simulation runs that were used to identify suitable locations for the placement of the anemometers and pressure tubing terminals

Appendix E1 - Constructing the 3D-Structure of the test specimen

E1.1 - RAV4 In-depth Modeling Procedure

Step 1. Acquire schematic documents for the car (plan, elevation of sides, front and back).

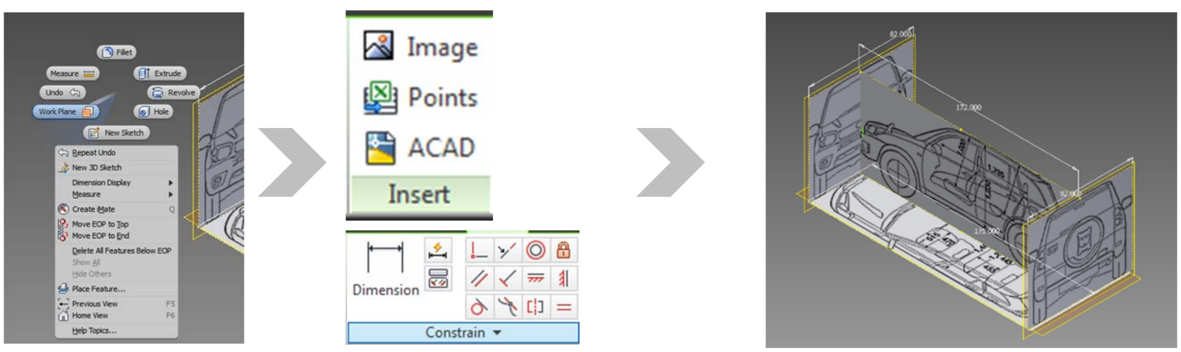
AutoCAD plans are preferable, but images with dimensions will work. For this model, images with reference dimensions are used.

PLAN SIDE ELEVATION FRONT BACK

Step 2. Setup work or reference planes to place images or cad files.

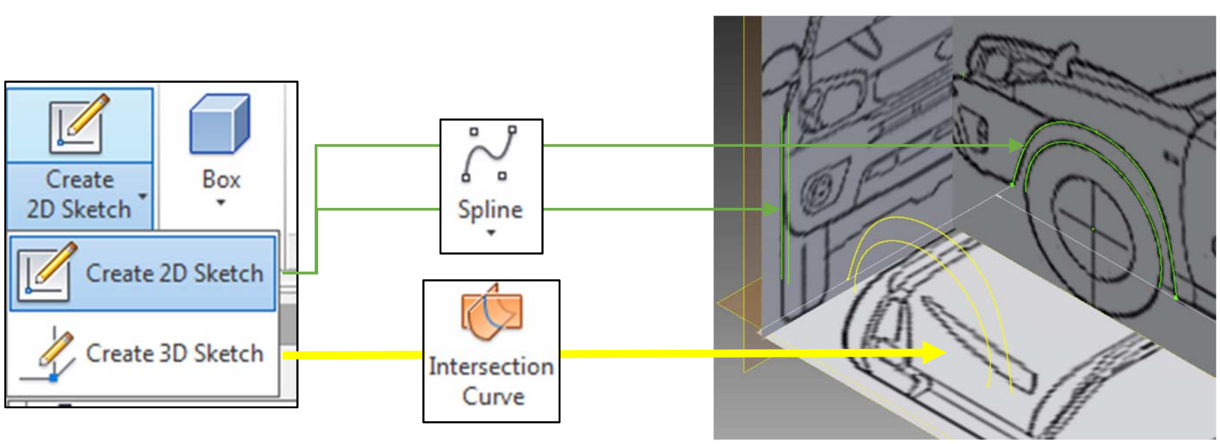
If images, scale using the dimension tool.

WORK PLANE IMAGE/CAD REPEAT FOR ALL IMAGES/CAD FILES



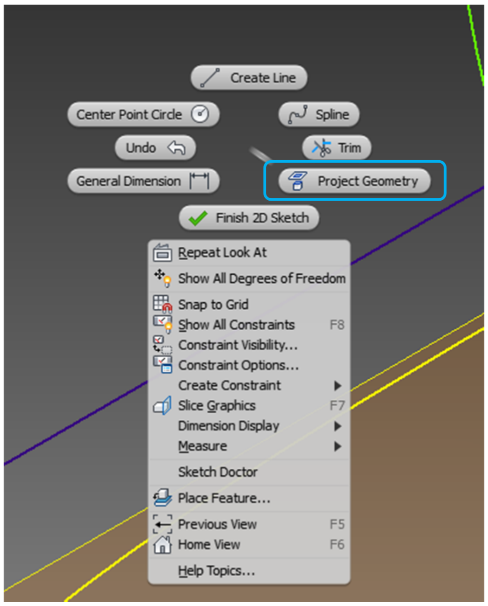
Step 3. Model the frame of the car using 2D sketch splines and 3D intersection curves.

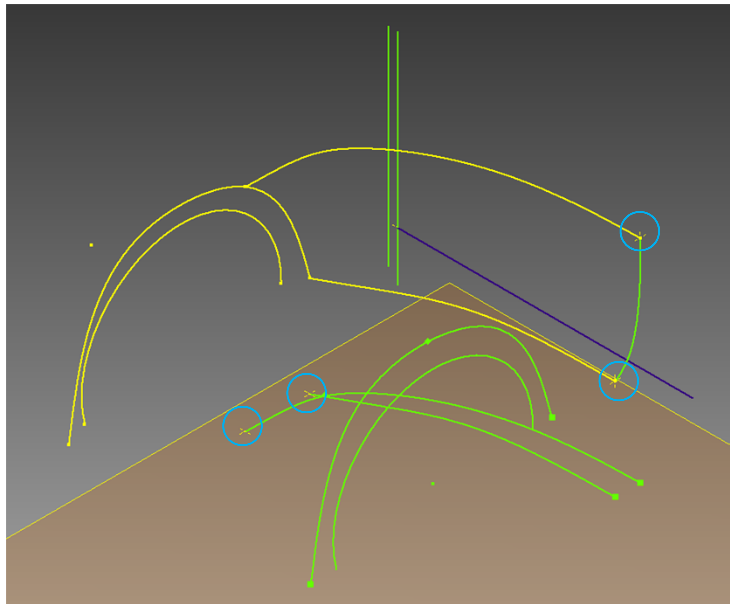
First create 2D Sketches for two planes. Then use 3D Sketch to create intersection curves.



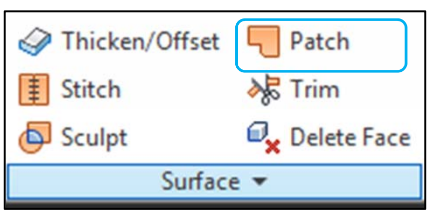
Step 4. Use project geometry while creating splines to insure all surfaces will intersect and not leave openings.

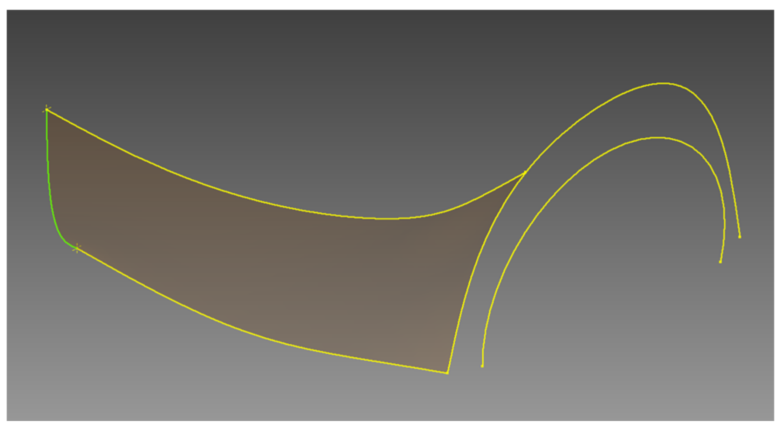
Project geometry of 2D points, curves allows current sketches to project or snap to each other.



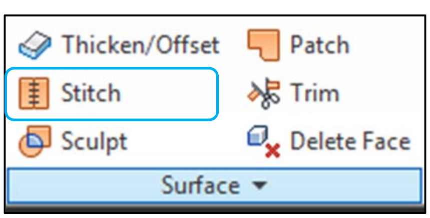


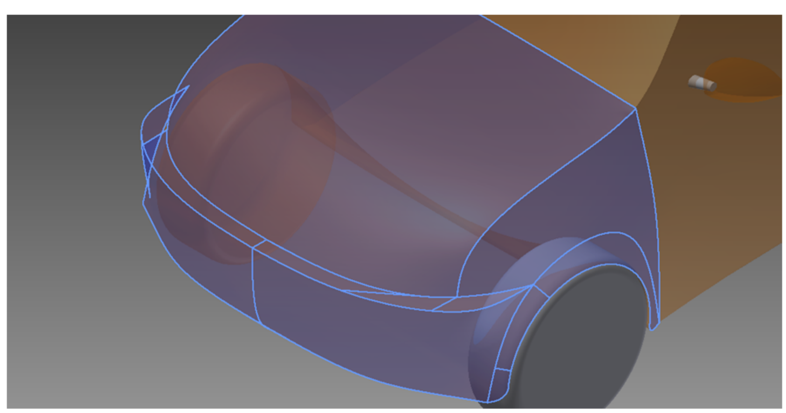
Step 5. Patch 3D Intersection curves to create surfaces.



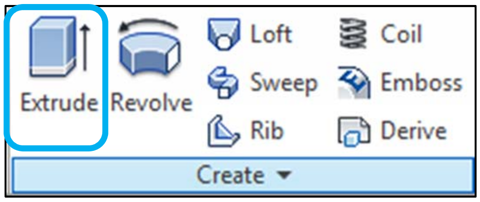


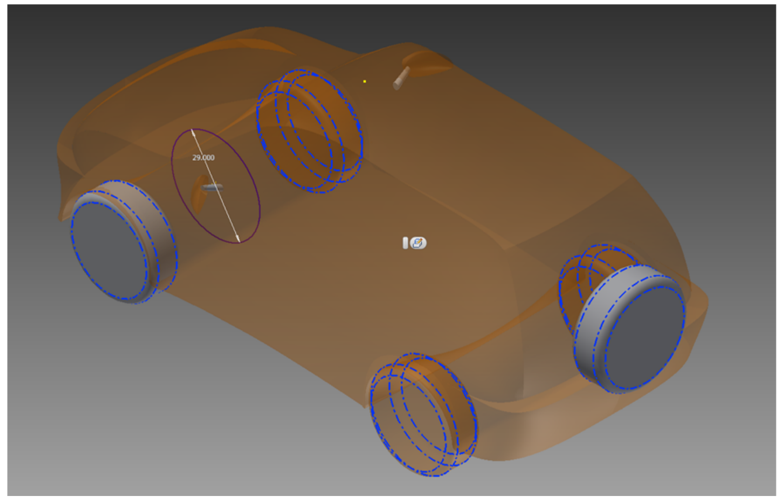
Step 6. Combine surfaces together using the Stitch command.





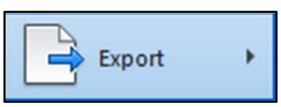
Step 7. Simple geometric objects can be easily modeled by using the Extrude command (ex. Wheels)

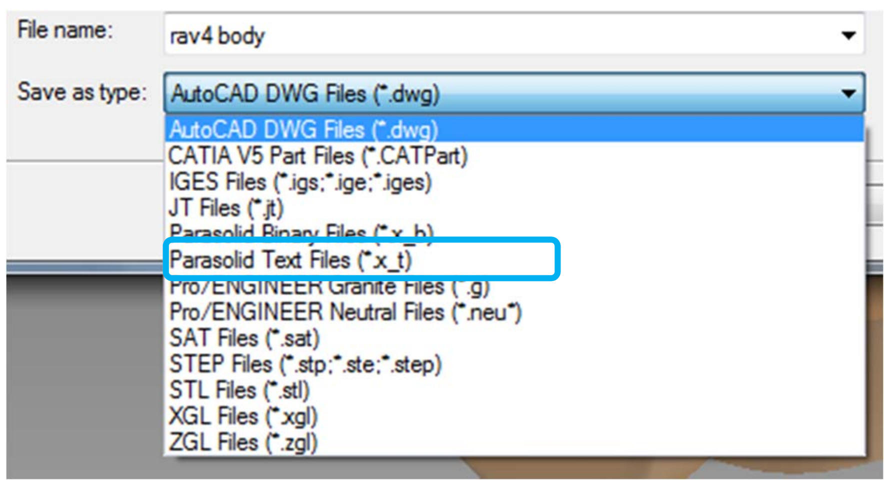




Step 8. Export as CAD format, parasolid (.x_t) file.

Turn off visibility for all unnecessary components such as work planes, 2D, 3D sketches, before exporting.





E1.2 - Keller Hall Modeling Procedure

Step 1. Use University of Hawaii at Manoa's CAD campus plan as a reference.

Step 2. Trace footprints of Keller Hall and its surrounding environment.

Step 3. Extrude building footprints to building heights as indicated in construction documents.

Step 4. Model any significant features of surrounding buildings.

Step 5. Model details for main focus (Keller Hall).

Step 6. Export as CAD format, parasolid (.x_t) file.

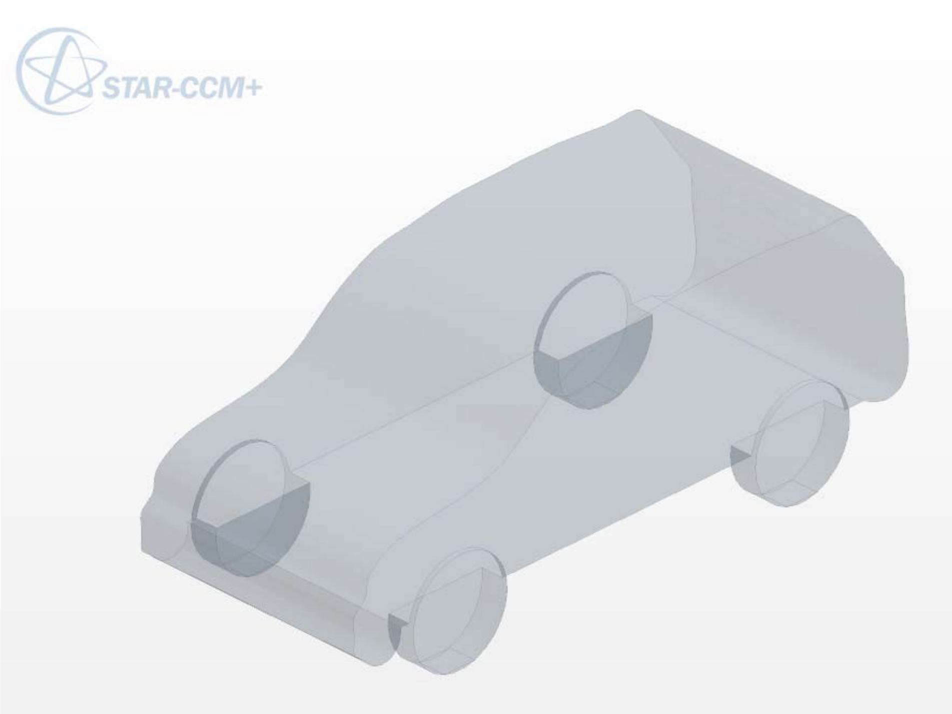


Figure 1: 3D CAD model in STAR-CCM+ in transparent visibility

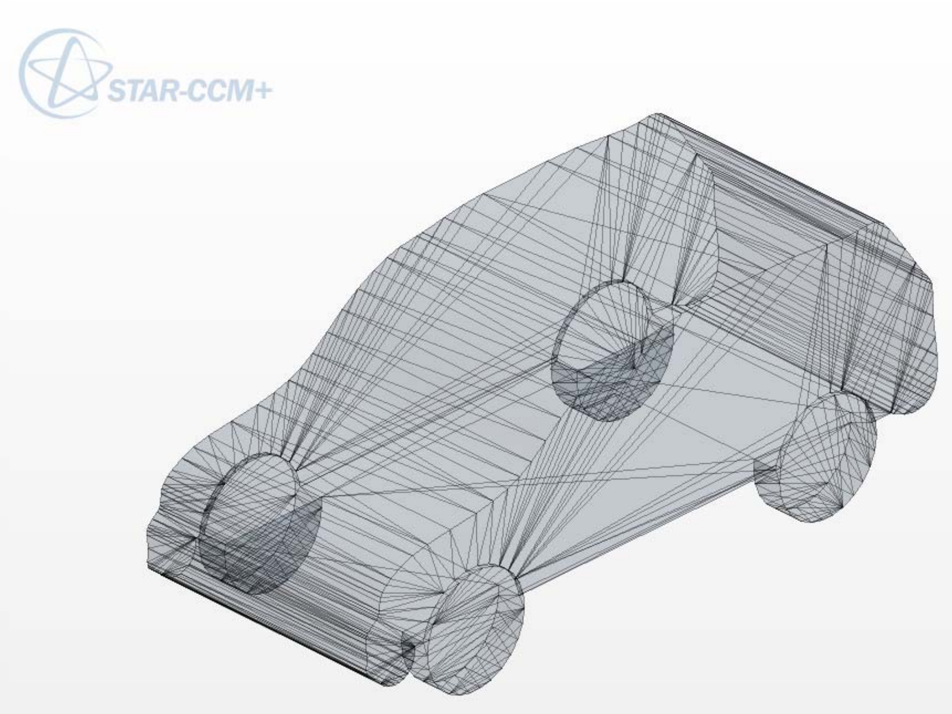


Figure 3: 3D CAD model in STAR-CCM+ in premeshing structure

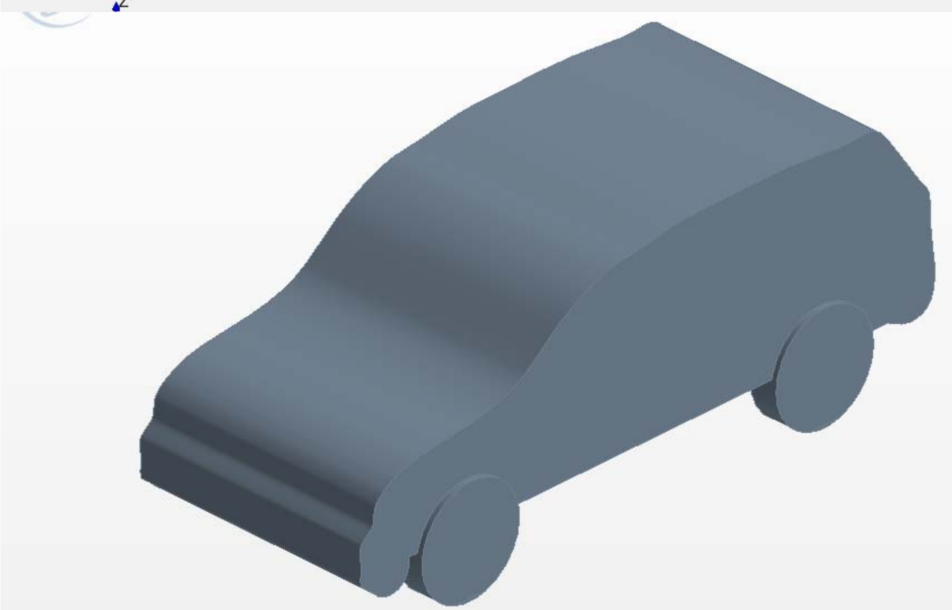


Figure 2: 3D CAD model in STAR-CCM+ in solid shaded visibility

CFD Experiment 2 (Pre-validation)

12/4/13

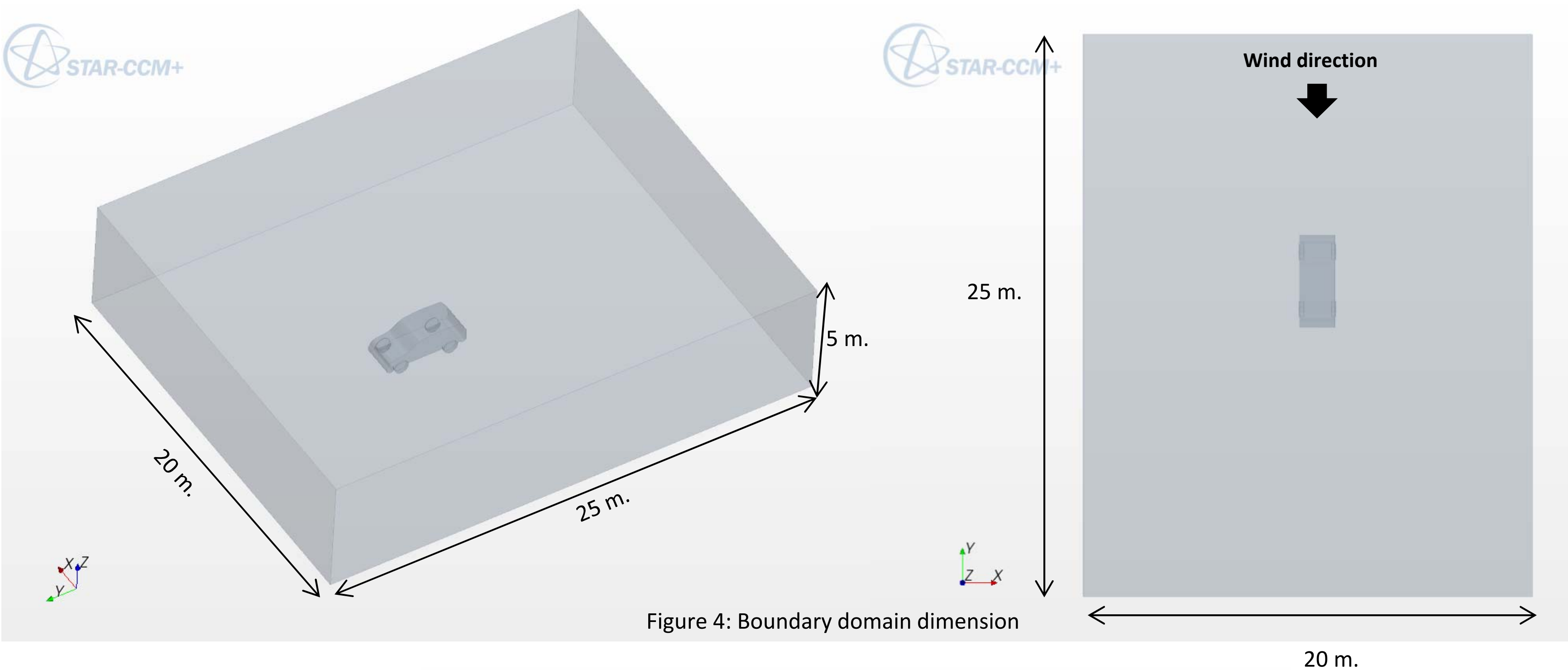


Figure 4: Boundary domain dimension

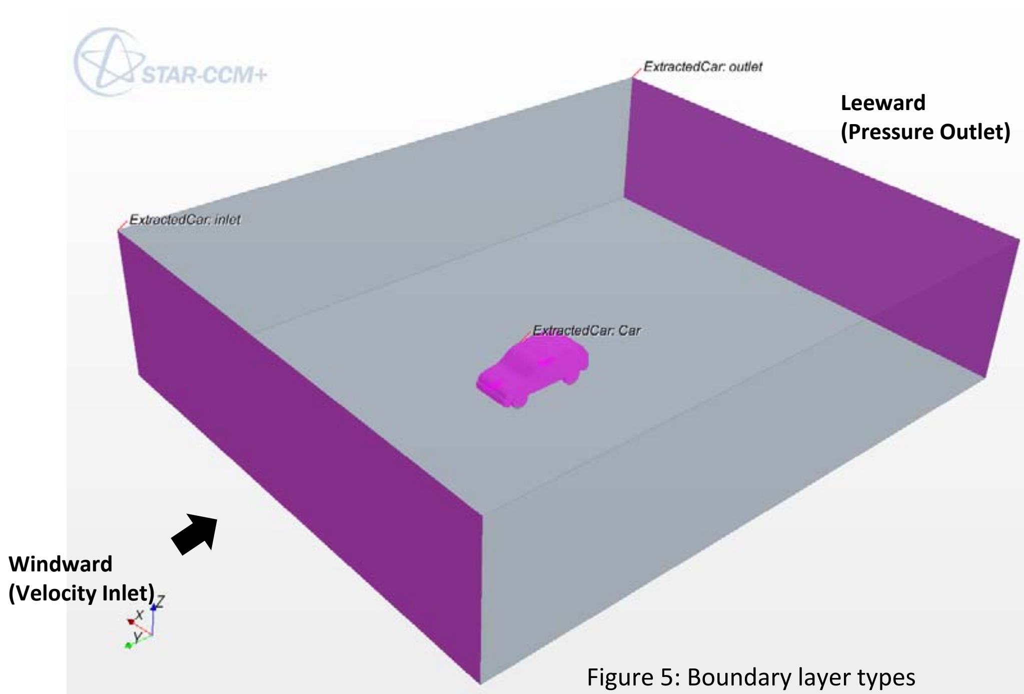


Figure 5: Boundary layer types

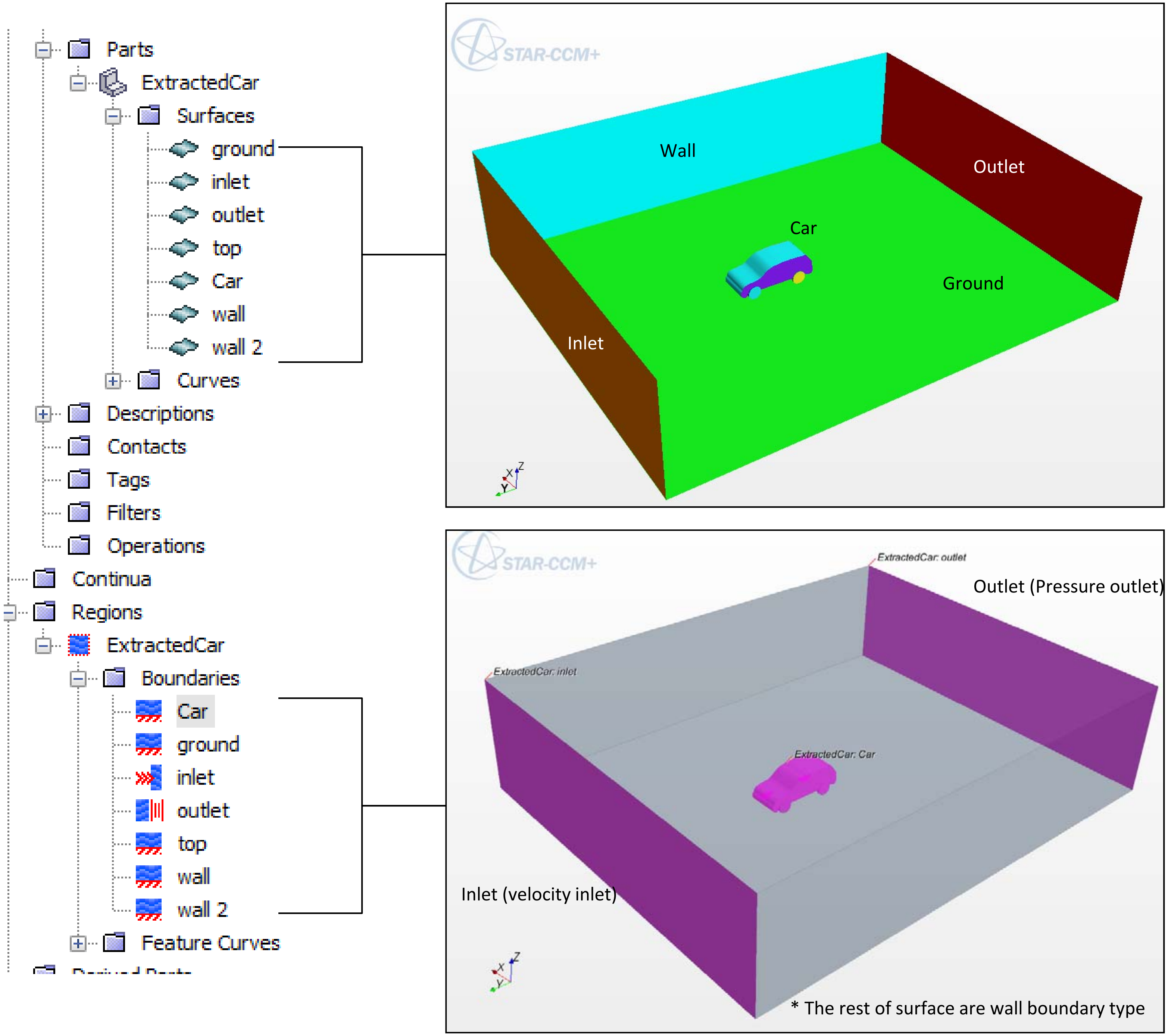
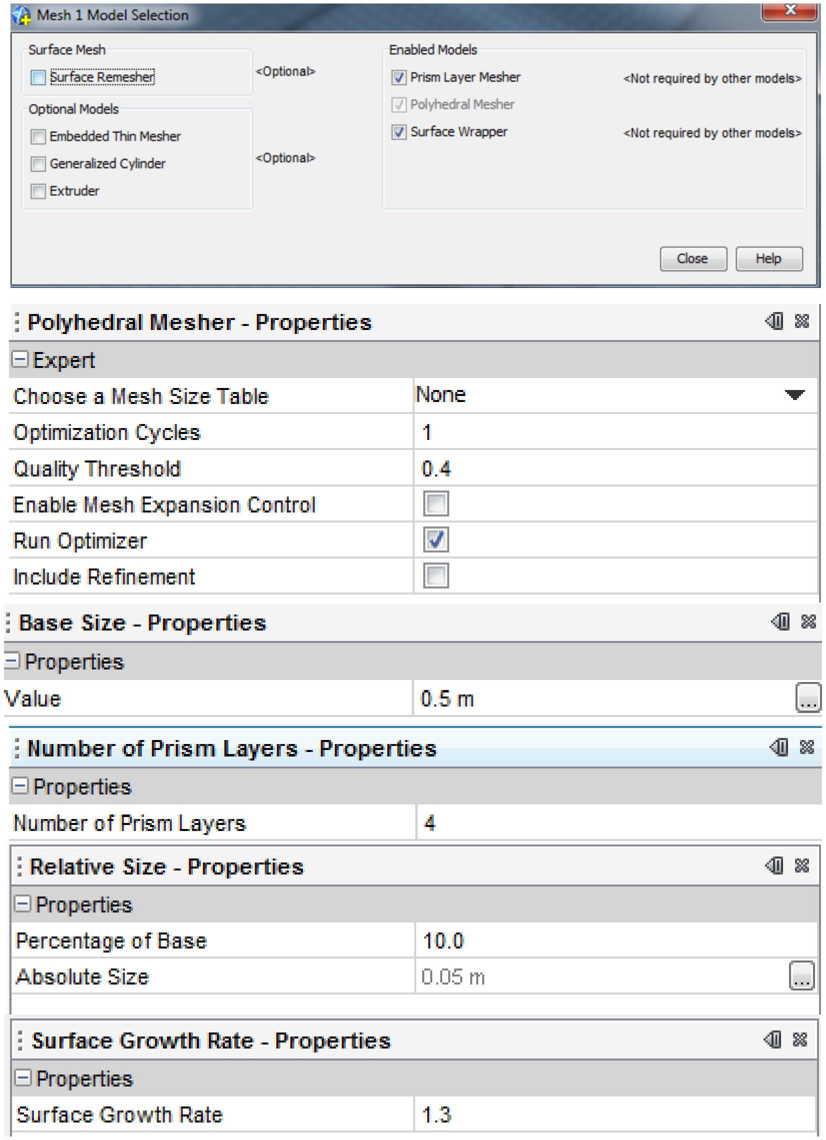


Figure 6: External CFD workflow for surface and regions set up

Continua: Mesh model set up



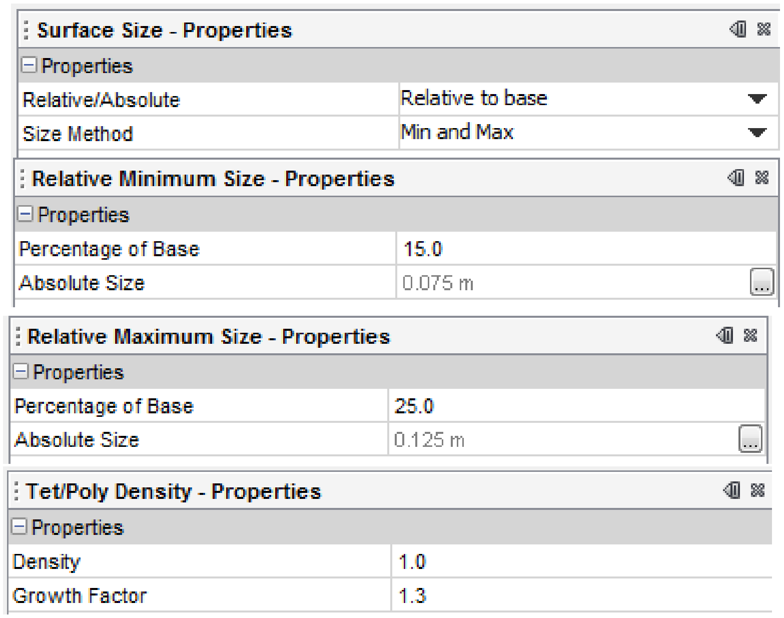


Figure 7: Continua meshing model set ups

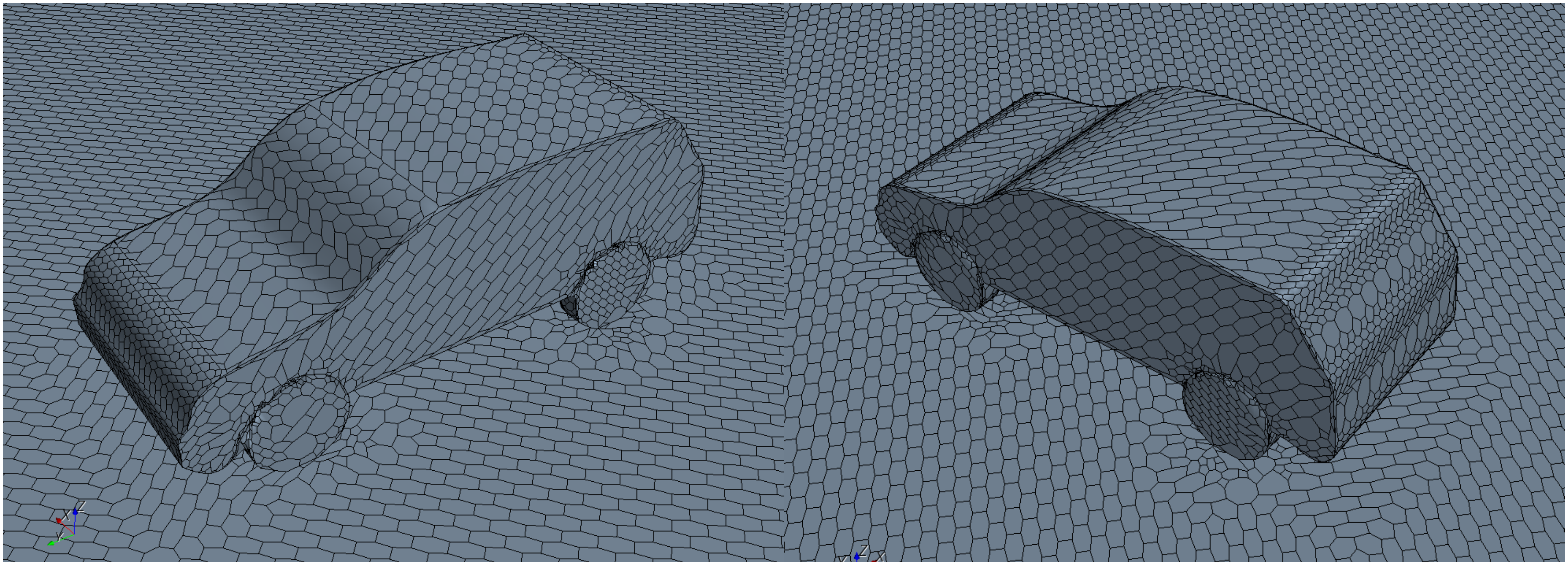


Figure 8: Polyhedral mesher

Continua: Physics model set up

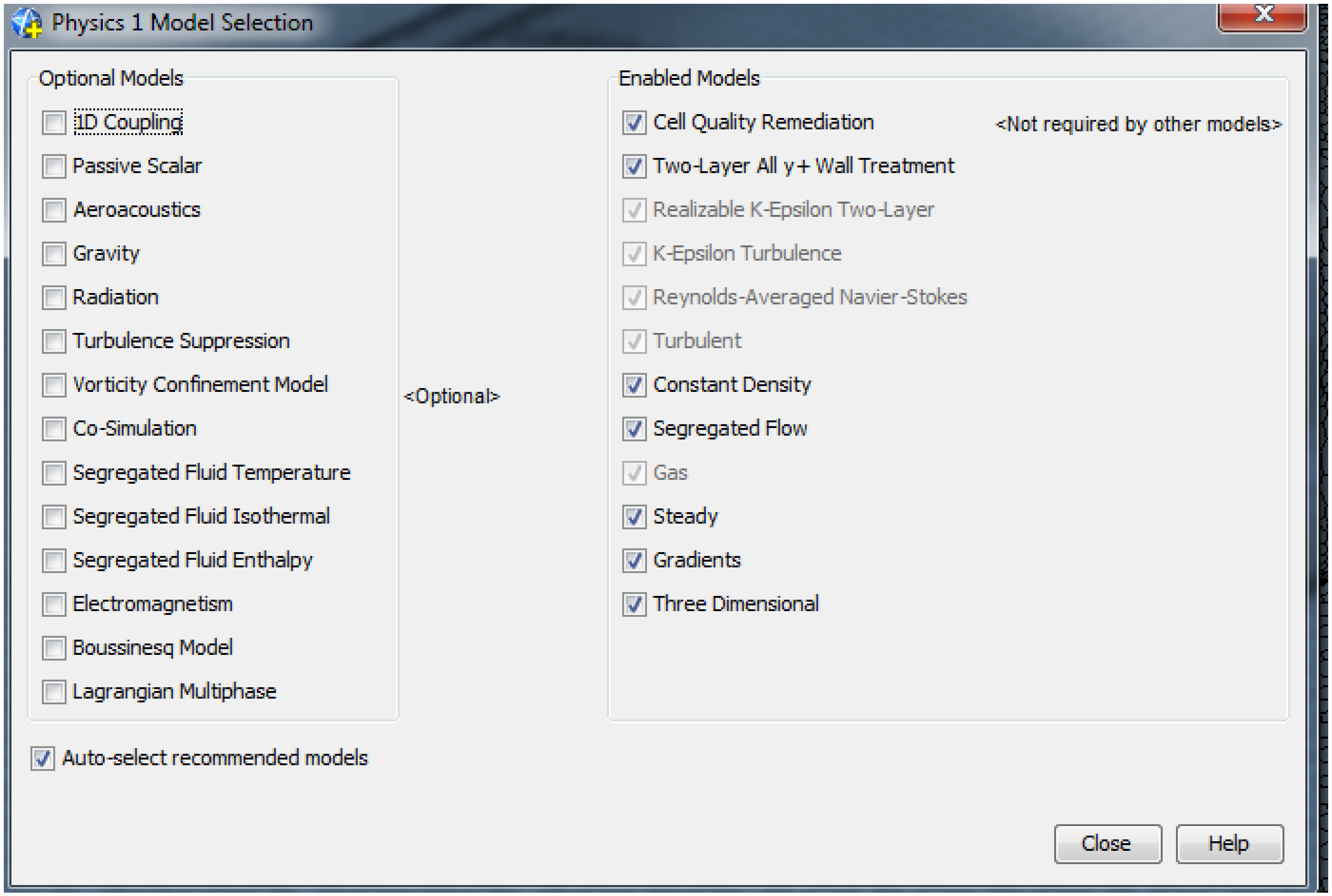
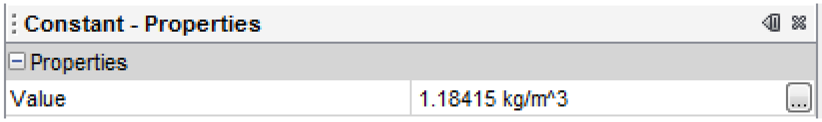
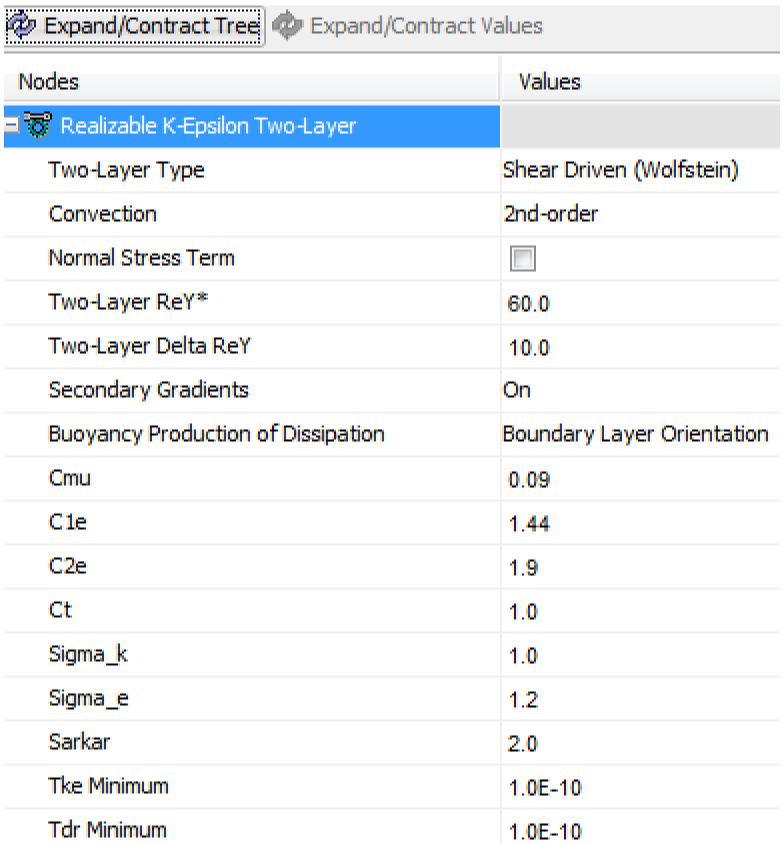


Figure 9: Continua physic model set up

Air density





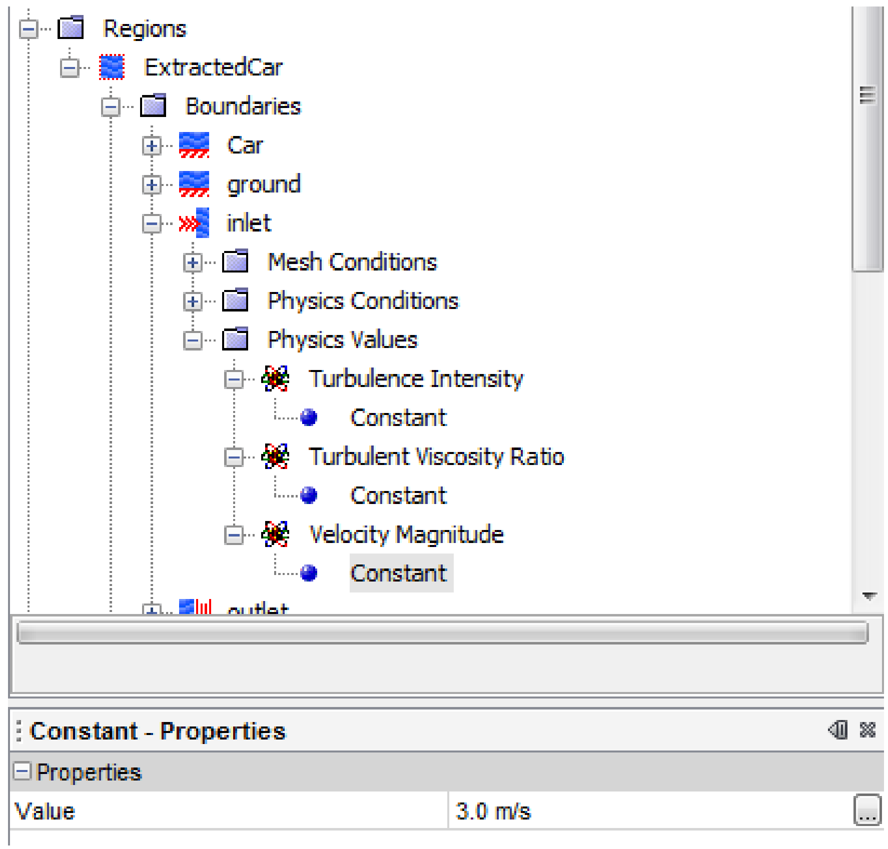
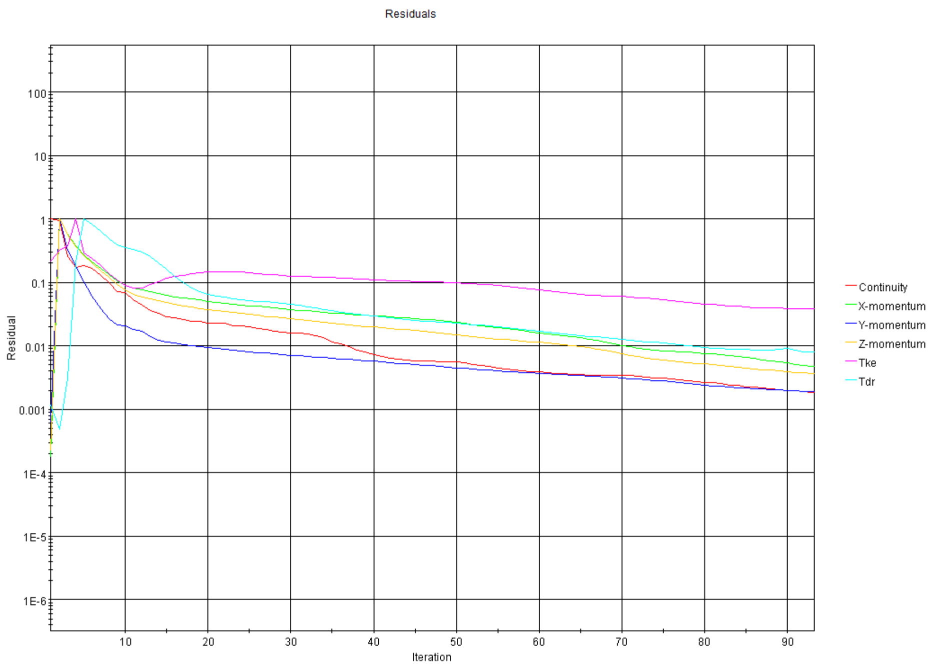


Figure 10: Example of Physic set up

Residual



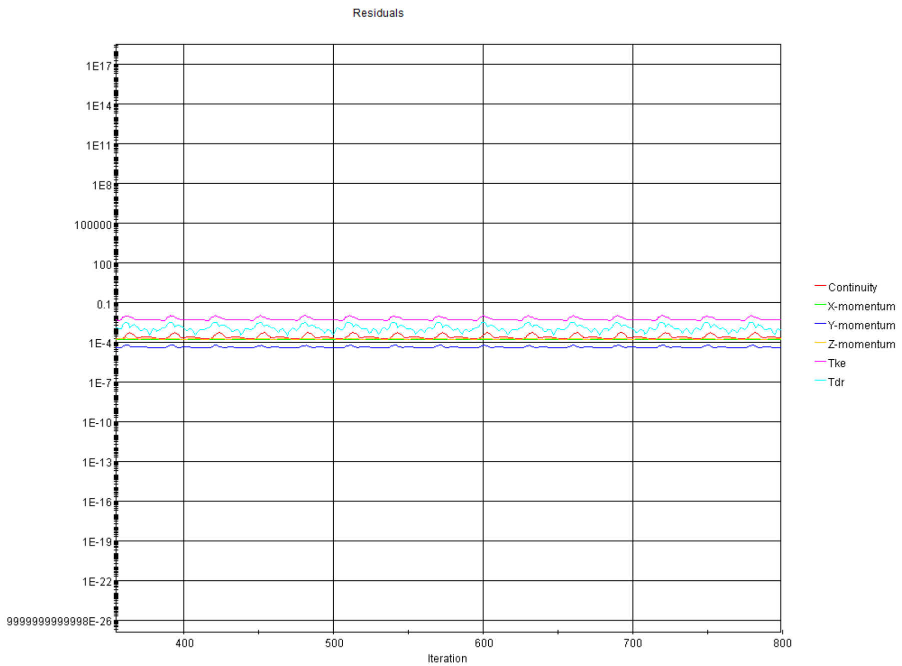


Figure 11: Residual report plot graph

WIND DIRECTION 1

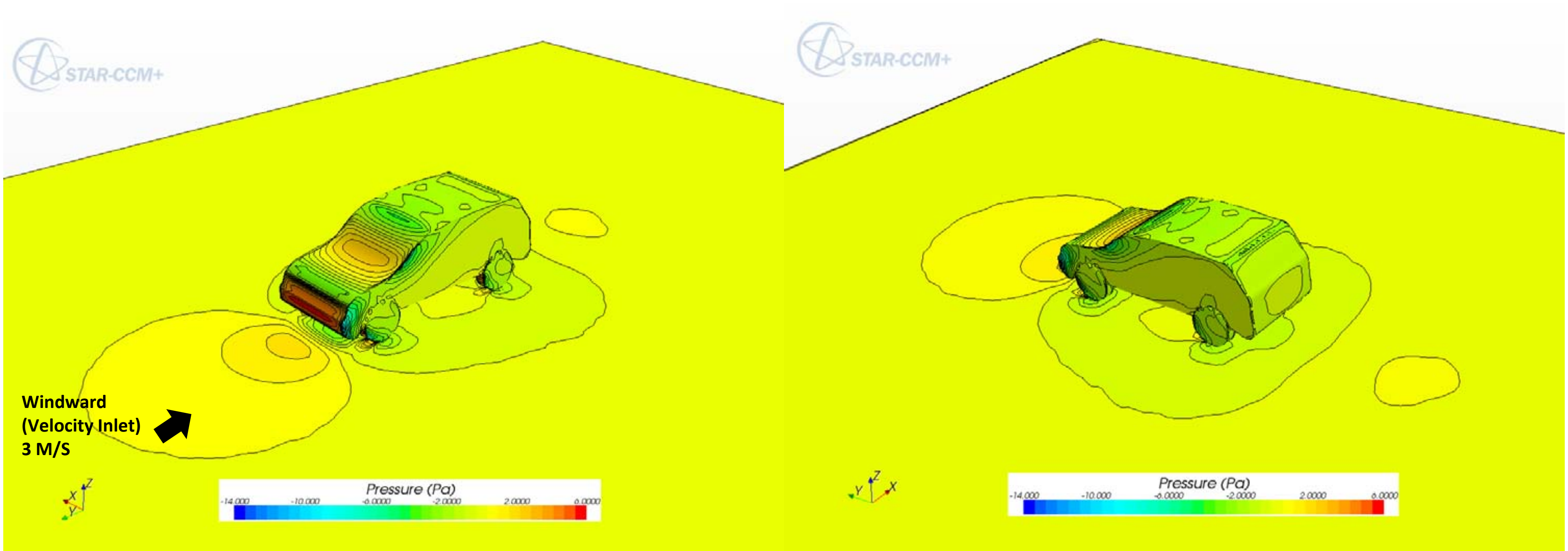


Figure 12: Example of pressure distribution on car surface in post simulation

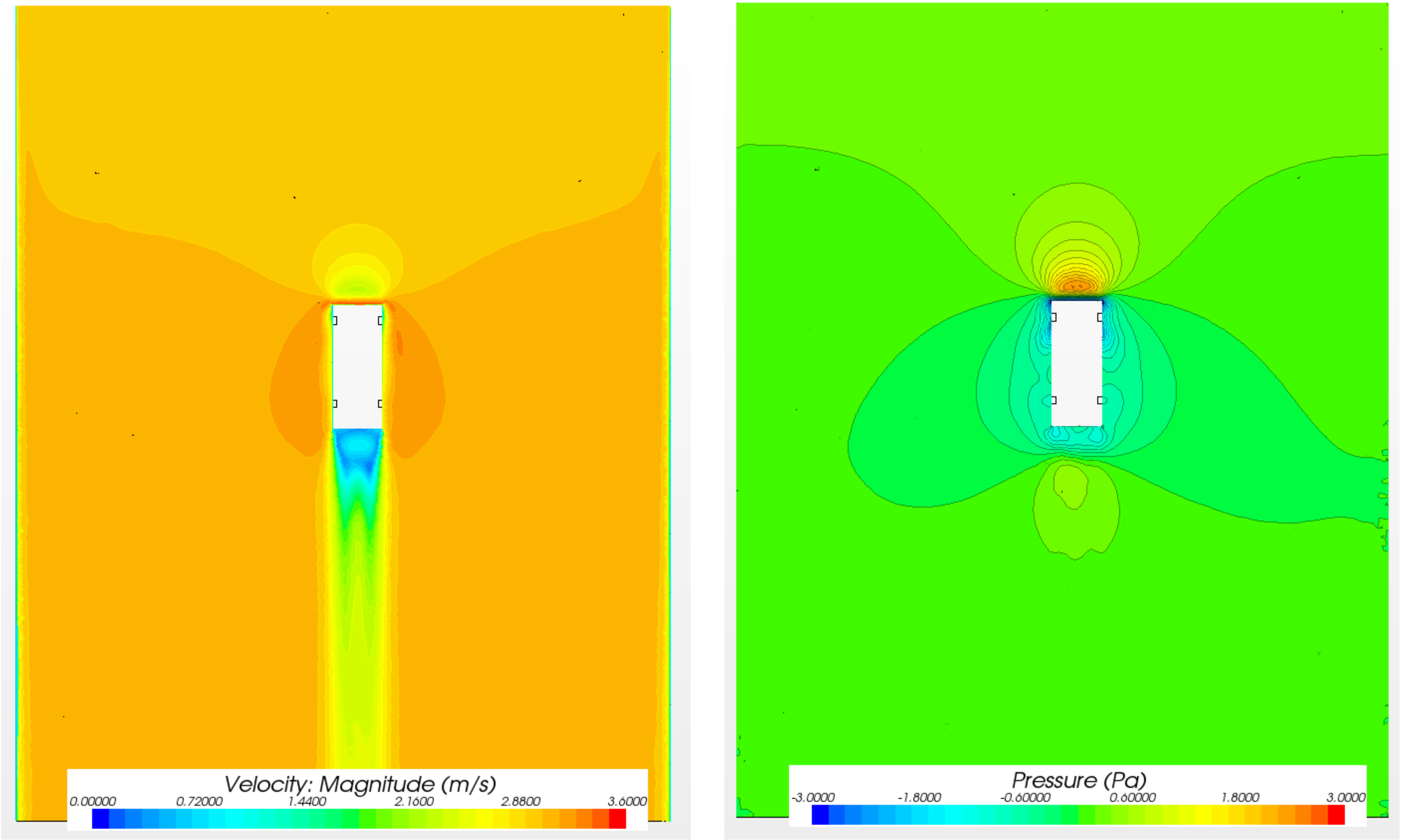


Figure 13: Example of velocity (m/s) and pressure (Pa) at 0.90 meter above ground

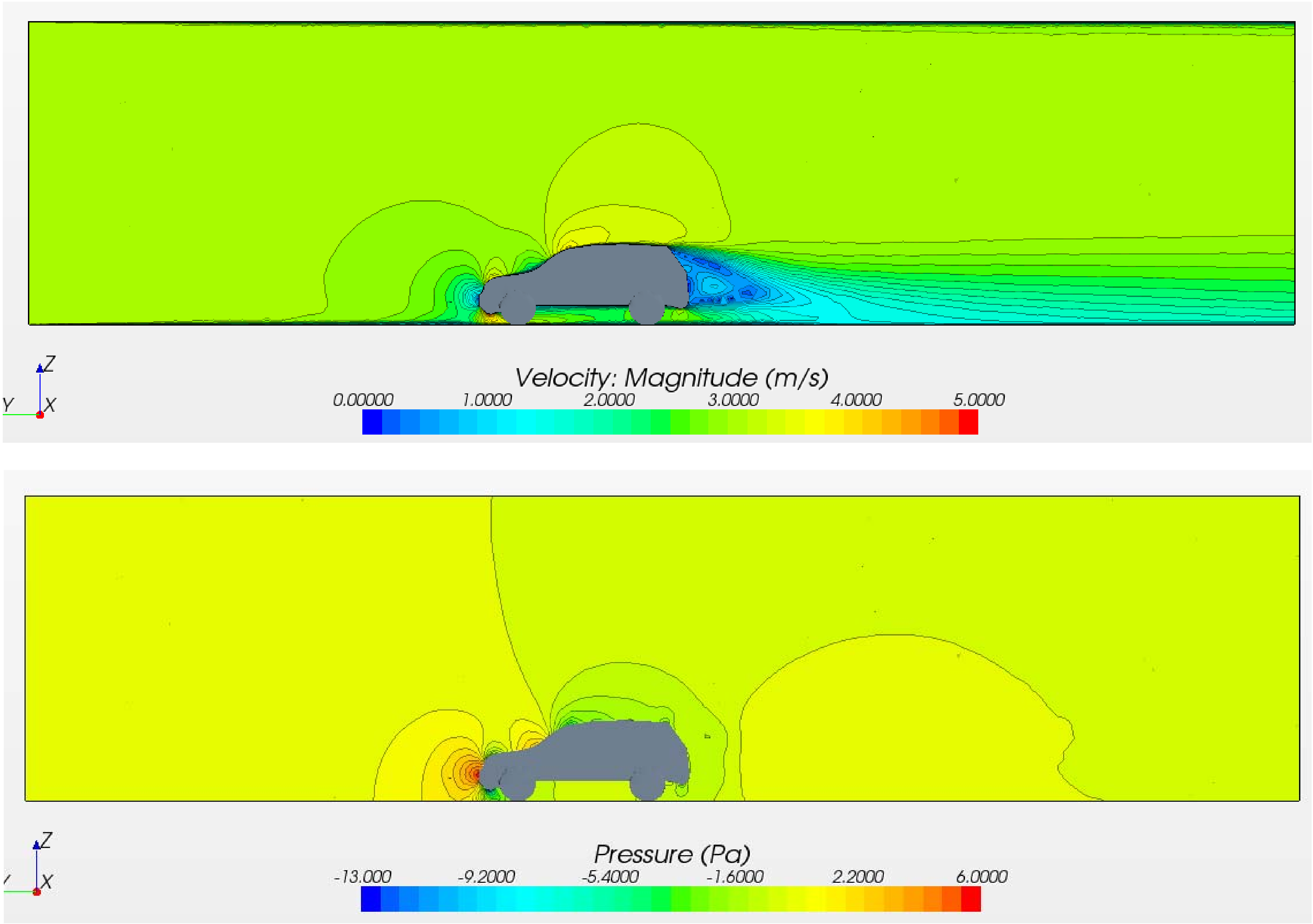


Figure 14: Example of velocity (m/s) and pressure (Pa) at cross section

WIND DIRECTION 2

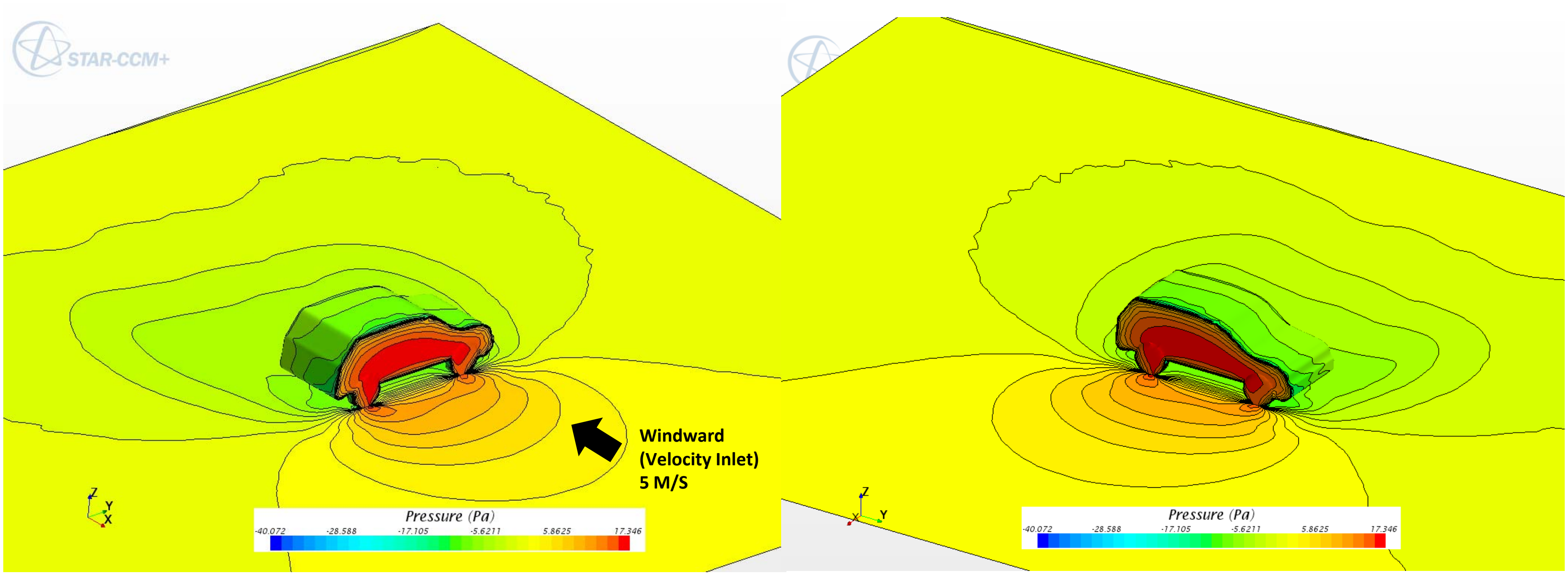


Figure 15: Example of pressure distribution on car surface in post simulation

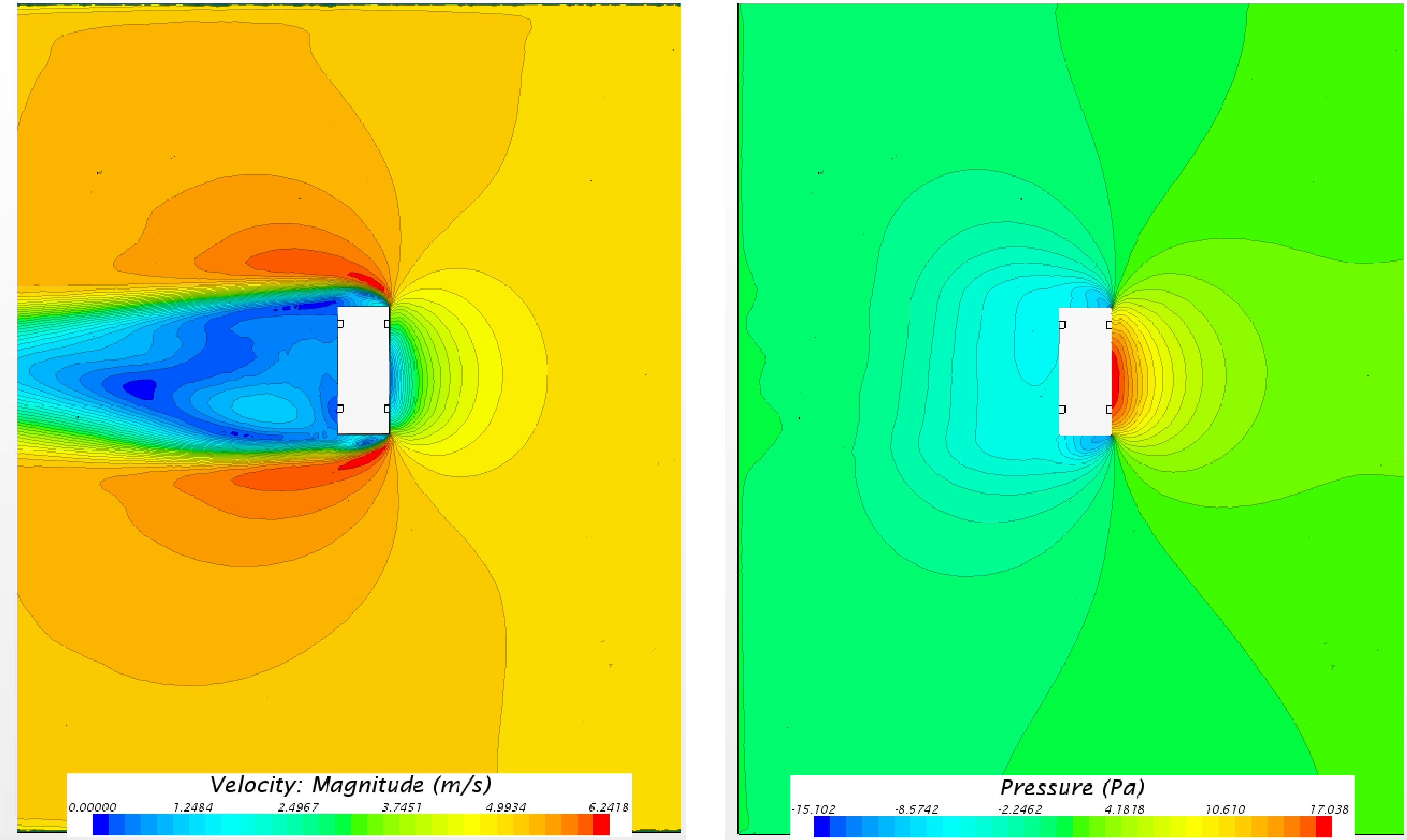


Figure 16: Example of velocity (m/s) and pressure (Pa) at 0.90 meter above ground

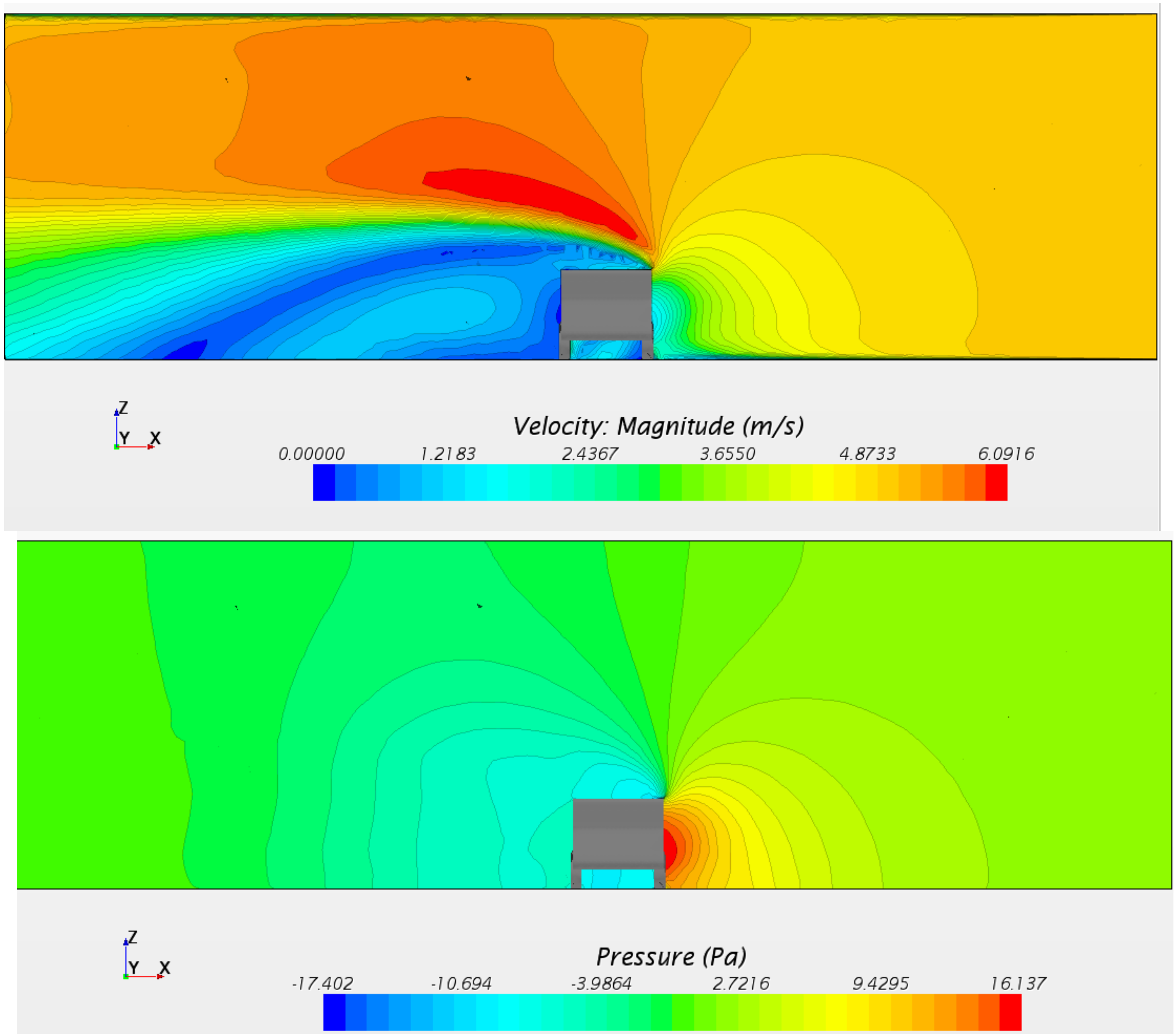


Figure 17: Example of velocity (m/s) and pressure (Pa) at cross section

Additional changed – modified:

1. Add wall roughness
2. Add LogWindProfile

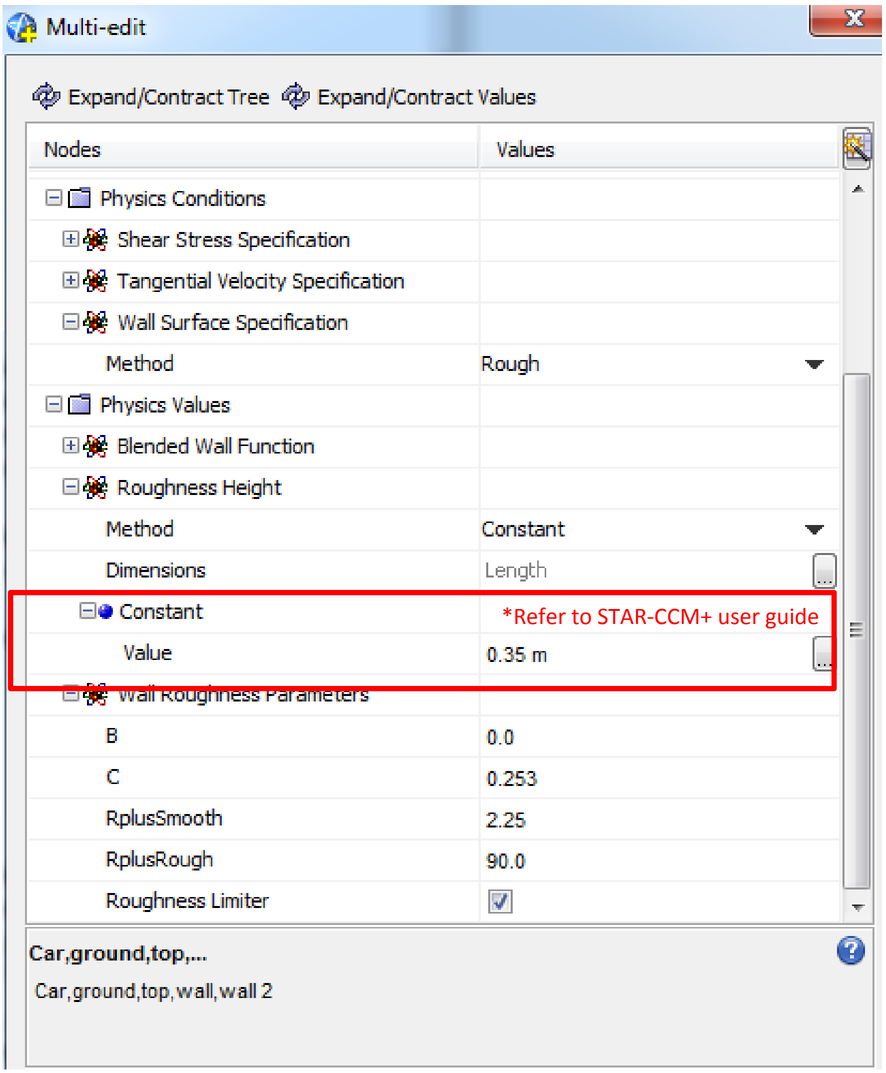


Figure 17: Wall roughness set up

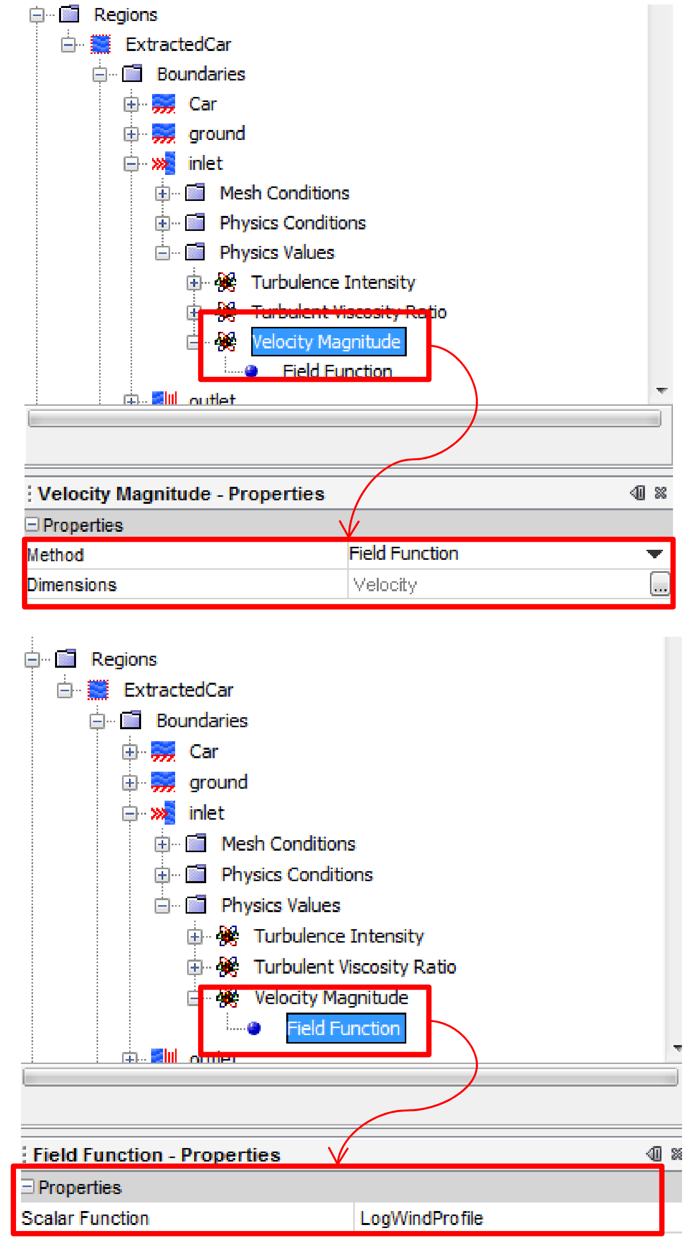


Figure 18: Physics value set up

Additional changed – modified:

1. Add wall roughness
2. Add LogWindProfile

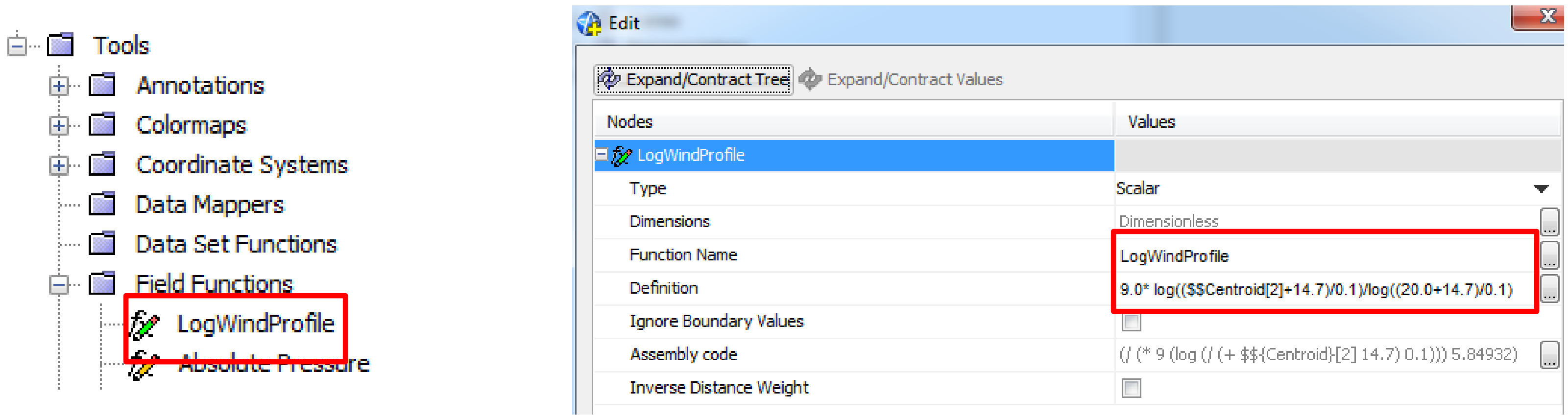


Figure 19: Create a new log file

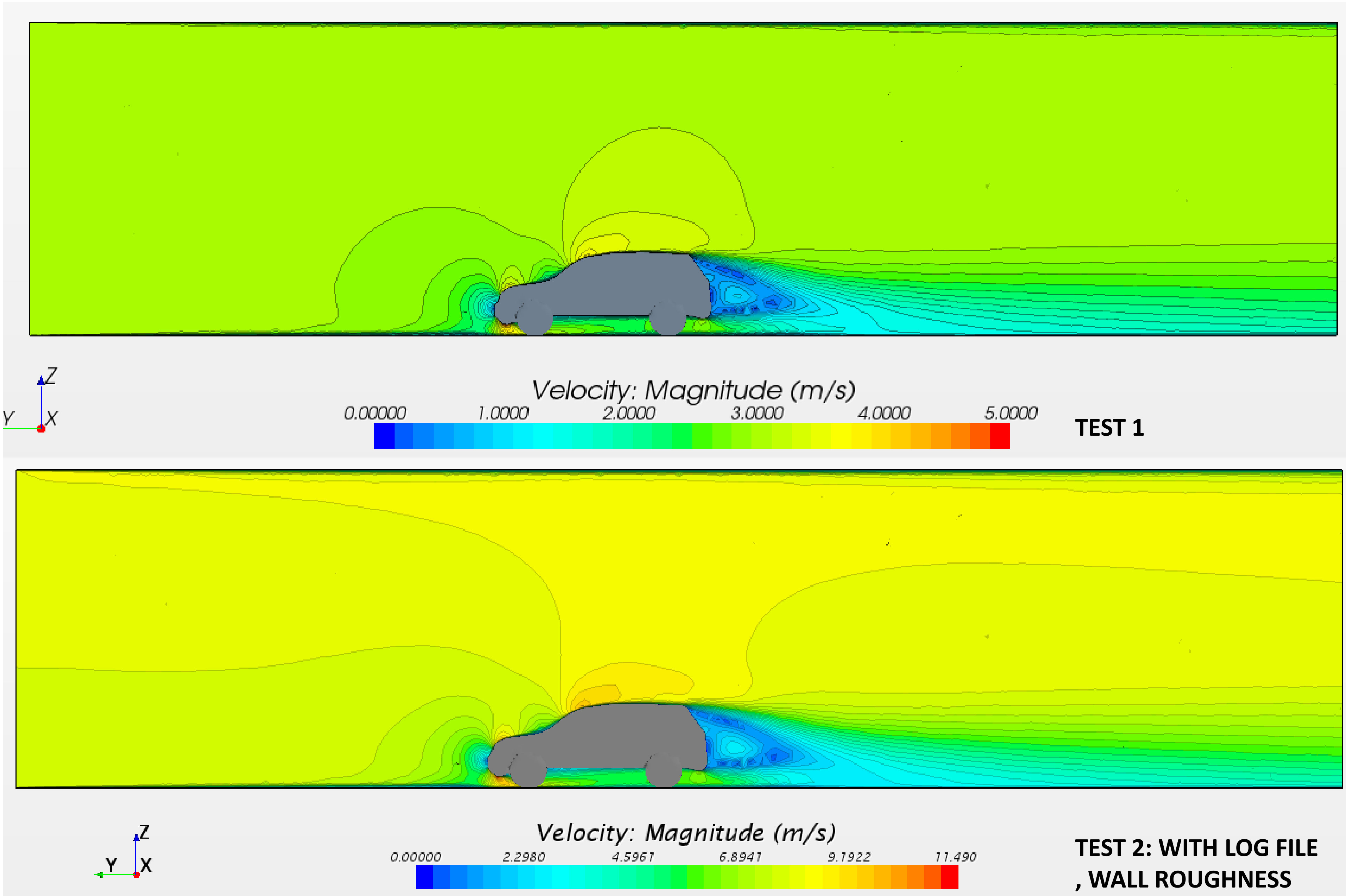


Figure 20: Compare simulation performance between Test 1 and Test 2

Contract # N000-14-13-1-0463

Computational Fluid Dynamics (CFD) Applications at the School of Architecture, University of Hawaii

Project Phase 1 – 7.A –

Task 7.a.3: Develop and Calibrate a Data Verification Process

Project Deliverable No. 3:

Report to Develop and Calibrate a Data Verification Process for External CFD Simulations

Appendix F – Final CFD Simulations and Comparison of CFD and Actual Field Measurements

Documentation of the results of the final CFD simulations that were used for the comparison with the actual field data

APPENDIX F
FIELD TEST MEASUREMENT AND CFD RESULT COMPARISON

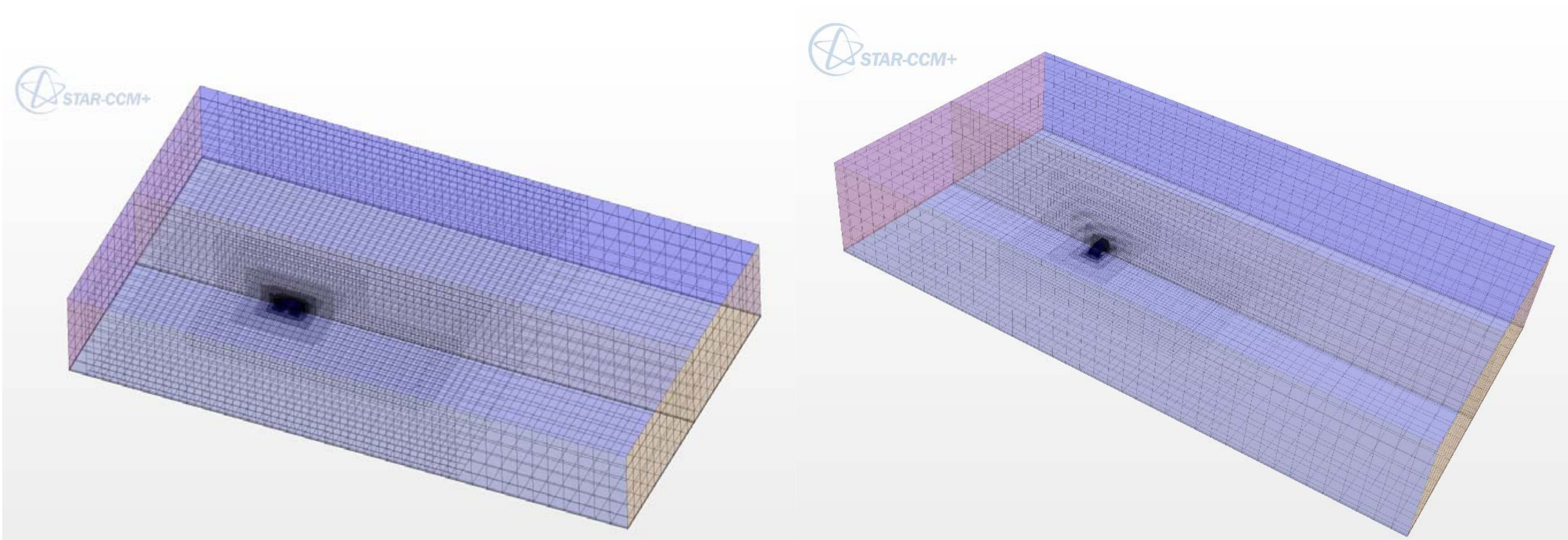


Figure 1: Meshing of the computational domain for two scenarios

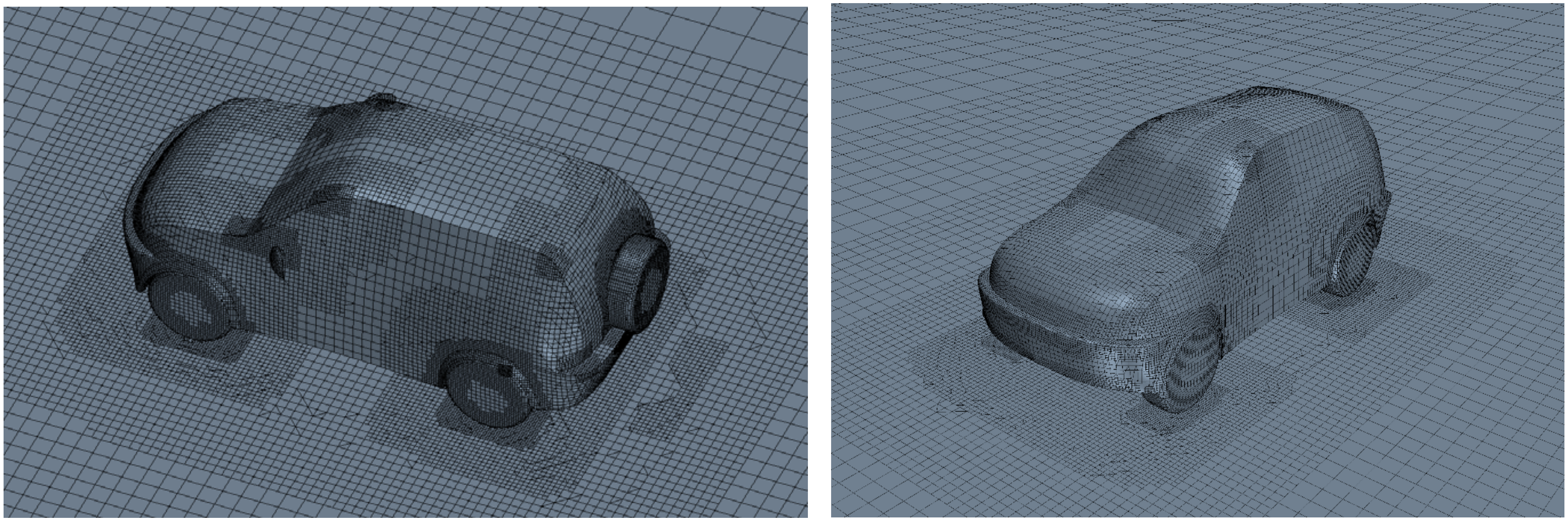


Figure 2: Detailed view of the car’s meshing for two scenarios.

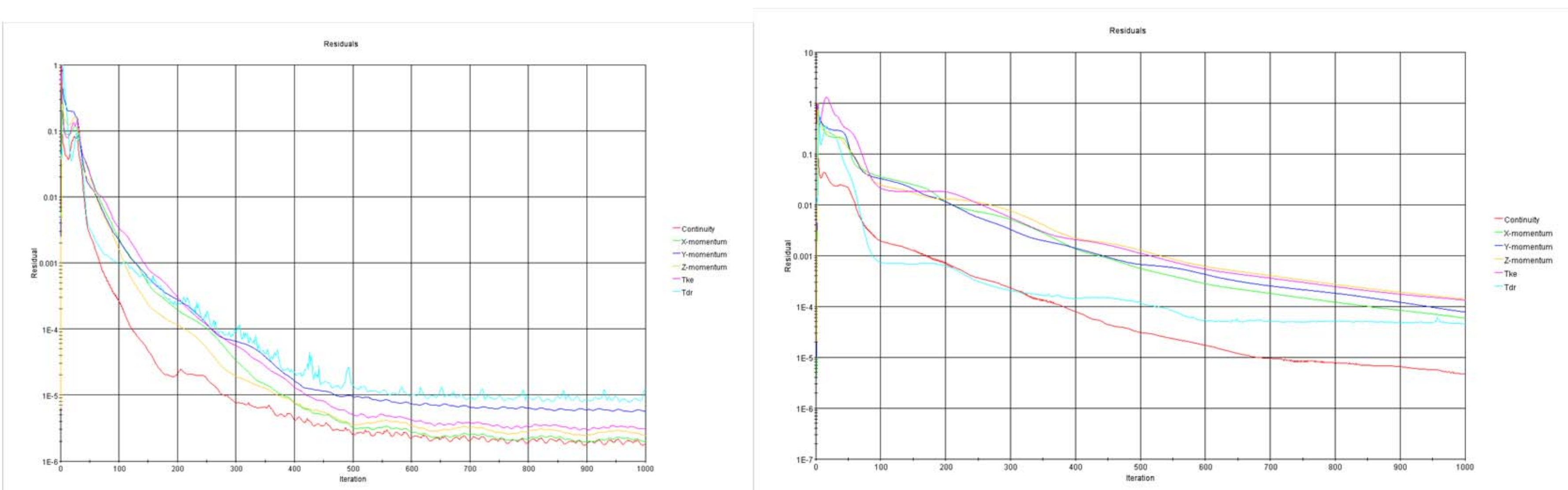


Figure 3: Residuals plots of convergence for two scenarios.

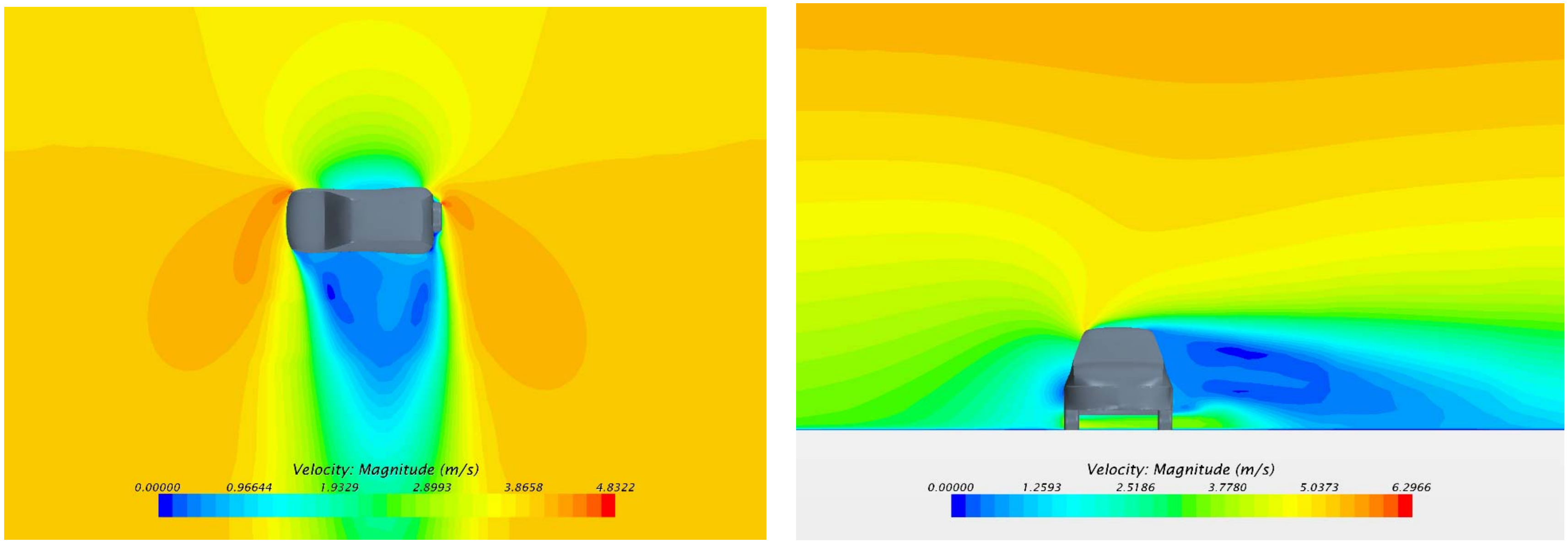


Figure 4: Velocity map on 3 feet elevation plane and at cross section (run 1: approach wind perpendicular to longitudinal axis of the car)

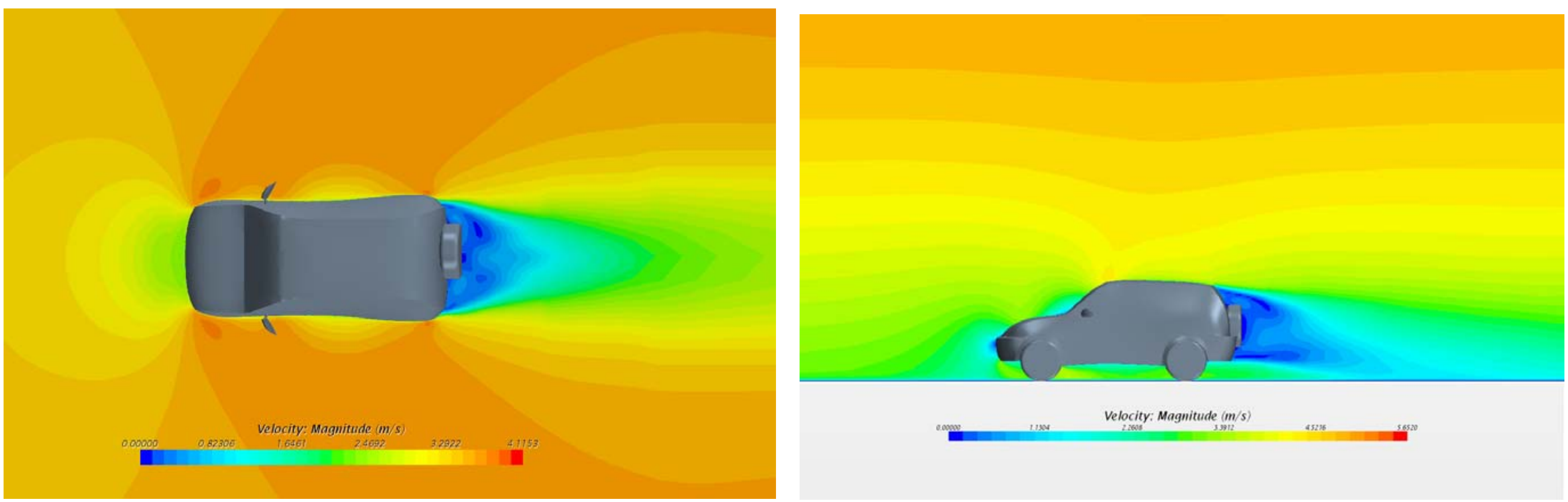


Figure 5: Velocity map on 3 feet elevation plane and at cross section (run 2: approach wind parallel to longitudinal axis of the car)

APPENDIX F
FIELD TEST MEASUREMENT AND CFD RESULT COMPARISON

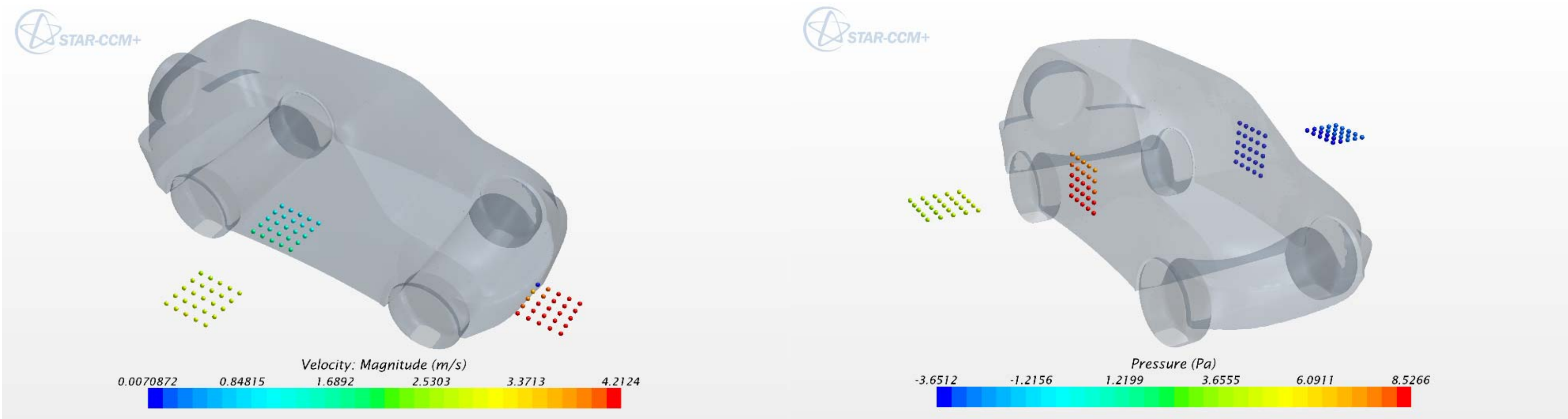


Figure 1: 1’x1’ grid probes locations for extracted velocities and pressure data from CFD results for comparison (run 1: approach wind perpendicular to longitudinal axis of the car)

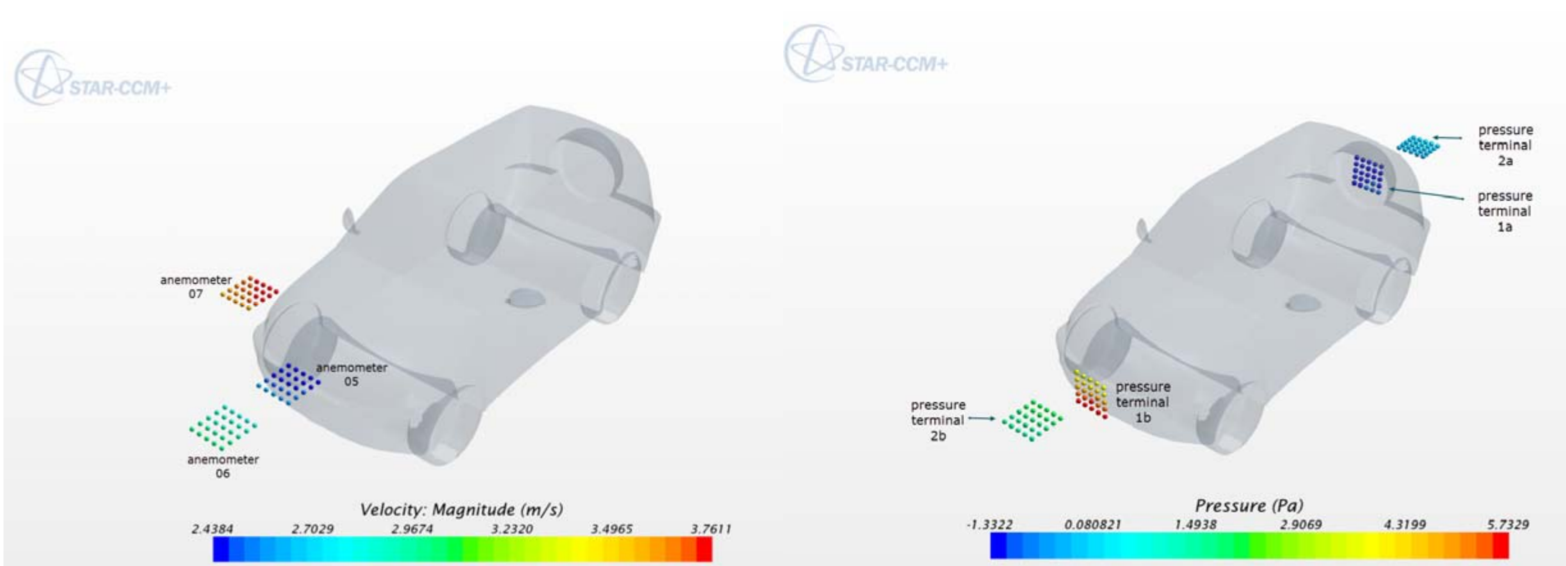


Figure 2: 1’x1’ grid probes locations for extracted velocities and pressure data from CFD results for comparison (run 2: approach wind parallel to longitudinal axis of the car)

EXTRACTED WIND VELOCITIES FROM CFD RESULTS

Run 1: approach wind perpendicular to longitudinal axis of the car

Anemometer 05				Anemometer 06				Anemometer 07			
X (m)	Y (m)	Z (m)	Velocity: Magnitude (m/s)	X (m)	Y (m)	Z (m)	Velocity: Magnitude (m/s)	X (m)	Y (m)	Z (m)	Velocity: Magnitude (m/s)
0.259747	-0.85354	-1.29387	1.72008283	0.285461	-0.84319	-2.35095	2.87800917	-1.98742	-1.13	-0.60282	4.13195114
0.160171	-0.85354	-1.29387	1.73503634	0.185885	-0.84319	-2.35095	2.87800917	-2.087	-1.13	-0.60282	4.20066974
0.060595	-0.85354	-1.29387	1.77299194	0.086309	-0.84319	-2.35095	2.89145272	-2.18657	-1.13	-0.60282	4.20713939
-0.03898	-0.85354	-1.29387	1.79674544	-0.013268	-0.84319	-2.35095	2.91108662	-2.28615	-1.13	-0.60282	4.17653627
-0.13856	-0.85354	-1.29387	1.82423948	-0.112844	-0.84319	-2.35095	2.91108662	-2.38573	-1.13	-0.60282	4.14235093
0.259747	-0.85354	-1.19152	1.55210622	0.285461	-0.84319	-2.24861	2.87800917	-1.98742	-1.13	-0.50048	4.04960006
0.160171	-0.85354	-1.19152	1.56761399	0.185885	-0.84319	-2.24861	2.87800917	-2.087	-1.13	-0.50048	4.18410629
0.060595	-0.85354	-1.19152	1.60726079	0.086309	-0.84319	-2.24861	2.89145272	-2.18657	-1.13	-0.50048	4.21356452
-0.03898	-0.85354	-1.19152	1.63245381	-0.013268	-0.84319	-2.24861	2.91108662	-2.28615	-1.13	-0.50048	4.20872744
-0.13856	-0.85354	-1.19152	1.66198174	-0.112844	-0.84319	-2.24861	2.91108662	-2.38573	-1.13	-0.50048	4.18682208
0.259747	-0.85354	-1.08918	1.18129395	0.285461	-0.84319	-2.14627	2.77136767	-1.98742	-1.13	-0.39813	3.80410972
0.160171	-0.85354	-1.08918	1.19850455	0.185885	-0.84319	-2.14627	2.77136767	-2.087	-1.13	-0.39813	4.11853912
0.060595	-0.85354	-1.08918	1.24236926	0.086309	-0.84319	-2.14627	2.78764066	-2.18657	-1.13	-0.39813	4.18255934
-0.03898	-0.85354	-1.08918	1.27105896	-0.013268	-0.84319	-2.14627	2.81078066	-2.28615	-1.13	-0.39813	4.21051394
-0.13856	-0.85354	-1.08918	1.30551552	-0.112844	-0.84319	-2.14627	2.81078066	-2.38573	-1.13	-0.39813	4.20387104
0.259747	-0.85354	-0.98683	0.98919743	0.285461	-0.84319	-2.04392	2.64900671	-1.98742	-1.13	-0.29579	3.6211058
0.160171	-0.85354	-0.98683	1.00691484	0.185885	-0.84319	-2.04392	2.65643188	-2.087	-1.13	-0.29579	4.05978653
0.060595	-0.85354	-0.98683	1.05279929	0.086309	-0.84319	-2.04392	2.66566983	-2.18657	-1.13	-0.29579	4.14864544
-0.03898	-0.85354	-0.98683	1.08363861	-0.013268	-0.84319	-2.04392	2.68963166	-2.28615	-1.13	-0.29579	4.19972908
-0.13856	-0.85354	-0.98683	1.12099113	-0.112844	-0.84319	-2.04392	2.70421868	-2.38573	-1.13	-0.29579	4.20355626
0.259747	-0.85354	-0.88449	0.83308349	0.285461	-0.84319	-1.94158	2.58287553	-1.98742	-1.13	-0.19344	1.49400058
0.160171	-0.85354	-0.88449	0.85174094	0.185885	-0.84319	-1.94158	2.59101161	-2.087	-1.13	-0.19344	3.97836133
0.060595	-0.85354	-0.88449	0.89913872	0.086309	-0.84319	-1.94158	2.60117026	-2.18657	-1.13	-0.19344	4.09301951
-0.03898	-0.85354	-0.88449	0.93221744	-0.013268	-0.84319	-1.94158	2.62704816	-2.28615	-1.13	-0.19344	4.17266149
-0.13856	-0.85354	-0.88449	0.9728148	-0.112844	-0.84319	-1.94158	2.64266364	-2.38573	-1.13	-0.19344	4.19083073
			1.312				**2.772**				**4.015**

Table 1: Extracted wind velocities from CFD results (run 1: approach wind perpendicular to longitudinal axis of the car)

EXTRACTED WIND VELOCITIES FROM CFD RESULTS

Run 2: approach wind parallel to longitudinal axis of the car

Anemometer 05				**Anemometer 06**				**Anemometer 07**			
X (m)	**Y (m)**	**Z (m)**	**Velocity: Magnitude (m/s)**	**X (m)**	**Y (m)**	**Z (m)**	**Velocity: Magnitude (m/s)**	**X (m)**	**Y (m)**	**Z (m)**	**Velocity: Magnitude (m/s)**
-2.01626	-0.82544	-0.13662	2.40464533	-2.662996	-0.82544	-0.14603	2.81035125	-1.36952	-0.82544	-1.23255	3.71828812
-2.09497	-0.82544	-0.13662	2.41397481	-2.741701	-0.82544	-0.14603	2.86505401	-1.44823	-0.82544	-1.23255	3.70542863
-2.17367	-0.82544	-0.13662	2.42561041	-2.820406	-0.82544	-0.14603	2.91234528	-1.52693	-0.82544	-1.23255	3.68104814
-2.25237	-0.82544	-0.13662	2.48137688	-2.89911	-0.82544	-0.14603	2.95391334	-1.60564	-0.82544	-1.23255	3.64450817
-2.33108	-0.82544	-0.13662	2.55882708	-2.977815	-0.82544	-0.14603	2.99060598	-1.68434	-0.82544	-1.23255	3.59670098
-2.01626	-0.82544	-0.05916	2.39544622	-2.662996	-0.82544	-0.06856	2.80294858	-1.36952	-0.82544	-1.15508	3.73810889
-2.09497	-0.82544	-0.05916	2.4055772	-2.741701	-0.82544	-0.06856	2.85879798	-1.44823	-0.82544	-1.15508	3.72905962
-2.17367	-0.82544	-0.05916	2.41481557	-2.820406	-0.82544	-0.06856	2.90700181	-1.52693	-0.82544	-1.15508	3.70481317
-2.25237	-0.82544	-0.05916	2.46996917	-2.89911	-0.82544	-0.06856	2.94933038	-1.60564	-0.82544	-1.15508	3.66442227
-2.33108	-0.82544	-0.05916	2.54822563	-2.977815	-0.82544	-0.06856	2.98667185	-1.68434	-0.82544	-1.15508	3.60911396
-2.01626	-0.82544	0.018314	2.39498339	-2.662996	-0.82544	0.008906	2.80122965	-1.36952	-0.82544	-1.07761	3.74763707
-2.09497	-0.82544	0.018314	2.40602272	-2.741701	-0.82544	0.008906	2.85733223	-1.44823	-0.82544	-1.07761	3.74138814
-2.17367	-0.82544	0.018314	2.41471265	-2.820406	-0.82544	0.008906	2.90574063	-1.52693	-0.82544	-1.07761	3.71747129
-2.25237	-0.82544	0.018314	2.46958994	-2.89911	-0.82544	0.008906	2.94823997	-1.60564	-0.82544	-1.07761	3.67483755
-2.33108	-0.82544	0.018314	2.54777287	-2.977815	-0.82544	0.008906	2.98572749	-1.68434	-0.82544	-1.07761	3.61502084
-2.01626	-0.82544	0.095782	2.40257074	-2.662996	-0.82544	0.086375	2.80523491	-1.36952	-0.82544	-1.00014	3.76069422
-2.09497	-0.82544	0.095782	2.41399637	-2.741701	-0.82544	0.086375	2.86070888	-1.44823	-0.82544	-1.00014	3.76375403
-2.17367	-0.82544	0.095782	2.42478985	-2.820406	-0.82544	0.086375	2.90861406	-1.52693	-0.82544	-1.00014	3.74282195
-2.25237	-0.82544	0.095782	2.48007786	-2.89911	-0.82544	0.086375	2.95069525	-1.60564	-0.82544	-1.00014	3.69536975
-2.33108	-0.82544	0.095782	2.55743407	-2.977815	-0.82544	0.086375	2.98782542	-1.68434	-0.82544	-1.00014	3.62395548
-2.01626	-0.82544	0.173251	2.41980184	-2.662996	-0.82544	0.163844	2.81486135	-1.36952	-0.82544	-0.92267	3.74578133
-2.09497	-0.82544	0.173251	2.43054368	-2.741701	-0.82544	0.163844	2.86882365	-1.44823	-0.82544	-0.92267	3.76774812
-2.17367	-0.82544	0.173251	2.44546113	-2.820406	-0.82544	0.163844	2.91553056	-1.52693	-0.82544	-0.92267	3.76130395
-2.25237	-0.82544	0.173251	2.50143451	-2.89911	-0.82544	0.163844	2.95662495	-1.60564	-0.82544	-0.92267	3.71524555
-2.33108	-0.82544	0.173251	2.57706474	-2.977815	-0.82544	0.163844	2.99292124	-1.68434	-0.82544	-0.92267	3.62413375
			2.456				**2.904**				**3.700**

Table 2: Extracted wind velocities from CFD results (run 2: approach wind parallel to longitudinal axis of the car)

EXTRACTED WIND-DRIVEN DIFFERENTIAL PRESSURES FROM CFD RESULTS

Run 1: approach wind perpendicular to longitudinal axis of the car

Pressure Termal 1a				Pressure Termal 1b				Pressure Termal 2a				Pressure Termal 2a			
X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)
0.266712	-0.61951	0.931301	-3.58809	0.280412	-1.06639	-0.90525	8.551476	0.28629	-0.83058	1.864767	-3.39052	0.285461	-0.84319	-2.35095	3.89757
0.167136	-0.61951	0.931301	-3.59406	0.280412	-0.96681	-0.90525	8.541071	0.186714	-0.83058	1.864767	-3.39552	0.185885	-0.84319	-2.35095	3.89757
0.067559	-0.61951	0.931301	-3.62514	0.280412	-0.86724	-0.90525	8.420601	0.087138	-0.83058	1.864767	-3.40295	0.086309	-0.84319	-2.35095	3.851566
-0.03202	-0.61951	0.931301	-3.64188	0.280412	-0.76766	-0.90525	8.209412	-0.01244	-0.83058	1.864767	-3.41321	-0.01327	-0.84319	-2.35095	3.78338
-0.13159	-0.61951	0.931301	-3.6589	0.280412	-0.66809	-0.90525	7.434173	-0.11201	-0.83058	1.864767	-3.41478	-0.11284	-0.84319	-2.35095	3.78338
0.266712	-0.72185	0.931708	-3.54882	0.178067	-1.06639	-0.90525	8.528471	0.28629	-0.83058	1.967111	-3.32426	0.285461	-0.84319	-2.24861	3.89757
0.167136	-0.72185	0.931708	-3.56689	0.178067	-0.96681	-0.90525	8.520648	0.186714	-0.83058	1.967111	-3.32478	0.185885	-0.84319	-2.24861	3.89757
0.067559	-0.72185	0.931708	-3.60313	0.178067	-0.86724	-0.90525	8.396589	0.087138	-0.83058	1.967111	-3.33542	0.086309	-0.84319	-2.24861	3.851566
-0.03202	-0.72185	0.931708	-3.6225	0.178067	-0.76766	-0.90525	8.186799	-0.01244	-0.83058	1.967111	-3.3426	-0.01327	-0.84319	-2.24861	3.78338
-0.13159	-0.72185	0.931708	-3.64238	0.178067	-0.66809	-0.90525	7.440609	-0.11201	-0.83058	1.967111	-3.33575	-0.11284	-0.84319	-2.24861	3.78338
0.266712	-0.82419	0.932116	-3.51243	0.075723	-1.06639	-0.90525	8.508507	0.28629	-0.83058	2.069456	-3.17218	0.285461	-0.84319	-2.14627	4.217531
0.167136	-0.82419	0.932116	-3.53101	0.075723	-0.96681	-0.90525	8.497505	0.186714	-0.83058	2.069456	-3.17218	0.185885	-0.84319	-2.14627	4.217531
0.067559	-0.82419	0.932116	-3.57124	0.075723	-0.86724	-0.90525	8.371461	0.087138	-0.83058	2.069456	-3.17311	0.086309	-0.84319	-2.14627	4.16434
-0.03202	-0.82419	0.932116	-3.59304	0.075723	-0.76766	-0.90525	8.160108	-0.01244	-0.83058	2.069456	-3.16937	-0.01327	-0.84319	-2.14627	4.088354
-0.13159	-0.82419	0.932116	-3.61508	0.075723	-0.66809	-0.90525	7.405374	-0.11201	-0.83058	2.069456	-3.16937	-0.11284	-0.84319	-2.14627	4.088354
0.266712	-0.92654	0.932523	-3.47259	-0.02662	-1.06639	-0.90525	8.462074	0.28629	-0.83058	2.171801	-3.00827	0.285461	-0.84319	-2.04392	4.584512
0.167136	-0.92654	0.932523	-3.49316	-0.02662	-0.96681	-0.90525	8.43893	0.186714	-0.83058	2.171801	-3.00827	0.185885	-0.84319	-2.04392	4.560159
0.067559	-0.92654	0.932523	-3.53705	-0.02662	-0.86724	-0.90525	8.296378	0.087138	-0.83058	2.171801	-2.99905	0.086309	-0.84319	-2.04392	4.532351
-0.03202	-0.92654	0.932523	-3.56311	-0.02662	-0.76766	-0.90525	8.067146	-0.01244	-0.83058	2.171801	-2.98223	-0.01327	-0.84319	-2.04392	4.457135
-0.13159	-0.92654	0.932523	-3.59125	-0.02662	-0.66809	-0.90525	7.263654	-0.11201	-0.83058	2.171801	-2.98223	-0.11284	-0.84319	-2.04392	4.408699
0.266712	-1.02888	0.93293	-3.47983	-0.12897	-1.06639	-0.90525	8.431649	0.28629	-0.83058	2.274145	-3.00827	0.285461	-0.84319	-1.94158	4.77382
0.167136	-1.02888	0.93293	-3.50164	-0.12897	-0.96681	-0.90525	8.400104	0.186714	-0.83058	2.274145	-3.00827	0.185885	-0.84319	-1.94158	4.748474
0.067559	-1.02888	0.93293	-3.55281	-0.12897	-0.86724	-0.90525	8.242295	0.087138	-0.83058	2.274145	-2.99905	0.086309	-0.84319	-1.94158	4.71833
-0.03202	-1.02888	0.93293	-3.5801	-0.12897	-0.76766	-0.90525	7.996234	-0.01244	-0.83058	2.274145	-2.98223	-0.01327	-0.84319	-1.94158	4.639522
-0.13159	-1.02888	0.93293	-3.6067	-0.12897	-0.66809	-0.90525	7.14589	-0.11201	-0.83058	2.274145	-2.98223	-0.11284	-0.84319	-1.94158	4.590363
			-3.57859				**8.156686**				**-3.17984**				**4.208656**
Differential pressure between 1b-1a							**11.73527**	**Differential pressure between 2b-2a**							**7.3885**

Table 3: Extracted wind-driven differential pressures from CFD results (run 1: approach wind perpendicular to longitudinal axis of the car)

EXTRACTED WIND-DRIVEN DIFFERENTIAL PRESSURES FROM CFD RESULTS

Run 2: approach wind parallel to longitudinal axis of the car

Pressure Termal 1a				Pressure Termal 1b				Pressure Termal 2a				Pressure Termal 2a			
X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)	X (m)	Y (m)	Z (m)	Pressure (Pa)
2.276183	-0.98285	-0.26336	-1.17114	-2.16713	-1.13525	-0.1404	5.428737	3.351585	-0.82544	-0.17887	-0.12445	-2.663	-0.82544	-0.14603	2.304066
2.276183	-0.90414	-0.26336	-1.2129	-2.16713	-1.05654	-0.1404	5.153423	3.272881	-0.82544	-0.17887	-0.12445	-2.7417	-0.82544	-0.14603	2.106642
2.276183	-0.82544	-0.26336	-1.2485	-2.16713	-0.97784	-0.1404	4.598196	3.194176	-0.82544	-0.17887	-0.27165	-2.82041	-0.82544	-0.14603	1.930091
2.276183	-0.74674	-0.26336	-1.30589	-2.16713	-0.89914	-0.1404	4.001302	3.115471	-0.82544	-0.17887	-0.36176	-2.89911	-0.82544	-0.14603	1.774354
2.276183	-0.66803	-0.26336	-1.32669	-2.16713	-0.82043	-0.1404	3.492239	3.036766	-0.82544	-0.17887	-0.47044	-2.97782	-0.82544	-0.14603	1.635568
2.276183	-0.98285	-0.18589	-1.12741	-2.16713	-1.13525	-0.06293	5.538808	3.351585	-0.82544	-0.1014	0.013356	-2.663	-0.82544	-0.06856	2.329037
2.276183	-0.90414	-0.18589	-1.1649	-2.16713	-1.05654	-0.06293	5.250583	3.272881	-0.82544	-0.1014	0.013356	-2.7417	-0.82544	-0.06856	2.127971
2.276183	-0.82544	-0.18589	-1.20321	-2.16713	-0.97784	-0.06293	4.672007	3.194176	-0.82544	-0.1014	-0.1841	-2.82041	-0.82544	-0.06856	1.948511
2.276183	-0.74674	-0.18589	-1.25715	-2.16713	-0.89914	-0.06293	4.059706	3.115471	-0.82544	-0.1014	-0.27948	-2.89911	-0.82544	-0.06856	1.790287
2.276183	-0.66803	-0.18589	-1.31394	-2.16713	-0.82043	-0.06293	3.541309	3.036766	-0.82544	-0.1014	-0.38737	-2.97782	-0.82544	-0.06856	1.649461
2.276183	-0.98285	-0.10843	-1.09395	-2.16713	-1.13525	0.014536	5.579792	3.351585	-0.82544	-0.02393	0.013356	-2.663	-0.82544	0.008906	2.334624
2.276183	-0.90414	-0.10843	-1.12529	-2.16713	-1.05654	0.014536	5.284082	3.272881	-0.82544	-0.02393	0.013356	-2.7417	-0.82544	0.008906	2.1327
2.276183	-0.82544	-0.10843	-1.16836	-2.16713	-0.97784	0.014536	4.69451	3.194176	-0.82544	-0.02393	-0.17606	-2.82041	-0.82544	0.008906	1.952631
2.276183	-0.74674	-0.10843	-1.19618	-2.16713	-0.89914	0.014536	4.078027	3.115471	-0.82544	-0.02393	-0.25361	-2.89911	-0.82544	0.008906	1.79387
2.276183	-0.66803	-0.10843	-1.27102	-2.16713	-0.82043	0.014536	3.557728	3.036766	-0.82544	-0.02393	-0.36175	-2.97782	-0.82544	0.008906	1.652573
2.276183	-0.98285	-0.03096	-1.07508	-2.16713	-1.13525	0.092005	5.546752	3.351585	-0.82544	0.053538	0.030301	-2.663	-0.82544	0.086375	2.320876
2.276183	-0.90414	-0.03096	-1.07274	-2.16713	-1.05654	0.092005	5.254552	3.272881	-0.82544	0.053538	0.030301	-2.7417	-0.82544	0.086375	2.121039
2.276183	-0.82544	-0.03096	-1.13229	-2.16713	-0.97784	0.092005	4.670519	3.194176	-0.82544	0.053538	-0.16601	-2.82041	-0.82544	0.086375	1.942568
2.276183	-0.74674	-0.03096	-1.16904	-2.16713	-0.89914	0.092005	4.059598	3.115471	-0.82544	0.053538	-0.25323	-2.89911	-0.82544	0.086375	1.785179
2.276183	-0.66803	-0.03096	-1.21799	-2.16713	-0.82043	0.092005	3.543232	3.036766	-0.82544	0.053538	-0.36469	-2.97782	-0.82544	0.086375	1.644992
2.276183	-0.98285	0.046512	-1.07144	-2.16713	-1.13525	0.169474	5.442252	3.351585	-0.82544	0.131006	0.030301	-2.663	-0.82544	0.163844	2.287811
2.276183	-0.90414	0.046512	-1.11123	-2.16713	-1.05654	0.169474	5.162918	3.272881	-0.82544	0.131006	0.030301	-2.7417	-0.82544	0.163844	2.092835
2.276183	-0.82544	0.046512	-1.13405	-2.16713	-0.97784	0.169474	4.600601	3.194176	-0.82544	0.131006	-0.16528	-2.82041	-0.82544	0.163844	1.918282
2.276183	-0.74674	0.046512	-1.1486	-2.16713	-0.89914	0.169474	4.004646	3.115471	-0.82544	0.131006	-0.26	-2.89911	-0.82544	0.163844	1.764256
2.276183	-0.66803	0.046512	-1.19063	-2.16713	-0.82043	0.169474	3.497576	3.036766	-0.82544	0.131006	-0.36918	-2.97782	-0.82544	0.163844	1.626966
			-1.1927				**4.58852**				**-0.176**				**1.95869**
Differential pressure between 1b-1a							**5.78121**	**Differential pressure between 2b-2a**							**2.13464**

Table 4: Extracted wind-driven differential pressures from CFD results (run 2: approach wind parallel to longitudinal axis of the car)

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