ANL-Cummins CRADA: Integrated External Aerodynamic and Underhood Thermal Analysis for Heavy Vehicles

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Project ID #:
VSS080

Overview

Timeline
- April 2012
- April 2015
- New start

Budget
- $1,900K
  - DOE share: 50%
  - CRADA partner’s share: 50%
    (in-kind contributions and tests)
- DOE Funding received
  - FY11: $350K
  - Fy12: $100K

Barriers
- Computation models, design and simulation methodologies
- Vehicle efficiency beyond engine alone
- Reduce cooling system size and increase engine thermal efficiency

Target
- Improve heavy truck engine thermal efficiency to 50% by2015 and to 55% by 2018

Partner
- Cummins Inc.
- Project leads:
  - T. Sofu (ANL)
  - L. K. Hwang (Cummins)

Project Objectives and Relevance

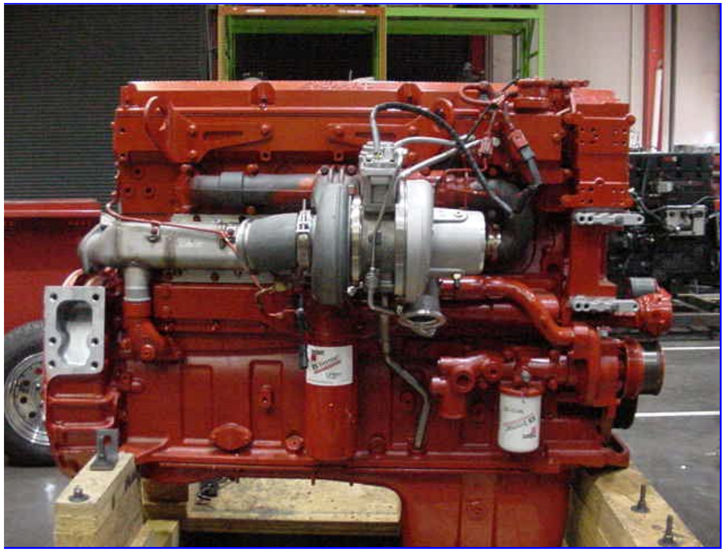
- Objective is development of a predictive analytical capability to address unique heavy-vehicle underhood thermal design challenges while keeping the aerodynamic considerations in perspective
  - Specific issues related to emission control technologies needed to meet the new diesel engine emission requirements and increased electrification of the engine system
- Optimal design of vehicle thermal system is important for energy efficiency as well
  - Less than one-third of the total fuel energy provides useful mechanical work, remainder is lost through the exhaust system and heat rejection
  - Predicting the engine and component temperatures accurately speeds up underhood design cycle and helps achieve fuel efficiencies through cooling system optimizations and radiator size reduction
- The analytical capability being developed is aimed to help with the overall heavy-vehicle optimization through analysis of interdependent phenomena
  - Underhood configurations
  - Cooling system
  - Vehicle external aerodynamics

Approach

- This project will provide a methodology to fully characterize a heavy vehicle energy balance based on combined use of 1-D thermo-fluids system model for the engine and cooling system, and 3-D computational fluid dynamics (CFD) techniques for the underhood and external aerodynamics analyses
  - CFD, although computationally intensive, is the tool of choice for simulations of the entire vehicle in 3-D
  - When coupled with 1-D systems models to represent the engine and cooling system response, CFD can be used to simulate thermal-flow conditions in the underhood compartment
- Combined use of CFD and 1-D system models offers unique advantages:
  - System model accounts for thermal energy balance and heat distribution inside the engine through 1-D network of flow loops
  - CFD model addresses multi-dimensional flow and heat transfer effects wherever needed
  - The combined model only needs basic ambient conditions and component performance curves by exchanging data between 1-D and 3-D models.

Approach (cont.)

- In this collaboration, a network of 1-D representation of a Cummins ISX engine internal flow loops will be developed with *Flowmaster*
  - Combined with a lumped-parameter approach to characterize thermal interactions between flow loops through the engine structure as major conduction paths
- *Flowmaster* model accounts for thermal energy balance by considering the heat generated from combustion to be transferred to various discrete component surfaces
  - Cylinder head, valve cover, front cover, engine block, ECM, intake and exhaust manifolds etc.
- CFD model of the underhood compartment and external aerodynamic configuration will be developed using *Fluent* or *Star-CCM+*
- Coupling of CFD model with *Flowmaster* systems model will be achieved via a custom interface developed at ANL

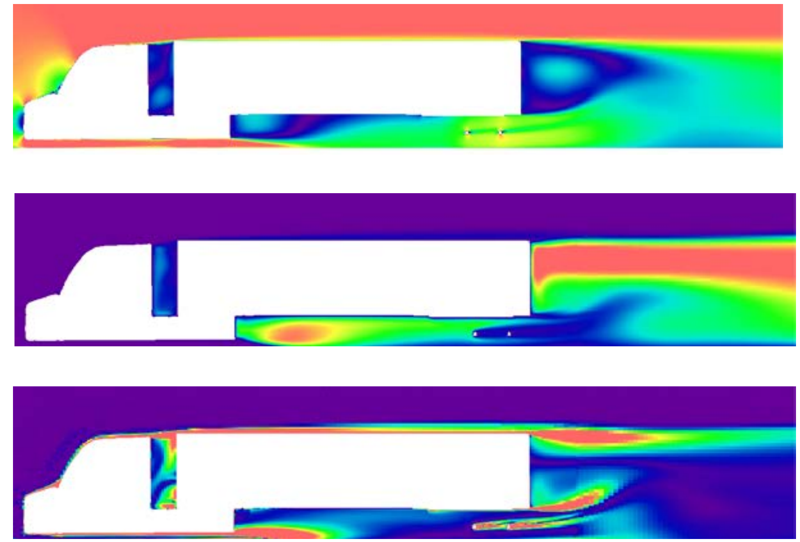


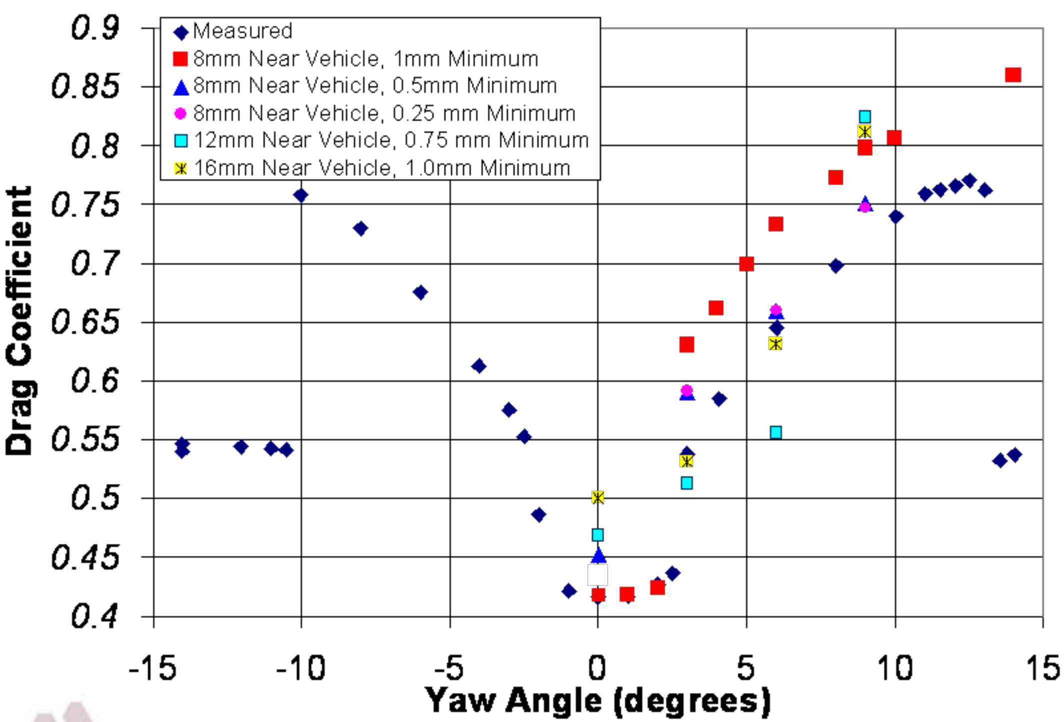
ANL Experience with Heavy Vehicle Aerodynamics

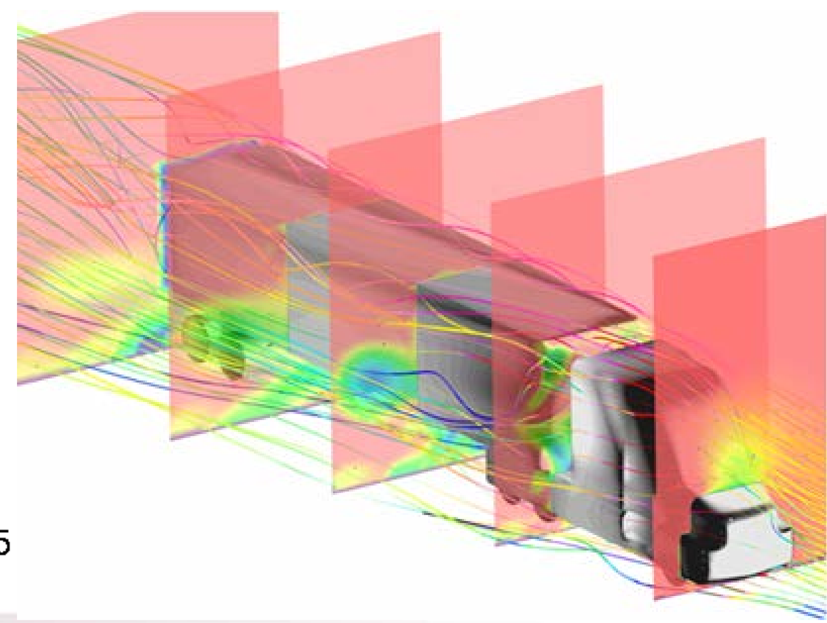
- Analysis of a “Generic Conventional Truck-Trailer Model” (GCM) as part of the DOE Consortium
  - Supported with very high quality test data from high Reynolds number wind-tunnels at NASA
  - In addition to the overall drag force, detailed surface pressure measurements were also taken
  - Complex flow field behind the trailer and in the gap between the truck and trailer was characterized via super-fine resolution LDV measurements
- CRADA with PACCAR Tech Center on aerodynamic analysis of a realistic truck-trailer configuration
- CRADA with Caterpillar on truck electrification and its impact on aerodynamics
- Smaller scale collaborations with vendors that market add-on drag reduction devices

CFD Validation Using the GCM geometry

- Extensively tested in NASA wind-tunnels at zero and non-zero yaw angles (up to 15-degrees)
- ANL predicted drag coefficient at zero yaw within 1% of value measured in 1/8th scale wind tunnel
- Predictions are within 1-3% at small yaw angles and 5-7% at nominal yaw for models of similar size

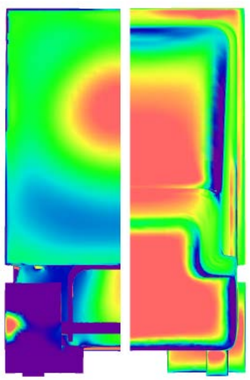


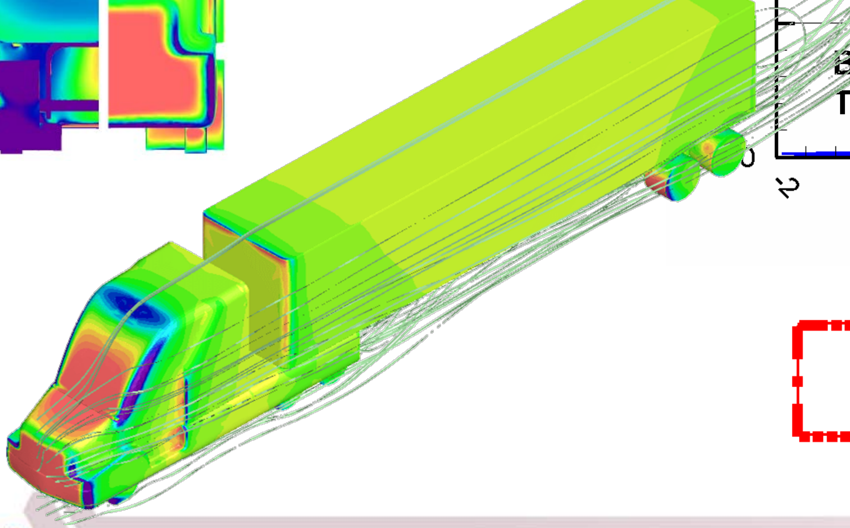


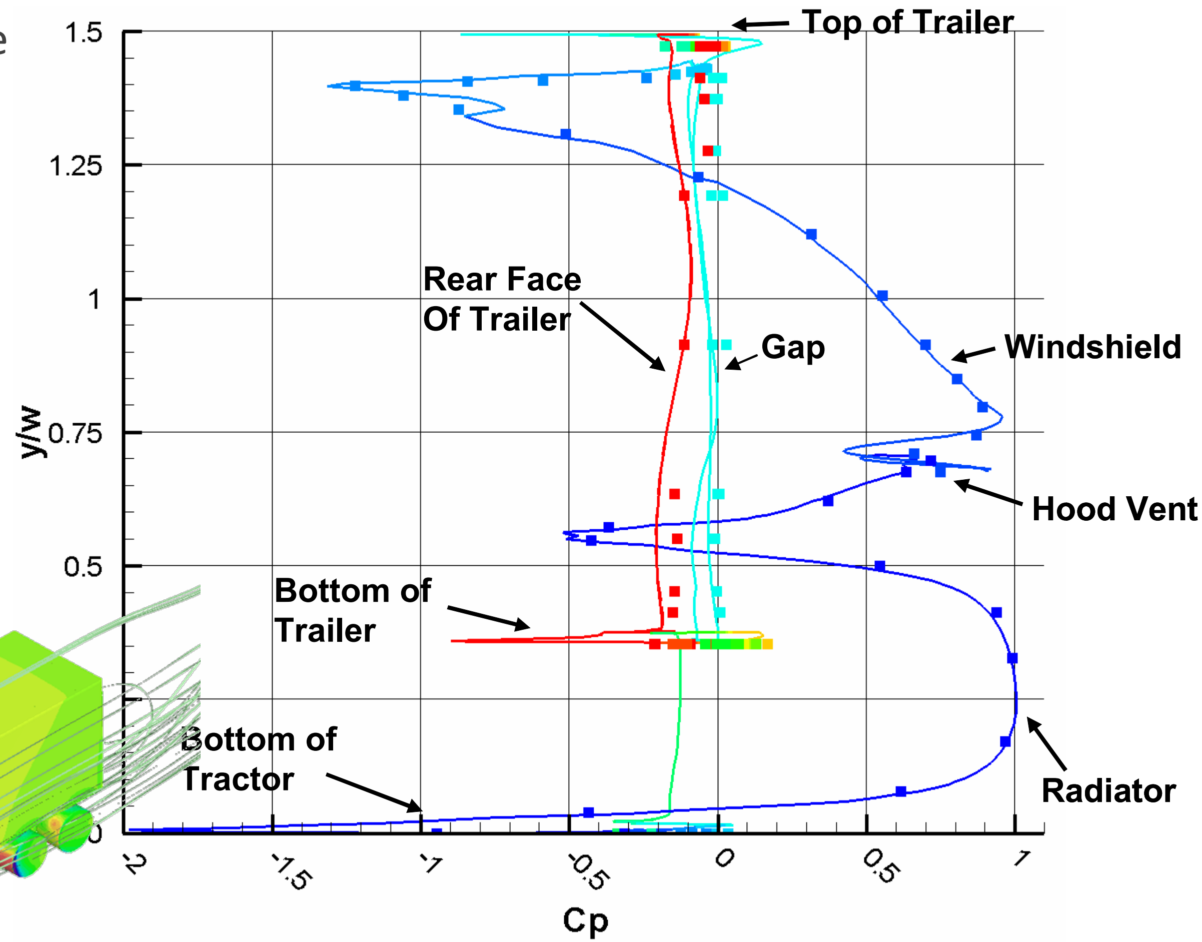


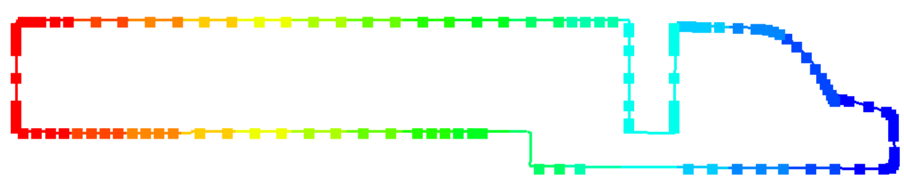
Comparison of Surface Pressure Predictions for GCM

- Drag comparisons alone are not sufficient to call an approach “validated”
- Simulations are also compared with detailed surface pressure measurements









Strategy for Deployment

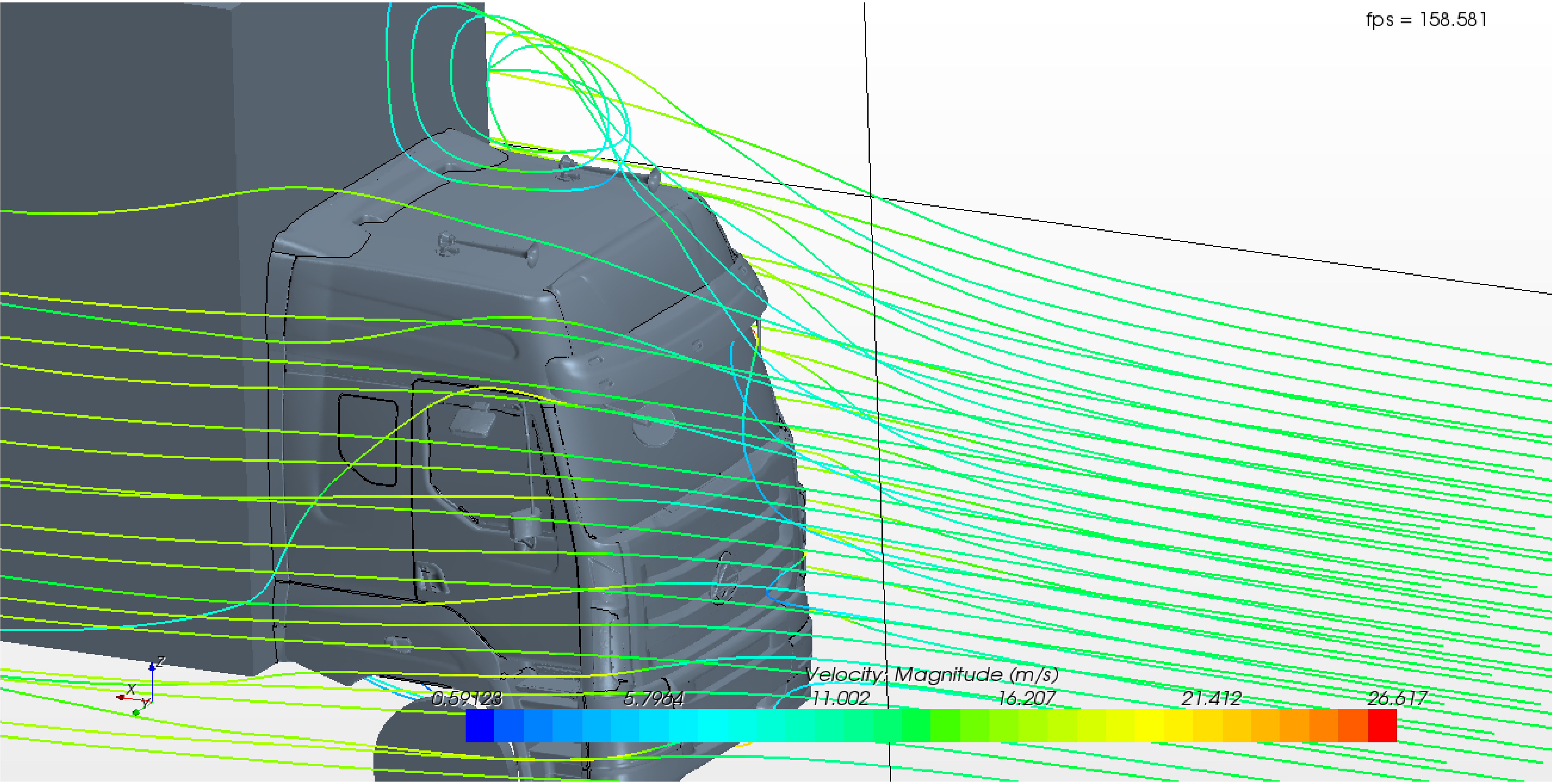
- Cummins is a major U.S. engine manufacturer for heavy vehicles with extensive experience on vehicle integration
  - They work closely with OEM's for engine installation issues and cooling system optimizations
- Typical underhood thermal management challenge is to avoid component overheating due to tight packaging
  - Since high temperatures can reduce component durability and life, the assessment of temperature distributions under the hood is an important element of a design cycle
- However, fuel efficiency considerations also tie Cummins' work to external aerodynamics of different heavy vehicle designs
  - Need for a comprehensive analytical capability to make aerodynamic drag assessments for different design options in addition to traditional focus on underhood
- The analytical capability developed is expected to be utilized by Cummins vehicle integration program
  - Cummins has already adopted the heavy vehicle underhood thermal assessment practices developed as part of the earlier CRADA
  - Training of their R&D center staff at Cummins Research and Technology India (CRTI) took place in May 2008 in Pune, India

Technical Accomplishments and Progress

- This project is a new start, but it takes advantage of the progress made in an earlier ANL-Cummins collaboration:
- In 2006, a network of 1-D representation of a Cummins ISX engine internal flow loops was developed and combined with a lumped-parameter approach to characterize thermal interactions between them through the engine structure as major conduction paths
  - Model can predict the complete engine thermal system performance by analyzing the interactions of the engine with the coolant and oil loops
  - It accounts for thermal energy balance by considering the heat generated from combustion to be transferred to various discrete component surfaces (e.g., cylinder head, valve cover, front cover, engine block, cylinder head, ECM, etc.) through specified conduction paths
- In 2007, work on CFD modeling (using Fluent) of the underhood compartment of a generic class-8 heavy vehicle, and its coupling with the 1-D systems model was achieved
- In 2008, the results of the coupled CFD and network flow models were compared with the test data from Cummins for validation
  - Excellent agreement between the model results and test data was demonstrated

Technical Accomplishments and Progress (cont.)

- So far for the current phase of the project, Cummins has identified a truck configuration via participation of a foreign manufacturer, and ANL has developed a CFD model for a “proof-of-principle” aerodynamic analysis



Scope of Collaborations

- This new collaboration between ANL and Cummins will take the predictive model developed in earlier phase to next step for a combined analysis of vehicle aerodynamics and underhood thermal design
- A computational framework for combined underhood thermal and external aerodynamics simulations will be developed through collaborations
  - The analytical models of Cummins ISX engine and the selected heavy-vehicle underhood and external aerodynamics models will be developed at ANL
  - Validation of the underhood thermal analysis models will be performed through comparisons with tests to be performed at the Cummins Vehicle Integration Lab in Columbus, Indiana
  - Validation of the external aerodynamics models will be performed through collaborations with an OEM or a fleet owner such as FedEx or Wal-Mart

Summary

- The purpose of this project is development of an analytical capability to quantify the impact of cooling system optimizations on overall heavy vehicle energy efficiency through assessment of changes in aerodynamic drag
  - Cummins will provide the design information for an identified prototypical heavy vehicle configuration, and conduct tests to obtain experimental data for validation.
  - Using the information and data from Cummins, the analysts at ANL will develop computational models of the selected heavy vehicle configuration
  - ANL and Cummins will jointly validate the models using test data
  - The resulting capability will allow comprehensive analysis of energy efficiency considerations including the impact of cooling system optimizations as well as aerodynamic drag
- This project will enable to extend the scope of underhood thermal analyses to measure the impact of underhood design changes on the overall vehicle energy efficiency through aerodynamic drag assessments
  - Will provide the industry with a predictive capability to shorten component design and test cycles with a validated high-fidelity, but also a practical, simulation tool

Technical Back-up Slides

Underhood Challenge Problem

- Specific underhood problem aimed to be addressed is related to EPA 2010 regulation to assure that medium and heavy-duty trucks run cleaner with greater fuel efficiency
  - Require that NOx levels be reduced to almost zero
- Cummins is studying the use of Selective Catalytic Reduction (SCR) as an after treatment system
  - By treating the exhaust gases outside of the engine and using less exhaust-gas recirculation, SCR technology may also improve fuel consumption by as much as 6%
- However, the SCR system thermal management is a critical issue
  - High temperature is required to generate ammonia and neutralize NOx with high efficiency, but at the same time, the SCR system control electronics reliability and durability demand a low temperature environment
  - These competing requirements need a system level understanding of the thermal environment that, if it can be predicted analytically, can lead to significant system optimizations