Combined Aero and Underhood Thermal Analysis for Heavy Duty Trucks

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Project ID#: VS132

Vehicle Technologies - Annual Merit Review – Jun 8, 2016

Overview

Lead: T. Sofu and S.N.P. Vegendla (Argonne Natl. Lab.)

Partners: L.K. Hwang, R. Saha and M. Kumar (Cummins, Inc.)

Project Funding (Duration): $1,050K over multiple years with matching funds from Cummins

Funding Source	FY12	FY13	FY14	FY15	FY16
VSST	$350K	$125K	$100K	$0K	$50K
Industry/Govnt. Cost Share	50/50 cost share				

Timeline

- Project signed in Sep 2012
- Project started in Oct 2012
- Project **60%** completed

Goals

- Development of a computational framework for combined underhood and aerodynamics analysis as a novel predictive analytical capability
- Quantify the impact of cooling system optimizations on overall energy efficiency through assessment of changes in aerodynamics drag coefficient
- Also address emission control issues to meet the new diesel engine requirements and increased electrification of the engine system

Supported by L. Slezak (Vehicle System Optimization)

Objectives

- The analytical capability being developed is aimed to help with the overall heavy-vehicle optimization through analysis of interdependent phenomena
  - Vehicle external aerodynamics
  - Cooling system performance
  - Underhood thermal analysis

- Optimal design of vehicle thermal system is important for energy efficiency
  - 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 under the hood accurately speeds up design cycle and helps achieve greater fuel efficiencies through coolant system optimizations
    - With impact on aerodynamics

Approach

FY13

Perform Aerodynamics and Thermal Analysis

Selected Vehicle CAD Surfaces

CAD Import and processing for CFD simulations

FY14/FY15

Vehicle Aerodynamics and Thermal Improvements

FY15/FY16

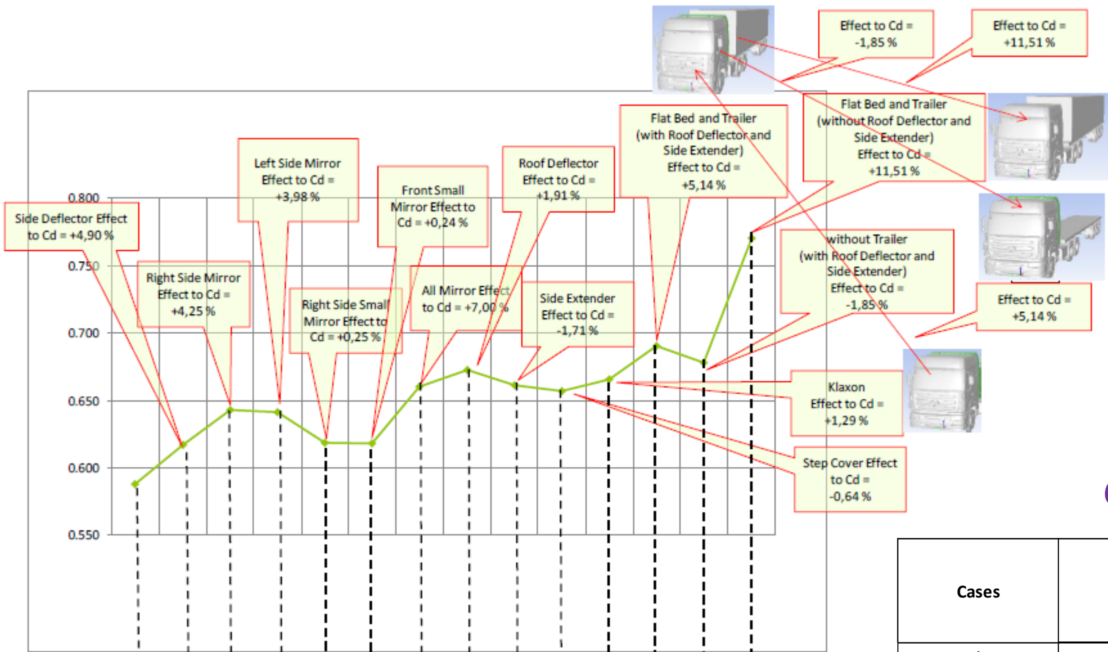
Vehicle Platooning Aerodynamics and Underhood Thermal Analysis

Vehicle Underhood Optimization Fan-Shroud Optimization

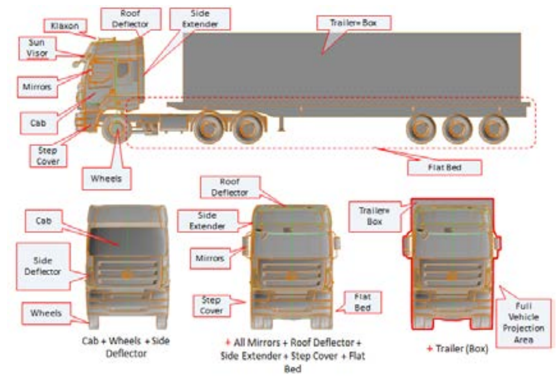
Project Milestones

- FY13
  - Two different heavy-duty vehicles CAD models were processed to run the 3D Computational Fluid Dynamic (CFD) aerodynamic drag and underhood thermal simulations.
  - Validated aerodynamic drag result with two different commercially available software, StarCCM+ and Fluent.
  - Aerodynamic drag analysis performed for each component in heavy-duty vehicle (e.g. mirrors, klaxon, extended deflectors etc.)
- FY14
  - Medium-duty delivery truck, CAD model were processed to run the 3D-CFD aerodynamic drag and underhood thermal simulations.
  - Validated aerodynamic drag result with two different commercial software, StarCCM+ and PowerFlow®.
  - Optimized aerodynamic drag (fuel economy) configuration was identified.
- FY15
  - Vehicle platooning simulations performed for five different configurations;
    - Single-lane traffic with leading and trailing vehicle.
    - Two-lane traffic with leading and trailing vehicles in two separate lanes.
    - Two vehicles are in side-by-side lanes.
    - Three vehicles are in side-by-side lanes.
    - Two leading vehicles are in side-by-side lanes and one vehicle followed in one of the leading vehicles.
- FY16
  - Cooling package optimization in heavy-duty vehicles (fan-shroud optimization)
  - Vehicle platooning underhood thermal simulations performed for two different configurations;
    - Single-lane traffic with leading and trailing vehicle.
    - Two-lane traffic with leading and trailing vehicles in two separate lanes.

Accomplishments: Aerodynamic Drag Analysis of Heavy-Duty Truck [FY13]



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CAB	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
SIDE DEFLECTOR	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
RIGHT MIRROR	N	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
LEFT MIRROR	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y
RIGHT SMALL MIRROR	N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y
FRONT SMALL MIRROR	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
ROOF DEFLECTOR	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y
SIDE EXTENDER	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	N
DOOR STEP COVER	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y
KLAXON	N	N	N	N	N	N	N	N	N	N	Y	N	N	N
FLAT BED	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y
TRAILER	N	N	N	N	N	N	N	N	N	N	N	Y	N	Y



Aerodynamic drag analysis performed for each component.

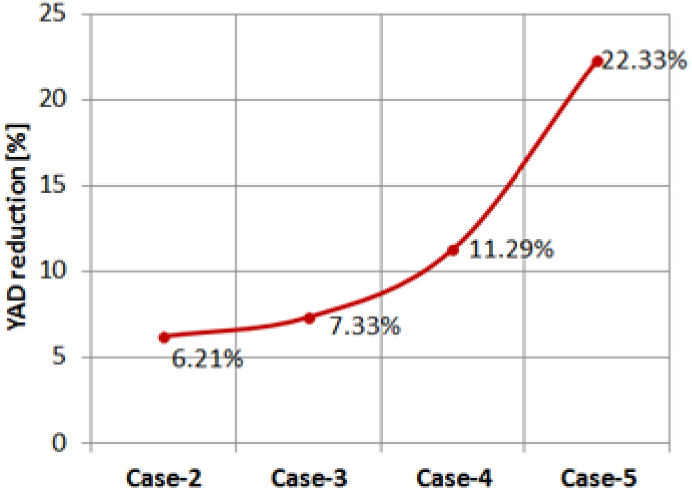
CAB ANALYSIS WITHOUT TRAILER

Cases	A; Projection Area (m^2)	F; Drag Force (Newton)	Cd; Drag Coef.	Cd Effect %	Incremental @100 KM/HR Fuel Economy Effect %
1	8.236	1854.05	0.588	-10.90	5.45
2	8.236	1944.84	0.617	-6.54	3.27
3	8.354	2056.60	0.643	-2.56	1.28
4	8.327	2044.60	0.641	-2.82	1.41
5	8.247	1952.40	0.618	-6.30	3.15
6	8.236	1949.51	0.618	-6.31	3.16
7 (Baseline)	8.454	2136.00	0.660	0.00	0.00
8	8.755	2254.30	0.673	1.91	-0.95
9	8.851	2240.08	0.661	0.17	-0.08
10	8.851	2225.73	0.657	-0.47	0.24
11	8.851	2254.46	0.665	0.81	-0.41

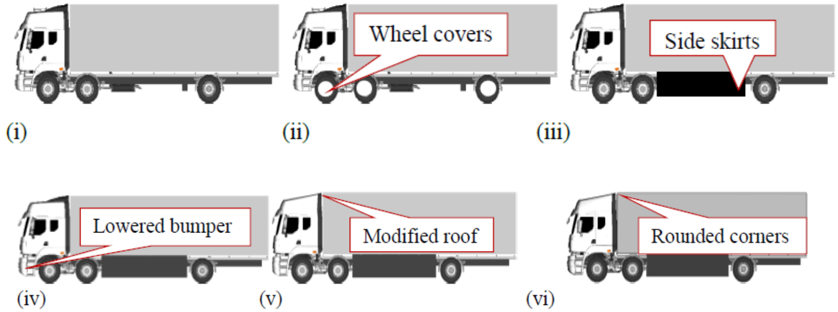
CAB +TRAILER ANALYSIS

Cases	A; Projection Area (m^2)	F; Drag Force (Newton)	Cd; Drag Coef.	Cd Effect %	Incremental @100 KM/HR Fuel Economy Effect %
12	9.794	2589.34	0.691	-10.32	5.16
13	9.240	2397.71	0.678	-11.98	5.99
14 (Baseline)	9.794	2887.37	0.770	0.00	0.00

Accomplishments: Aerodynamic Drag Analysis of Medium-Duty Delivery Truck [FY14]



YAD: Yaw avg. aerodynamic drag reduction



Vehicle configurations: (i) Base configuration, (ii) Case-1, (iii) Case-2, (iv) Case-3, (v) Case-4, and (vi) Case-5.

Max fuel benefit: 11% for Case-5 Configuration

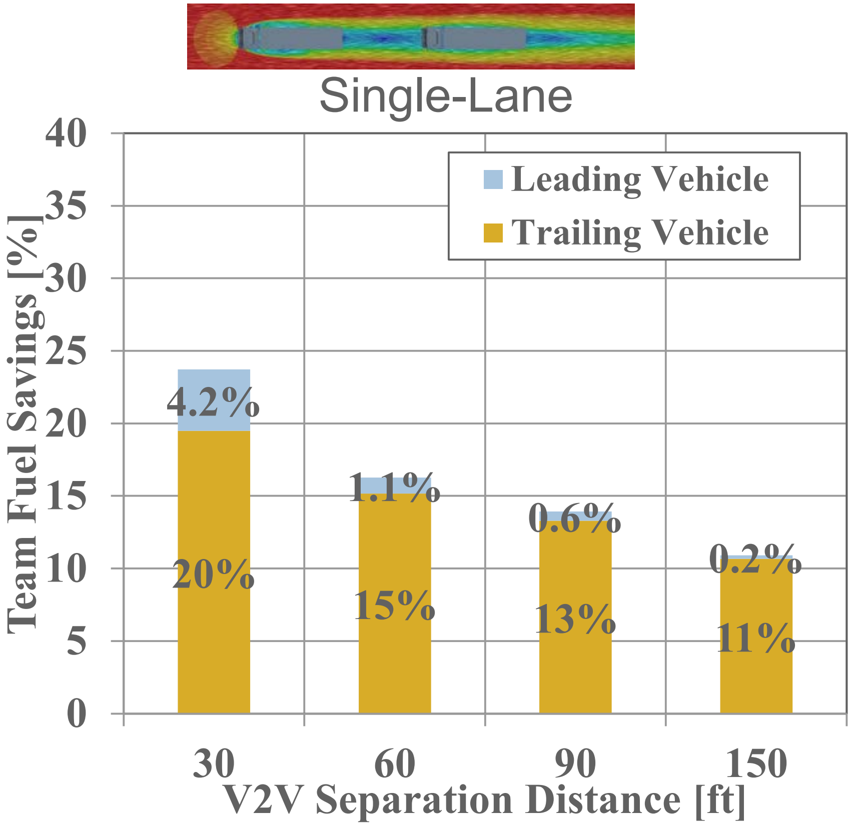
Run#	Model Details
Base configuration	Original medium-duty vehicle
Case -1	Base config. + wheel covers
Case -2	Base config. + side skirts
Case -3	Case -2 + no-klaxon + lowered front bumper
Case -4	Case -3 + optimized side extender and roof deflection
Case -5	Case -4 + aerodynamic mirrors + rounded corners

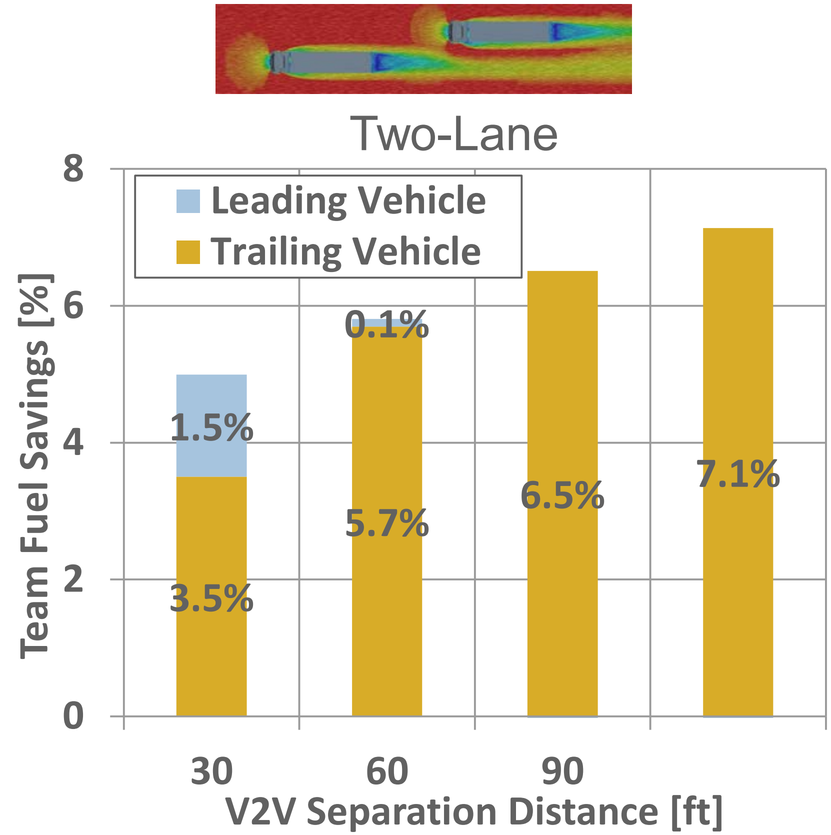
The important findings;

- ❑ The optimum curvature radius of the rounded trailer edges found to be 125 mm, with an arc length of 196.3 mm.
- ❑ Aerodynamic drag reduction increases with dropping clearance of side skirts between wheels and ground.
- ❑ Aerodynamic drag reduction increases with an extension of front bumper towards the ground.

Vegendla et al. Aerodynamic Drag Optimization of Medium-duty Delivery Truck. Int. Journal of Aerodynamics (submitted).

Accomplishments: Aerodynamic Drag Analysis in Vehicle Platooning [FY15]





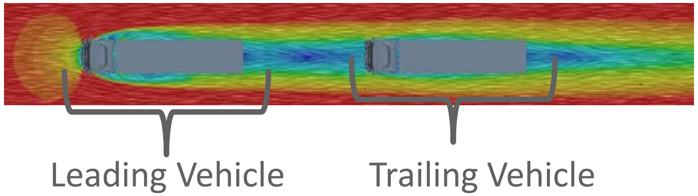
Max fuel benefit: 24.2% @ 30 ft

Max fuel benefit: 7.1% @ 150 ft

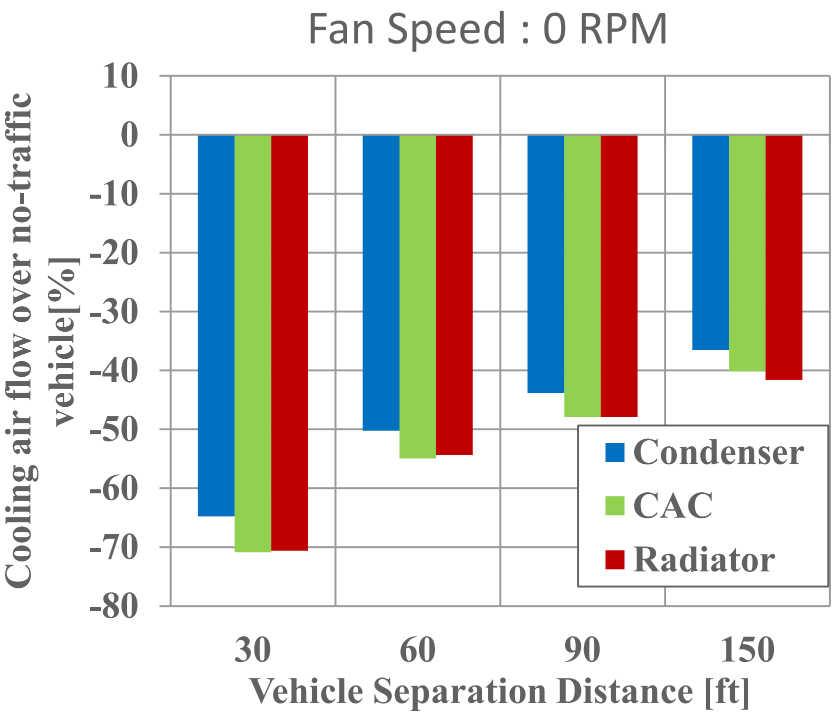
- Aerodynamic drag performance roughly double of the team fuel savings.
- In Single-lane traffic, team fuel savings drops with vehicle separation distance.
- In two-lane traffic, team fuel savings raises with vehicle separation distance due low velocity zone @ front cabin of trailing vehicle.

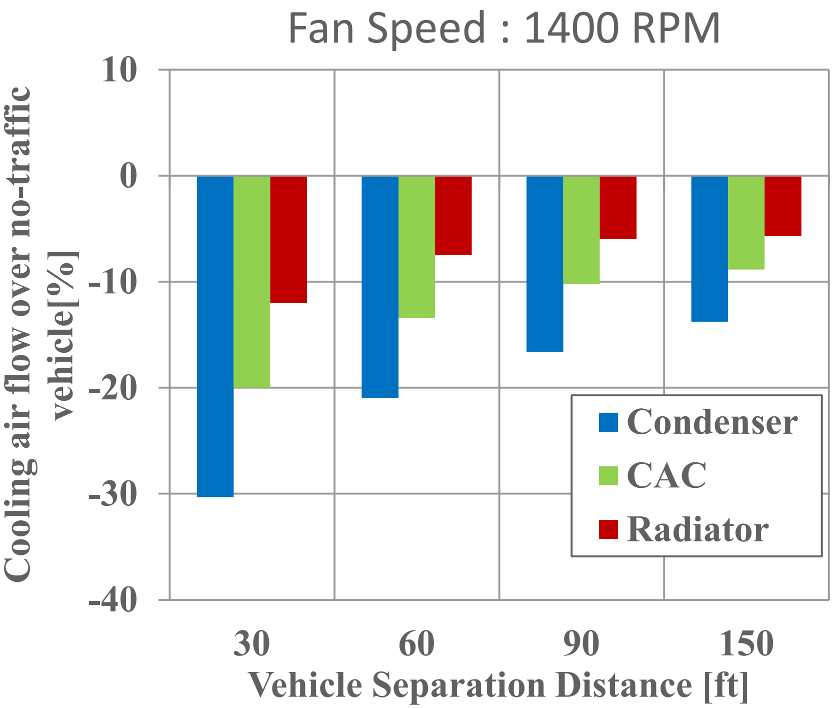
Vegendla et al. (2015). Investigation of Aerodynamic Influence on Truck Platooning. SAE International technical paper, 2015-01-2895. DOI:10.4271/2015-01-2895.

Accomplishments: Platooning Underhood Thermal Analysis



Single Lane – Trailing Vehicle





Lower air mass flow rates (negative performance) through Trailing Vehicle due to low velocity zone from Leading Vehicle. Air mass flow rates improved with vehicle separation.

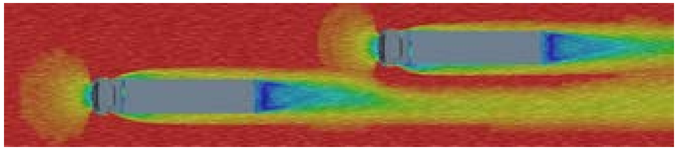
Lower air mass flow rates but higher mass flow rates (~100%) than in 0 RPM.

Lower mass flow rates leads to higher temperatures in heat exchangers [$Q=m\,C_p\,\Delta T$]

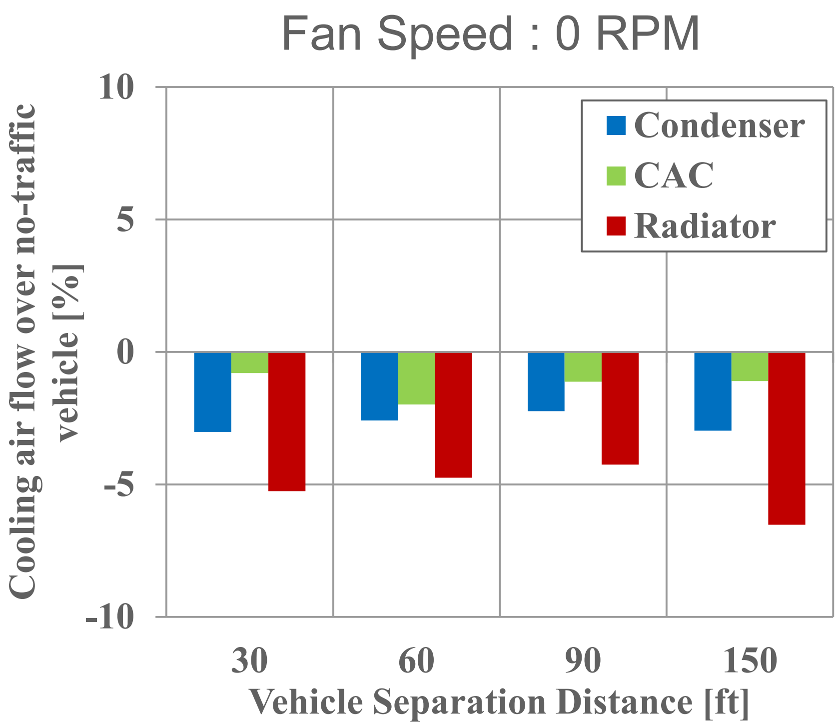
Wind-tunnel Inlet Velocity: 55 mph

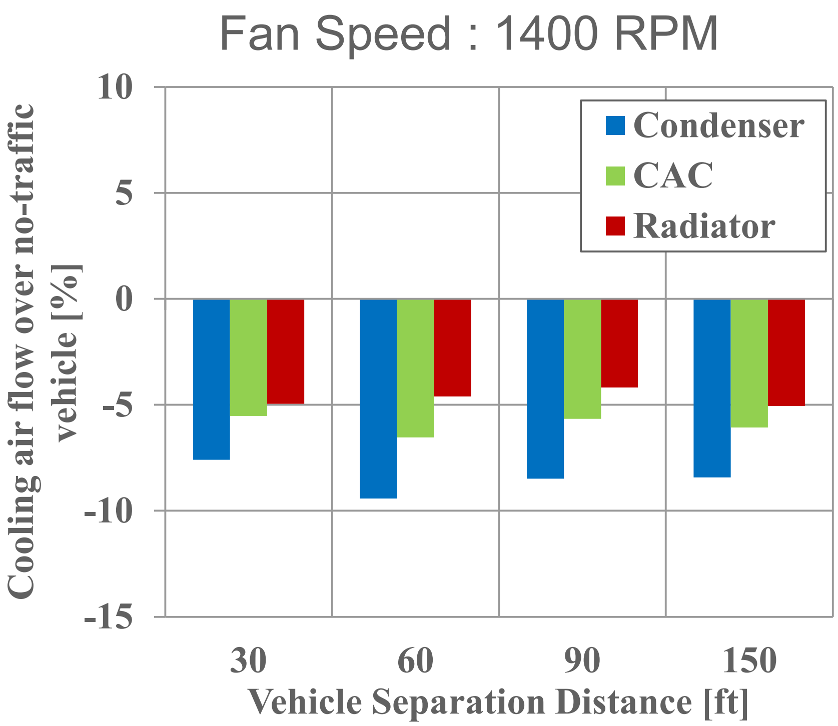
CAC: Charge Air Cooler

Accomplishments: Platooning Underhood Thermal Analysis (cont.)



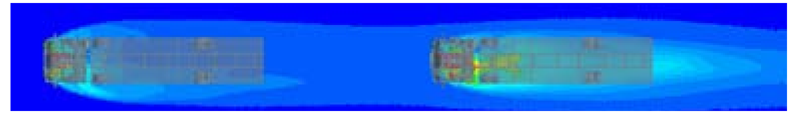
Two Lane – Trailing Vehicle



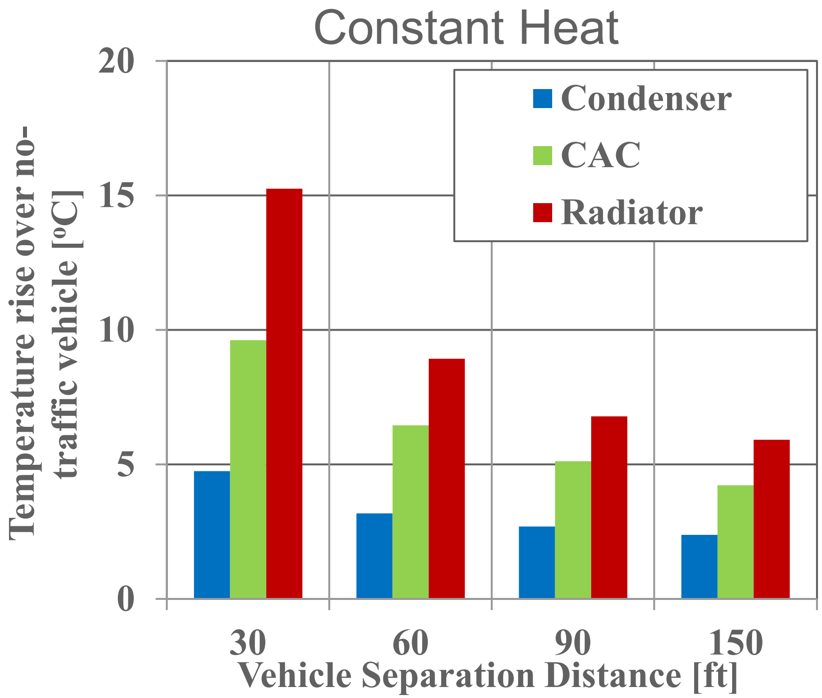


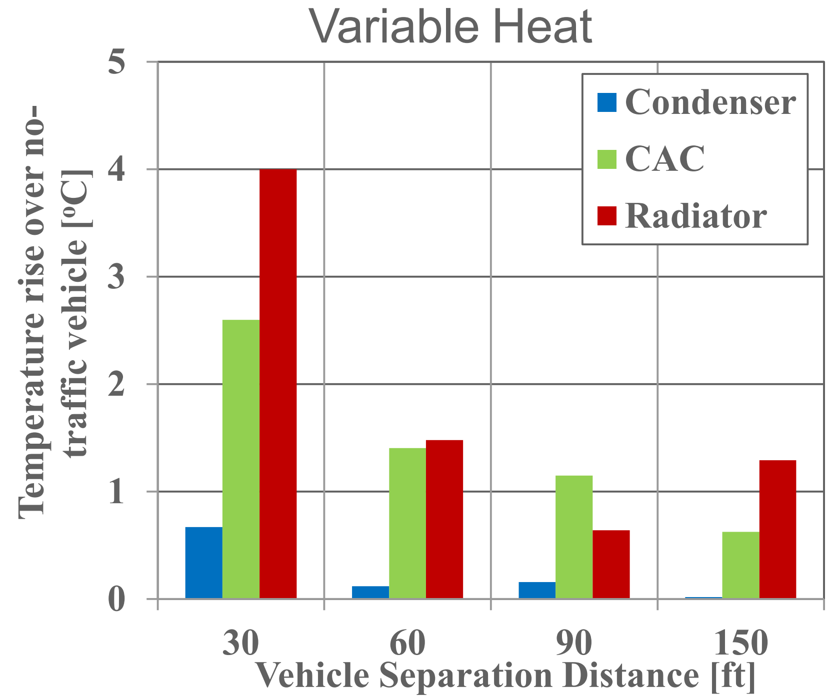
Lower air mass flow rates (negative performance) but negligible compared to Single Lane traffic and insignificant to the vehicle separation distance

Accomplishments: Platooning Underhood Thermal Analysis



Single Lane – Trailing Vehicle [Constant Heat Vs. Variable Heat Rejection]





Fan Speed : 1400 RPM; Wind-tunnel Inlet Velocity: 55 mph
Const. heat rejection Rates:
Condenser – 11 kW, CAC- 24.25 kW, Radiator- 55 kW

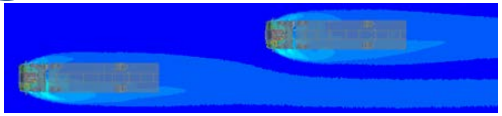
Temperature rise is lower compared to constant heat rejection in trailing vehicle [the amount of heat rejection is less due to lower aerodynamics drag leads to lower fuel consumption and ultimately lower heat rejection from engine].

$$\dot{Q} = \dot{Q}_{no-traffic}\left[1.0 - \frac{\left(1.0 - \frac{C_{d,i}}{C_{d,no-traffic}^{yaw=0^{0}}}\right)}{2}\right],$$

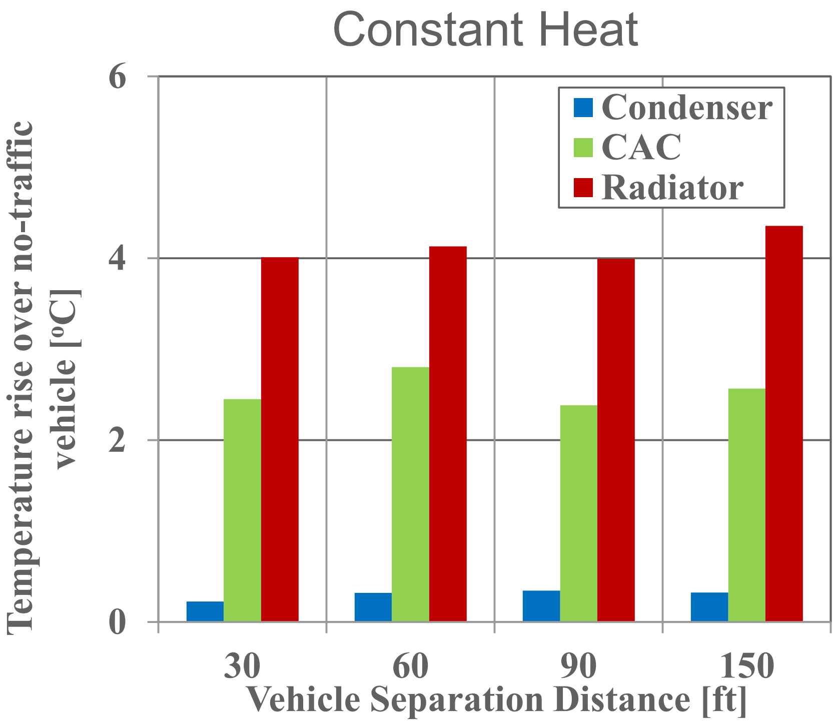
where i= 0, 6 and -6º Variable heat rejection rate

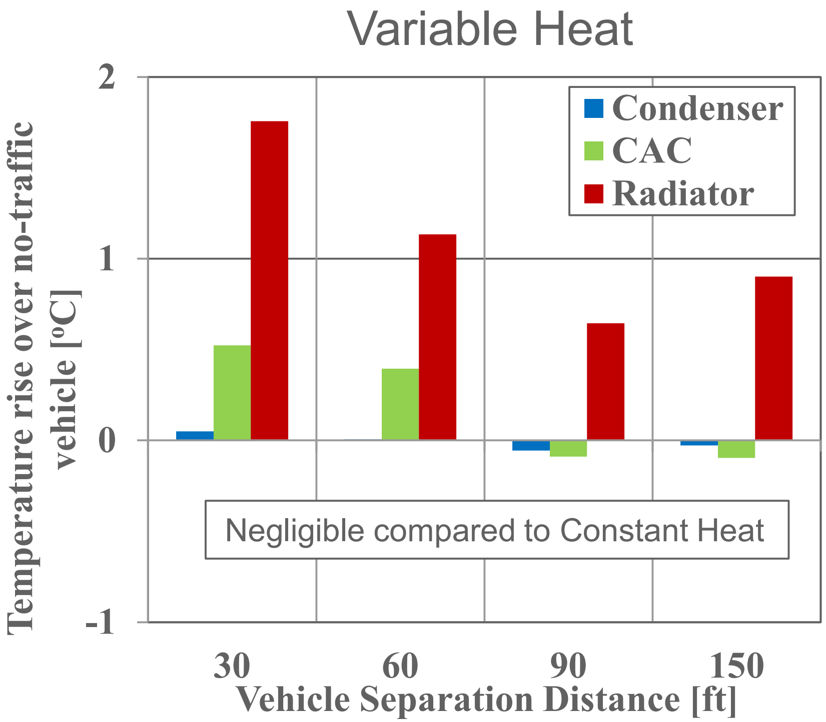
Vegendla et al. Investigation on Underhood Thermal Analysis of Truck Platooning. SAE International Commercial Vehicles (submitted).

Accomplishments: Platooning Underhood Thermal Analysis (cont.)



Two Lane – Trailing Vehicle [Constant Heat Vs. Variable Heat Rejection]

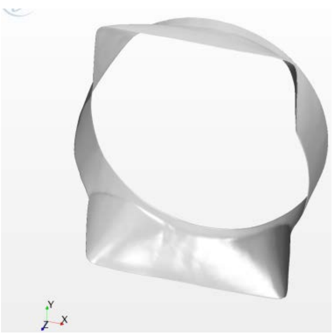




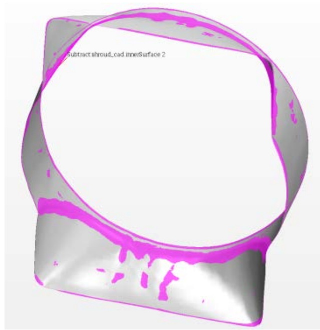
Fan Speed : 1400 RPM

Constant Heat: Temperature rise is independent to the vehicle separation distance and it is insignificant for variable heat rejection case

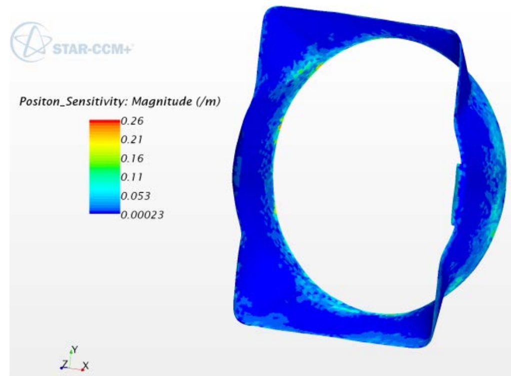
Accomplishments: Fan-shroud Optimization



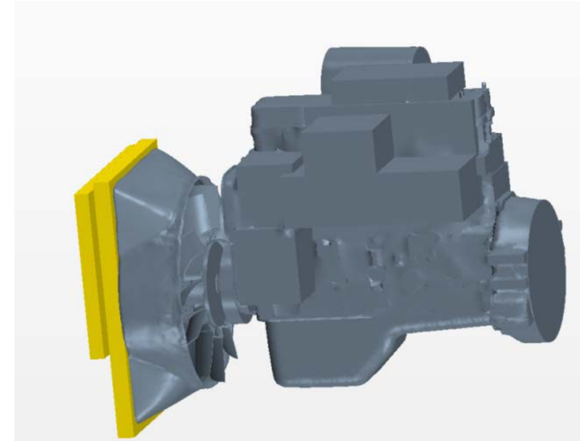
CAD model: Shroud Inner Surface



Optimized model: Shroud Inner Surface

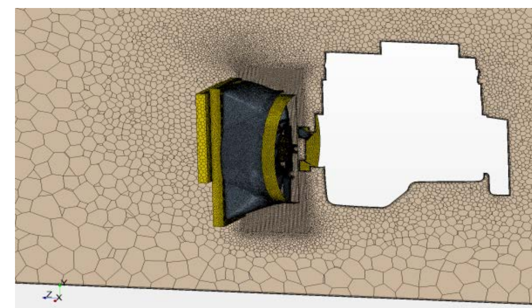


Position Sensitivities [surface optimizes @ higher position sensitivities]



Cooling Package + Engine

- ❖ *1.4% raise in cooling air flow observed with fan-shroud optimization.*
- ❖ Finding possible further improvements with StarCCM+ model, to increase the cooling flow rates.



Volume mesh across YZ-plane

Analysis conducted for:

- Heavy-duty cooling package including engine

Boundary conditions

- Computational domain Inlet Air Velocity 20kph and at ambient temperature
- Fan speed 1400 RPM

	Original	Optimized
Set point: Heat exchanger outflow [kg/s]	3.80	3.852 (~1.36% ↑)

Vegendla et al. (2016). Fan-shroud Optimization Using Adjoint Solver. SAE COMVEC-2016, Abstract accepted.

Collaborations

- Cummins Inc. Columbus, Indiana

Path Forward

- Optimization of the heat exchanger cooling air mass flow rate to further increase the thermal performance.
- Vehicle platooning underhood thermal transient analysis of varying heat rejection rate based on the fuel consumption using fan on and off condition with set point temperature.

Conclusions

- *Fan-shroud optimization:*
  - *1.4% raise in cooling air flow calculated with fan-shroud optimization.*
- Vehicle platooning underhood thermal analysis:
  - At 0 rpm fan speed; 70% lower air mass flow rates (negative performance) observed in Trailing Vehicle due to low velocity zone from Leading Vehicle. In single-lane traffic, air flow rates improved with vehicle separation distance.
  - At 1400 rpm fan speed; 30% lower air mass flow rates observed in Trailing Vehicle due to low velocity zone from Leading Vehicle. In single-lane traffic, air mass flow rates improved with vehicle separation distance.
  - In two-lane traffic, at 0 and 1400 rpm, lower air mass flow rates, but negligible compared to single-lane traffic and insignificant to the vehicle separation distance.
  - *In variable heat rejection*, the temperature rise is lower (<4^{o}C) compared to constant heat rejection (<15^{o}C) in trailing vehicle [the amount of heat rejection is less due to lower aerodynamic drag leads to lower fuel consumption and ultimately lower heat rejection from engine].
  - In two-lane traffic and constant heat rejection; the temperature raise is independent to the vehicle separation distance and it is insignificant in variable heat rejection case.

Conclusions (Cont.)

- Vehicle platooning aerodynamic drag analysis:
  - In Single-lane traffic, max fuel benefit was 24% at 30ft vehicle separation and fuel savings drops with separation distance.
  - In two-lane traffic, max fuel benefit was 7% at 150ft and fuel savings raises with separation distance.
- Medium-duty delivery truck aerodynamic drag optimization:
  - Maximum fuel benefit was 11% for Case-5 Configuration (optimized configuration)
  - The optimum curvature radius of the rounded trailer edges found to be 125 mm, with an arc length of 196.3 mm.