16th ETH CONFERENCE ON COMBUSTION GENERATED NANOPARTICLES
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DESIGN AND COMMISSIONING OF A WIND TUNNEL FOR INTEGRATED PHYSICAL AND CHEMICAL MEASUREMENTS OF PM DISPERSING PLUME HEAVY DUTY DIESEL TRUCK.

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EXTENDED SUMMARY

Over the past few decades there has been considerable progress made in understanding the processes leading to formation and evolution of particulate matter (PM) emissions from heavy duty diesel engines (HDDE). This progress has been primarily made under controlled laboratory conditions with the use of constant volume sampling (CVS) systems and to a limited extend through on-road chase studies. The understanding and knowledge has recently been further extended to new emission reduction technologies, such as the diesel particulate filter (DPF) which has dramatically changed the size distribution and chemical composition of PM. Additionally, the selective catalytic reduction (SCR) technology has shown to further enhance the formation of nucleation mode particles as well as alter their morphology. SCR technology has also allowed new engines to be calibrated for optimized fuel consumption while injecting higher amounts of diesel exhaust fluid (DEF), causing exhaust particulate matter to possibly undergo further considerable changes in terms of morphology and chemical composition.

Figure 1: WVU wind tunnel with mock up truck visible inside

Even with advances in technology there remains a considerable gap in the current level of understanding of PM formation and evolution, since the combustion generated PM from diesel engines is not discernible from the atmospheric background PM measured beyond 300m from highways. After being emitted from the vehicle exhaust system, the dilution process of exhaust by the atmosphere is leading to a multitude of PM transformation phenomena, such as volatilization, coagulation, and condensation. West Virginia University (WVU) is attempting to close the present knowledge gap by conducting detailed experiments in a custom designed and constructed environmental wind tunnel. This paper describes the design and commissioning process of the wind tunnel focusing on both, aerodynamic and structural constraints, which ultimately led to the definition of the main characteristics of the facility. The resulting design is a subsonic, non-recirculating, suction type tunnel, with a 16ft high and 16ft wide test section capable of housing a full-size a heavy-duty tractor cab. It is capable of accommodating a full-scale class-8 tractor including its trailer. This solution was chosen to adhere as closely as possible to real world conditions, since no indications are present in literature regarding scale model of vehicle plume interaction with background air. A 2,200hp suction fan is employed to provide up to 80 mph wind speeds.

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The 115ft test cell length guarantees for a 2 seconds residence time for the exhaust plume evolution (at 35 mph) and complies with turbulence and quality flow standards as identified for this type of application. In addition, the West Virginia University (WVU) wind tunnel has been equipped with a custom made sampling system able to move in all three dimensions in order to measure spatially resolved plume characteristics.

With the primary parameters and targets pre-defined, the first step of the design process was to identify the typical plume dimensions for a large range of on-road and off-road vehicles with a roof height of less than 15ft. To that aim, computational fluid-dynamics simulations were performed with the commercially available CosmosFlow™ software (part of the SolidWorks™ suite), using a k-ε closure model. The exhaust gases were modeled by just a simple tracer constituent (i.e. CO_2), which allowed for estimating the interaction and mixing between background air and exhaust stream. The aerodynamics of the truck mainly affect the plume formation and mixing with background air. Different mixing patterns are observed for stack exhaust higher or lower the cabin faring. These results suggest how the two exhaust plumes encounter substantially different dilution processes, which may influence the formation and evolution of nucleation mode particles.

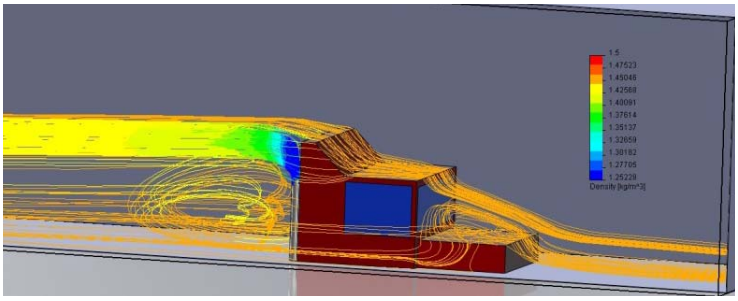

Figure 2: CFD Simulations, Exhaust stack lower than fairing

The qualification of the wind tunnel requires several step, the first one is related to the aerodynamics evolving inside due to the wall presence. Boundary Layer (BL) analyses indicate non-interference of the growing BL itself on the plume, guaranteeing and undisturbed mixing, fundamental in the replication of real world emission. The second key parameter, under the point of view of aerodynamics, is the turbulence intensity (TI) characterizing the flow field. For high quality wind tunnels a typical TI is usually lower than 0.5% within the entire test cell. The WVU wind tunnel is located in a region of low speed winds and the absence of buildings and other major artificial structures in the surroundings keeps the TI at the entrance of the tunnel around a value of 4%, averaged over a year, and below 3% over spring and summer times. Eventually, a single honeycomb set with ¼ in cell size and one screen with a 3mm mesh size would be sufficient to reduce the TI below 1%. This value was considered a reasonable compromise between the need to have a low turbulence intensity in the flow field upstream the truck model and the aim to keep flow conditions as representative as possible of typical on-road traffic areas. The direct benefit of having a minimum number of screens placed at the inlet of the tunnel is given by the lower differential pressure acting between the outside and inside of the tunnel, hence, lowering loads and forces acting onto the building. A wooden structure was selected to be the most suitable in terms of both costs and construction time. The building is affected by average values of stresses and loads deriving from the depression developing within the tunnel during normal operation. Results from CFD simulations indicated a maximum pressure load of 1000Pa for the worst case operating condition, which for safety reasons was increased to 2000Pa including the weight of the fully equipped instrumentation cart.

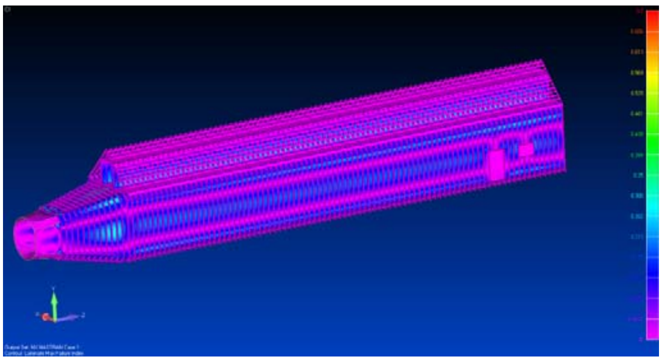

Figure 3: FEA results for operational conditions (load set 1), failure index contour plot

A complete CAD model of the WVU wind tunnel was generated with SolidWorks™ while the model needed for the finite element analysis (FEA) was developed in Femap™ and solved using the Nastran™ solver. The wind tunnel design takes a combination of different load analyses into consideration, due to the complexity and dimensions of the structure. Due to the orthotropic nature of the wood the Failure Index Method is used to validate the strength of the structure. The structure is considered safe from structural failure if the failure index remains within the range of 0 and 1. The color '*red*' in contour plots for FEA results was assigned to failure index 1 in order to effectively highlight critical areas. The first load set is related to the operational conditions of the wind tunnel where a pressure difference of 2000Pa is applied inward the structure. The second load set is related to snow accumulation of 1 m over the entire roof. The last load set considered for analysis is identified by a 50mph wind impacting onto the lateral surface of the wind tunnel. The results of the FEA analysis for the three load conditions indicate that the structure completely satisfies the threshold identified by the failure index method. Furthermore, the FEA analysis also indicates a safety margin for resonance problems (due to the propeller) and buckling.

Detailed plume analysis requires a system able to sample throughout the entire test cell, without affecting the dynamics of the flow itself. The instrumentation required to characterize the exhaust plume could not be placed within the flow field without strongly influencing it. However a single sampling probe could extract a localized fraction of the plume and redirect the sample to the instruments. In order to minimize the length of the transfer line connecting sampling probe and instrumentation and hence, the particulate matter losses, a novel solution has been adopted by implementing a cart carrying the entire suite of instruments and moving longitudinally within the ceiling of the tunnel. Underneath the cart, and within the test cell, a gantry system spans the probe vertically and horizontally. This configuration allows to sample throughout the cross-sectional area of the test cell, and to proficiently move the sampling probe around the truck model placed within tunnel. The instrumentation setup during a primary exhaust plume study is composed of three different sampling stations. The most important to this particular study is the mobile platform which is equipped with:

Figure 4: Exhaust plume sampling probe and flow field characterization sensors

- Omni-directional hot-wire anemometer
- Humidity, pressure, and temperature sensor
- NOx / NO Analyzer (CLD)
- CO2 / CO Analyzer (NDIR)
- Engine Exhaust Particle Sizer (EEPS™) spectrometer (TSI Inc., model 3090)
- Micro-aethalometer® Model AE51 (Magee Scientific)
- Dusttrack™ (TSI Inc.)

All analyzers are calibrated and operated according to recommendations outlined in Code of Federal Regulations (CFR), title 40, subpart 1065.The second sampling station measures the raw exhaust directly from the truck's exhaust stack, and is equipped with following instruments:

- Exhaust gas temperature (K-type thermocouple)
- Exhaust gas flow rate (Annubar® flow meter)
- NOx / NO Analyzer (CLD)
- CO2 / CO Analyzer (NDIR)
- THC Analyzer (FID)
- Continuous soot sensor (AVL MSS-483)
- Gravimetric PM (Sierra BG-3 Partial Flow Dilution)

The raw exhaust platform comprises WVU's Transportable Raw Emissions Laboratory (TREL), which was designed and constructed according to requirements outline in CFR, title 40, subparts 1033 and 1065, and capable of characterizing gaseous emissions of CO2, CO, NOx, NO as well as THC from raw (undiluted) exhaust.

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Outline

- Motivation
- Reference Project
- Description and Capabilities
- Design Process
- Flow Characterization
- Applications

Motivation

- Analyze the interaction between exhaust and background PM
- Further develop the knowledge of PM formation and evolution in real ambient conditions using current technologies
- Investigate the secondary PM formation from latest exhaust after-treatment technologies (DPF and SCR)

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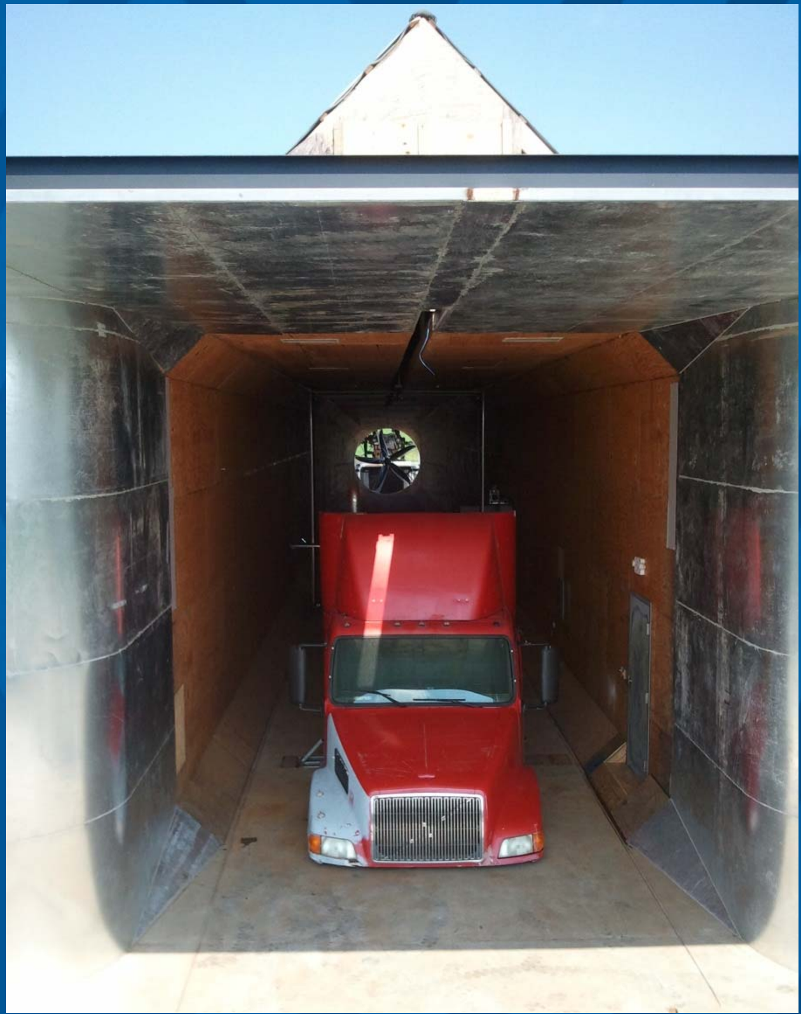
Reference Project

- The Wind Tunnel facility is built to accommodate the development of a tool to model the exhaust plume.
- Part of “Wind Tunnel Plume” project funded by CARB,EPA and NASA.
- This tool will help to analyze and predict nucleation mode in size particle distribution from different vehicles.
- Heavy Duty Class 8 tractor will be used to validate the model for this test campaign.

Wind Tunnel Spec.

- Large-scale wind tunnel
- Non-recirculating config.
- 16ft x 16ft cross test section (5m x 5m)
- 115ft test section Length (35m)
- Variable pitch propeller driven by 2200 Hp diesel engine



Wind Tunnel Spec.

- 3d gantry sampling and monitoring system
- Instrument cart in the ceiling

Wind Tunnel Spec.

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Wind Tunnel Capabilities

- Wind Speed up to 80mph (130 km/h)
- Turbulence intensity <1%
- Sampling accuracy <5mm
- Full scale model vehicle
- 2s residence time @ 35mph (55 km/h)
- High frequency custom made DAQ system

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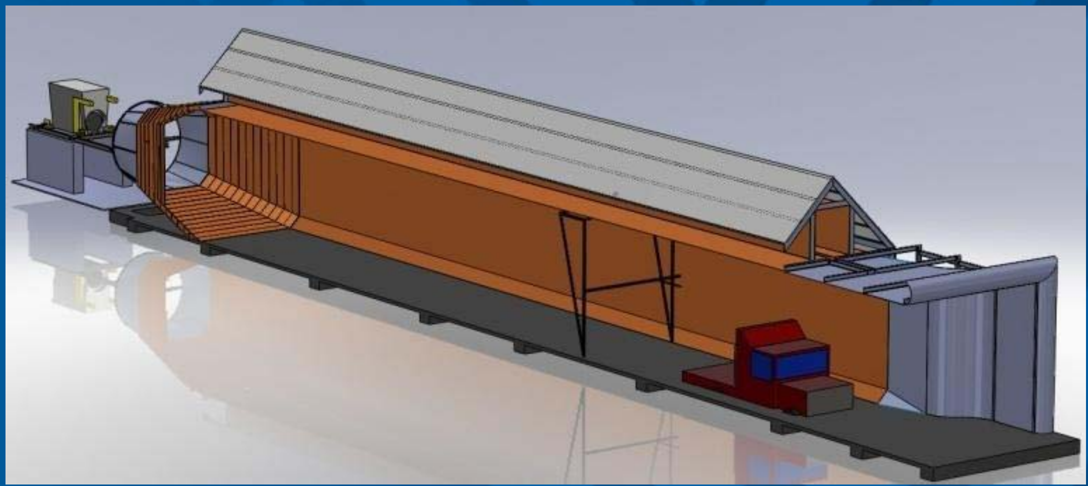
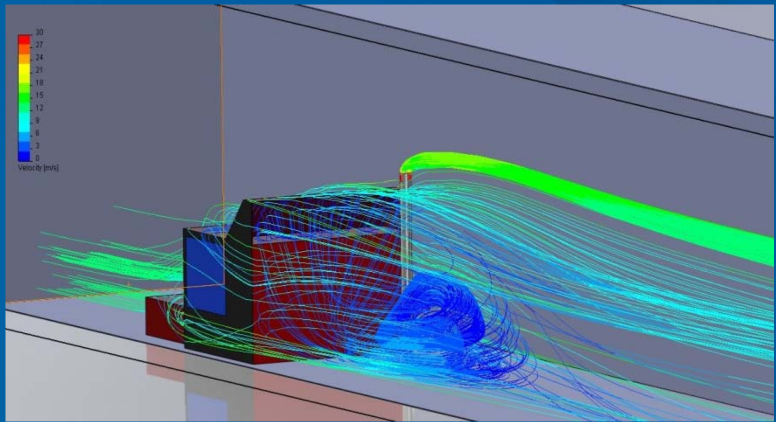
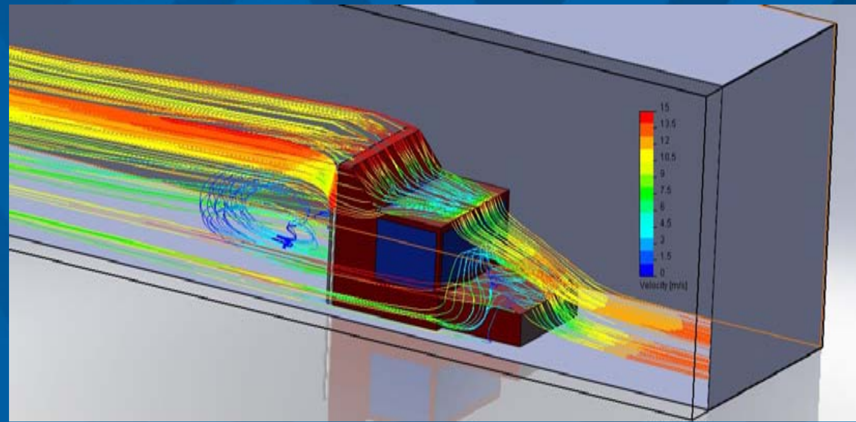
Design Process

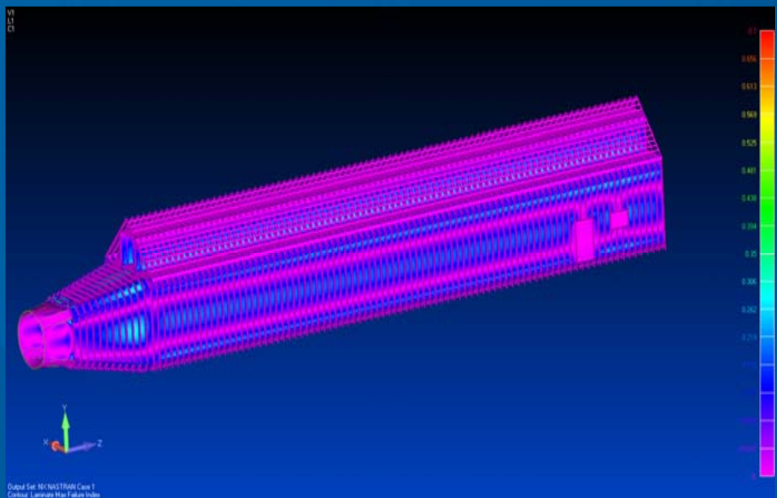
- Preliminary CFD analyses to identify plume dimensions, thus wind tunnel test cell dimensions.
- Defining all the structural constraint and measurement needs.
- Complete FEA Model
- Detailed Boundary Layer Analysis
- Construction Plan

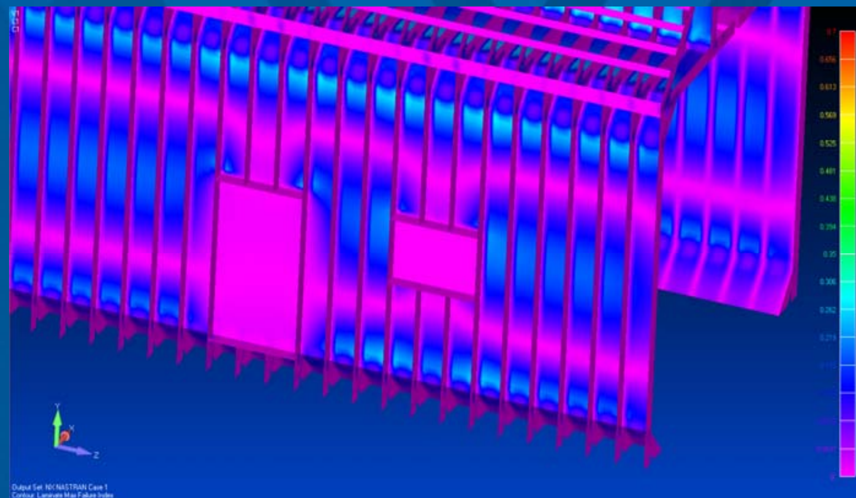


Design Process









Experimental Methodology

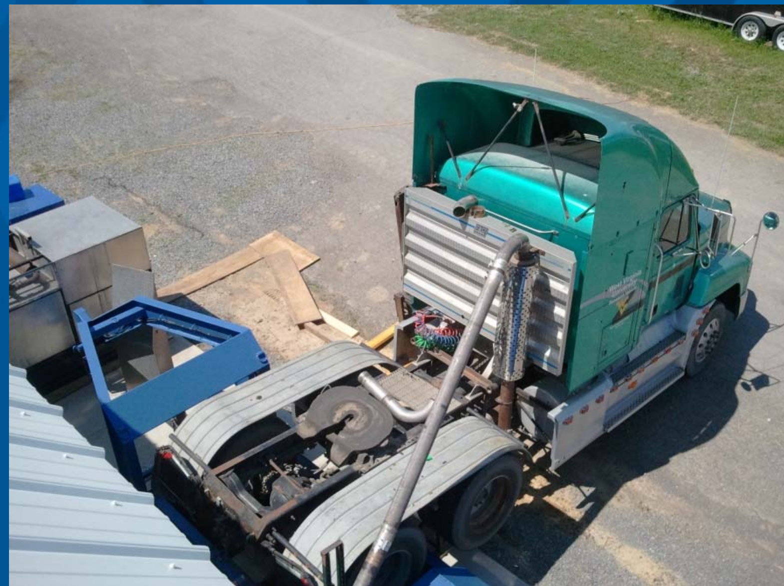
- Heavy-duty class 8 tractors investigated on :
  - heavy-duty chassis-dynamometer employed during the presented study is part of WVU's *Transportable Emissions Measurement System*(TEMS)
  - A pre-2007 heavy-duty diesel truck (without a DPF)
  - A post-2007 heavy-duty diesel truck equipped with a DOC-DPF assembly
  - A post-2010 heavy-duty diesel truck with a DOC-DPF and SCR systems

- Mock-up truck inside the tunnel:
  - To guarantee same aerodynamic conditions
  - Structural and logistic simplification

- Operating wind/truck speed
  - Idle with 5 mph wind speed(steady state).
  - Cruise at 35 mph (steady state).
  - Cruise at 20 mph (steady state).

Experimental Methodology

- Raw Exhaust Sampling Station (fixed)
  - WVU's *Transportable Raw Emissions Laboratory*(TREL)
  - Suite of Gaseous Analyzers [NOx/NO(CLD),CO2/ CO (NDIR),THC (FID)]
  - Continuous soot sensor (AVL MSS-483)
  - Gravimetric PM (Sierra BG-3 Partial Flow Dilution)



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Experimental Methodology

- Plume Sampling Station (mobile)
  - Omni-directional hot-wire anemometer
  - Humidity, pressure, and temperature sensor
  - Suite of Gaseous Analyzers [NOx/NO(CLD),CO2/ CO (NDIR)]
  - Engine Exhaust Particle Sizer (EEPS™) spectrometer(TSI Inc., model 3090)
  - Micro-aethalometer®Model AE51(Magee Scientific)
  - Dusttrack™ (TSIInc.)
- Background Air Sampling Station (fixed)
  - Hot-wire anemometer
  - Humidity, pressure, and temperature sensor
  - Fast Mobility Particle Sizer (FMPS™) spectrometer(TSI Inc. model 3091)
  - CO2Analyzer(NDIR)

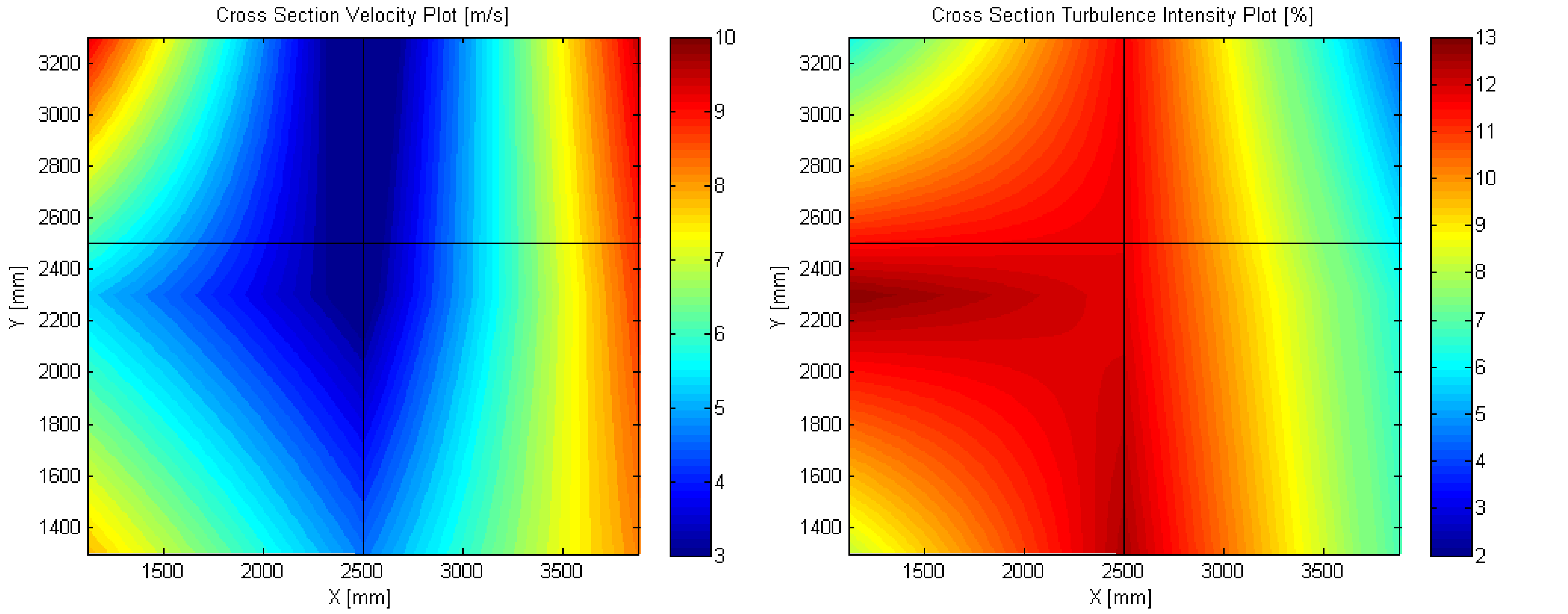
✓ Mobile and fixed stations are calibrated and operated according to recommendations outlined in Code of Federal Regulations (CFR), title 40, subpart 1033 and 1065.

Flow Characterization

- Parameter tests:
  - 3 analyzed plane (3m x 3m)
  - 9 points per plane
- Flow parameters analyzed:
  - Time averaged local wind speed
  - Turbulence intensity
- Flow Configuration:
  - Mock-up cabin in the wind tunnel
  - Wind speed of 7 m/s
- Instrumentation:
  - 3d needle hot wire anemometer
  - 1d hot wire anemometer
  - Thermocouple

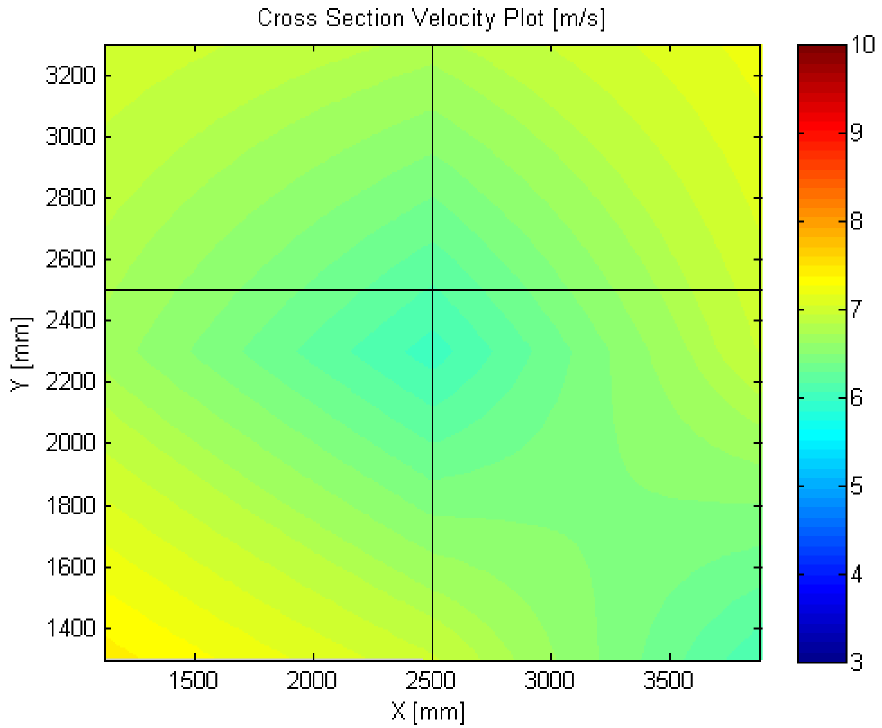
Flow Characterization (Plane 1)

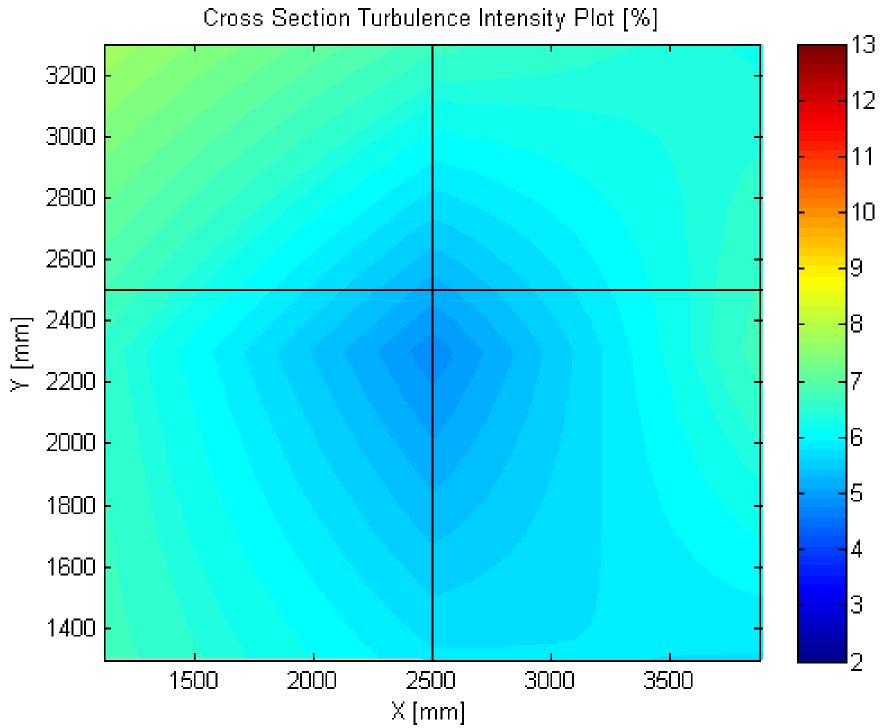
- 30cm behind cabin



Flow Characterization (Plane 2)

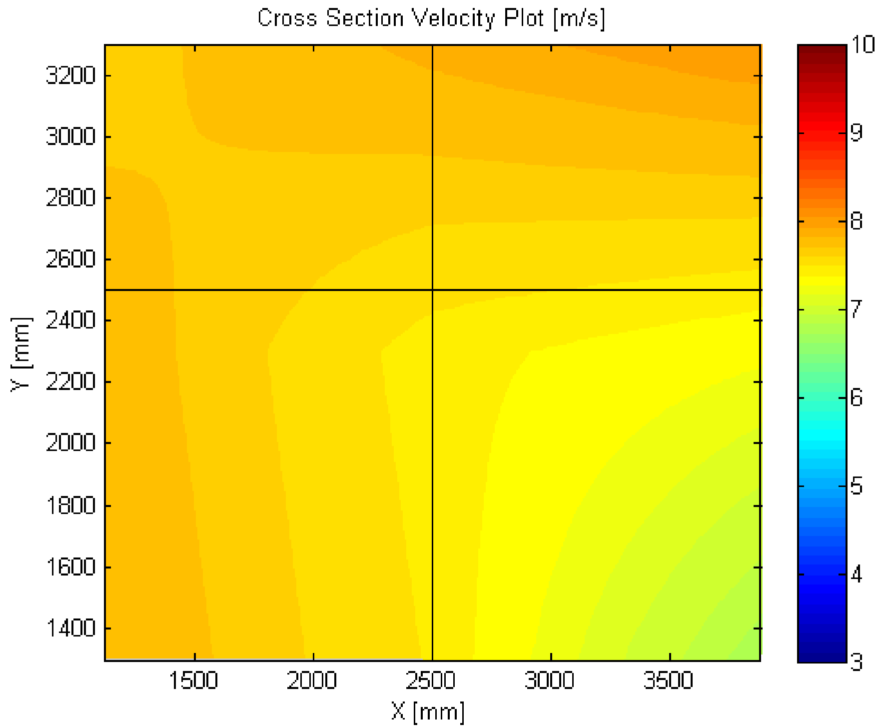
- 10m behind cabin

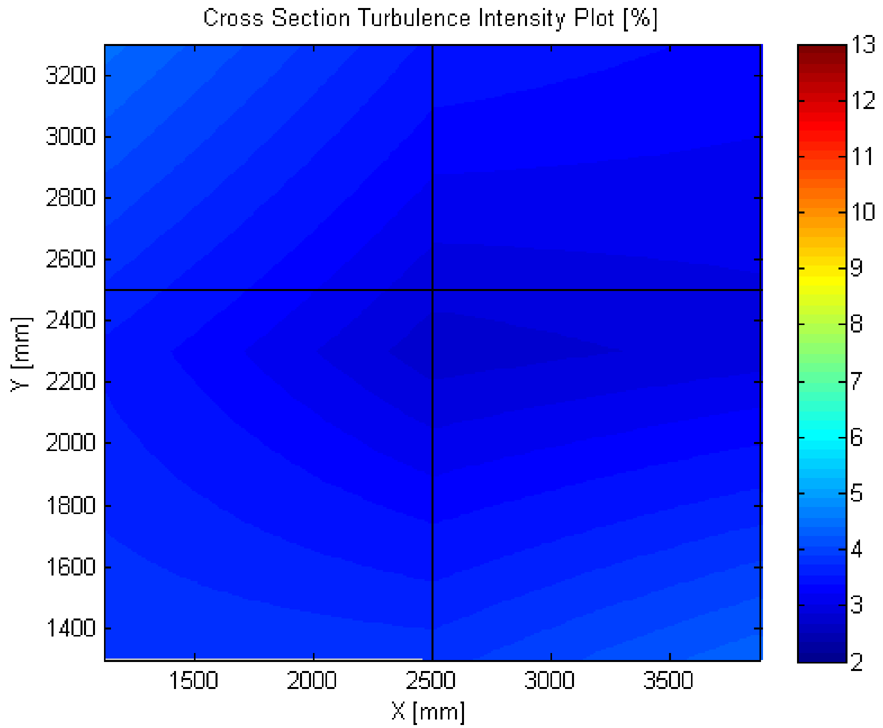




Flow Characterization (Plane 3)

- 25m behind cabin





Applications

- Advanced studies of the after-treatment component - external aerodynamics and related emissions effects.
- Controlled studies on the effect of cross winds on pollutant formation in the plume.
- Collect plume sample for smog chamber to analyze secondary pm formation and evolution.
- Wind effect on heat transfer in the engine compartment, and related emissions effects
- Environmental studies of pollutants/chemical/GHG on scale building of cities
- Atmospheric dispersion/development modeling

Applications

- Study of stability and control of micro aerial vehicles (MAVs) in a constant free-stream velocity. MAV will be tracked by a Vicon 3D motion tracking camera system during their mission.

- Rapid development of optimized flight control hardware (e.g., control surface size, location, and actuation response times) and software (i.e., control law algorithm).

Conclusion

- Development a new tool in the field of real-world emissions assessments, specifically designed to accommodate different vehicles, and study the related emissions effects over a wide range of wind speeds.
- Assessing a deeper knowledge of particle formation and evolution, it may aid regulatory agencies in identifying, developing new and improving current emissions standards.
- Flow Characterization data well agree with preliminary CFD simulations
- The flexibility of the tunnel allow to cover different applications (automotive and non) and analyze their plume formation and evolution.

Acknowledgment

- California Air Resource Board [CARB]
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- WVU CAFEE engineers, technicians and graduate students

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Vehicle Applications

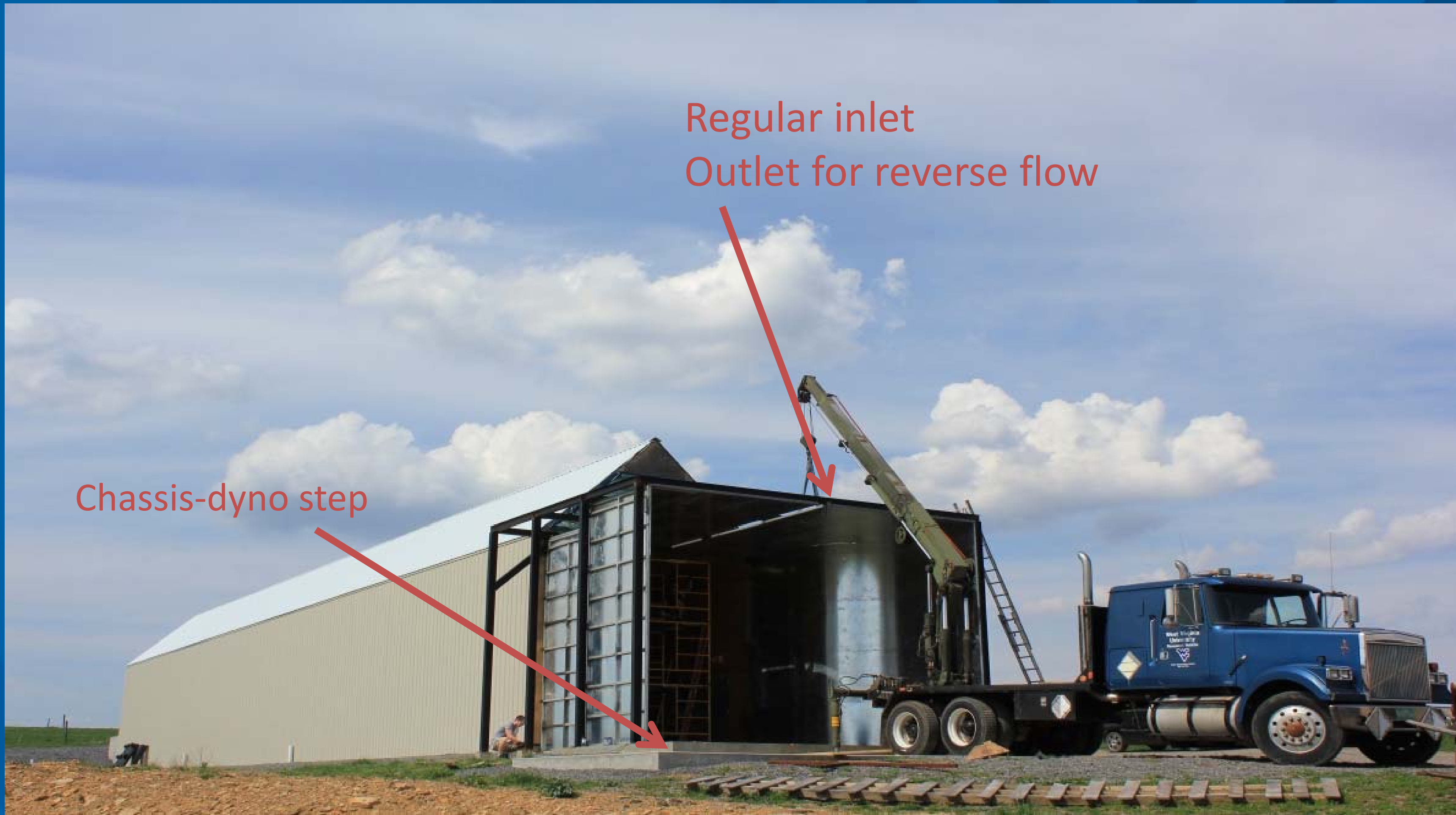
- Plume characterization from any on-road vehicles, and majority of off-road vehicle, with full scale model.
- Controlled studies on the effect of cross winds on pollutant formation in the plume.
- Advanced studies of the after-treatment component - external aerodynamics and related emissions effects.
- Wind effect on heat transfer in the engine compartment, and related emissions effects.
- Climate chamber for full scale vehicles.

Vehicle Applications

- For Plume characterization, the Wind tunnel operates with the original “pulling” configuration. The chassis-dyno and the tested truck are placed outside the tunnel and thanks to an underground passage the exhaust enters inside the Tunnel, where a mock-up cabin or truck and exhaust stack are placed.

- For wind effect on related raw emissions, the Wind Tunnel operates with a “pushing” configuration, reverting the flow. In this case a step just in front of the regular inlet (which now is the outlet) accommodates the chassis-dyno, in order the truck to be flush with the floor of the tunnel itself. This kind of study can help to understand how the external and internal aerodynamics of the truck can affect emissions.

Vehicle Applications



Enviroment Applications

- Wind turbine blade design and testing, using large scale models.
- Wind turbine farm testing, to evaluate the effect of the configuration pattern on the overall efficiency of the plant.
- Wind load on urban structures.
- Environmental studies of pollutants/chemical/GHG on scale building or scale cities.
- Atmospheric dispersion/development modeling
- For these applications a direct control of the boundary layer is fundamental, it is possible to achieve it with different techniques.
- For these applications the regular “pulling” configuration is the best suited to analyze the cases.
- Turbulence field instrumentation can be fitted.

Aerial Applications

- Study of stability and control of micro aerial vehicles (MAVs) in a constant free-stream velocity.
- RDT&E of advanced MAV propulsion and control system gust alleviation strategies in which implanted test section obstacles are actuated to produce regions of rapidly-changing freestream velocities that MAV models must negotiate while being tracked by a Vicon 3D motion tracking camera system.
- Rapid development of optimized flight control hardware (e.g., control surface size, location, and actuation response times) and software (i.e., control law algorithm).
- The team has been recently awarded with a grant: “ Evaluate stability and gust performance using a tethered MAV in the wind tunnel”.

Aerial Applications

- Testing of free-flight munitions drop experiments in which air-launched munitions are released from pylons into catch nets while being recorded by high speed camera systems.
- Advanced ordnance research for the experimental investigation of an emerging class of tube launched UAVs known as Hybrid Projectiles (HPs).
- HP experiments will focus on the free-flight glide and controlled flight target tracking behavior of current WVU HP designs.
-
- Bio-mimetic and biomechanical research will be performed which will investigate the form and function of naturally occurring wing designs (e.g., the fluttering of sphinx moth scales or leading edge feathers on a red-tailed hawk) to enhance the flow characteristics of low Reynolds number MAV fixed-wing and flapping flight.
- For these applications the regular “pulling” configuration is the best suited to analyze the cases.