A Computational Fluid Dynamic Analysis of a Driver Assistive Truck Platooning Prototype with Lateral Offset

Presented 4/10/2017
Luke Humphreys
Master's Defense

Committee members:
D. Steven Nichols – Chair, Assistant Professor of Aerospace Engineering
David M. Bevly – Co-Chair, Professor of Mechanical Engineering
David E. Scarborough – Member, Assistant Professor of Aerospace Engineering

Funded via Federal Highway Administration (FHWA) contract DTFH61-13-R-00011

AUBURN UNIVERSITY

Topics Covered

- **Introduction & Motivation**
- Validation Testing
  - Ahmed body meshing and solution
  - Single-Truck Solutions
- Two-Truck Simulations and Fuel Economy Results
- Lateral Offset Results
- Crosswind Results
- Conclusions & Future Work

Introduction to Platooning

- Driver Assistive Truck Platooning (DATP) builds off of Existing Cooperative Adaptive Cruise Control (CACC) systems

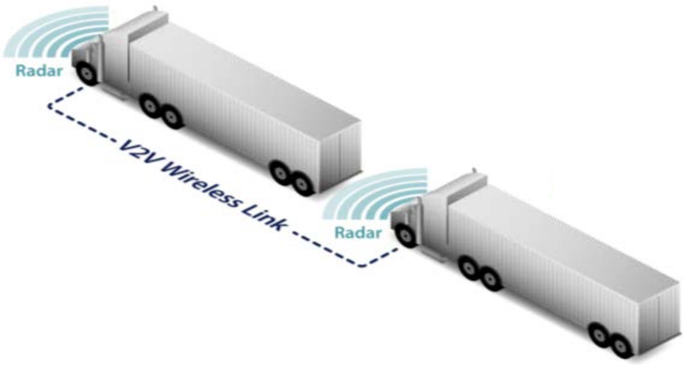


Figure 1) Overview of DATP system

- Introduction of Dedicated Short Range Communications (DSRC), D-RTK GPS systems, and an engine controller
  - Allows for even closer following by communicating the front truck's acceleration state

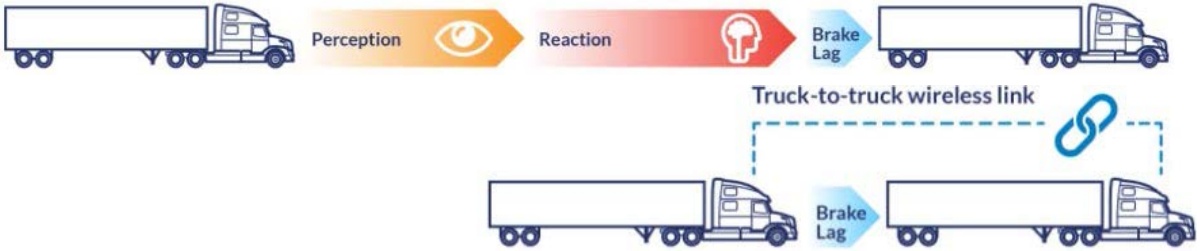


Figure 2) Demonstration of how DATP reduces response time [1]

Motivation

- Large number of fatal crashes due to heavy vehicles[2]
  - DATP Technologies represent a drastic reduction in the response time of the vehicles to an external braking event, increasing the safety of the heavy vehicles[3]

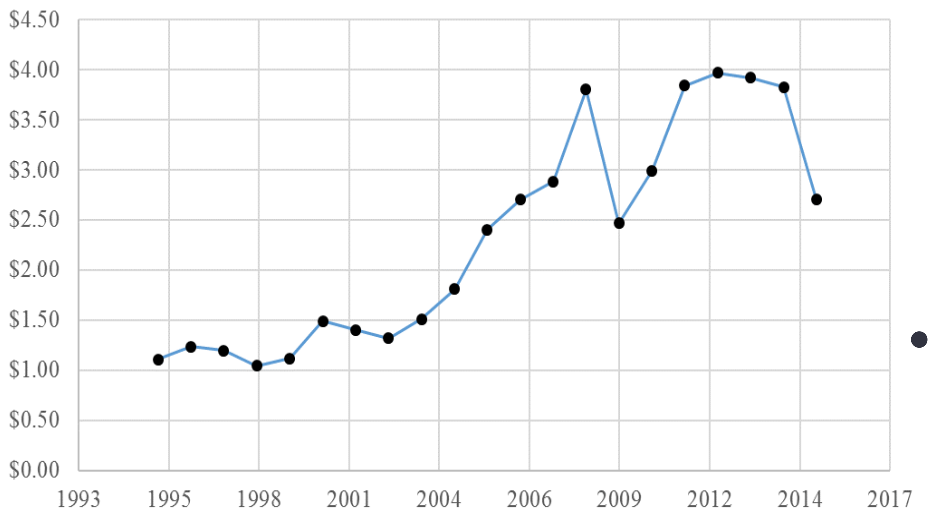


Figure 3: Annual No.2 Diesel Price for the United States [5]

- Fuel costs rising
  - Fuel represents second largest operating costs for fleets behind personnel[4]
  - Reduction in fuel consumption also reduces emissions
- Federal Highway Administration (FHWA) labeled DATP as requiring Exploratory Advanced Research (EAR)

Motivation (Cont'd)

- At highway speeds, the aerodynamic drag dominates the overall drag
  - Aerodynamic drag includes a dependence on the velocity squared

$$D = \underbrace{\frac{1}{2}\rho v^2 C_d A}_{\text{Aerodynamic Drag}} + \underbrace{F_n \mu_{rr}}_{\text{Rolling Resistance}}$$

- Large stagnation pressures on front surface of follow vehicle is diminished through close following distance – "drafting" reduces the velocity seen by the follow vehicle

Motivation (Cont'd)

- Computational Fluid Dynamics (CFD) used to determine the body forces acting on the vehicle by solving the Navier-Stokes equations
  - Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = S_m$$

  - Conservation of Momentum:

$$\frac{\partial}{\partial t}(\rho \bar{v}) + \nabla \cdot (\rho \bar{v})\bar{v} = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \bar{g} + \bar{F}$$

- No closed form analytic solution
- Allows for calculation of Drag force on the body, which can be used to determine C_d for comparison:

$$C_d = \frac{2D}{\rho_\infty v_\infty^2 A_{ref}}$$

- CFD typically more cost effective and flexible than traditional experimentation
  - More possible test cases with less expenditure, a fully resolved flow field
- ANSYS FLUENT used for CFD software
  - Good for low speed, low heat transfer flows

Topics Covered

- Introduction & Motivation
- **Validation Testing**
  - **Ahmed body meshing and solution**
  - **Single-Truck Solutions**
- Two-Truck Simulations and Fuel Economy Results
- Lateral Offset Results
- Crosswind Results
- Conclusions & Future Work

Ahmed Body Meshing

- Ahmed body chosen for validation[6]
  - Serves as a good representation of the wake structure behind a heavy vehicle
  - Well documented with wind tunnel and other traditional experimental methods for comparison
- Three mesh refinement regions identified[6]
  - Region I – Transition from far-field to near field
  - Region II – Underbody of the vehicle / body
  - Region III – Wake region

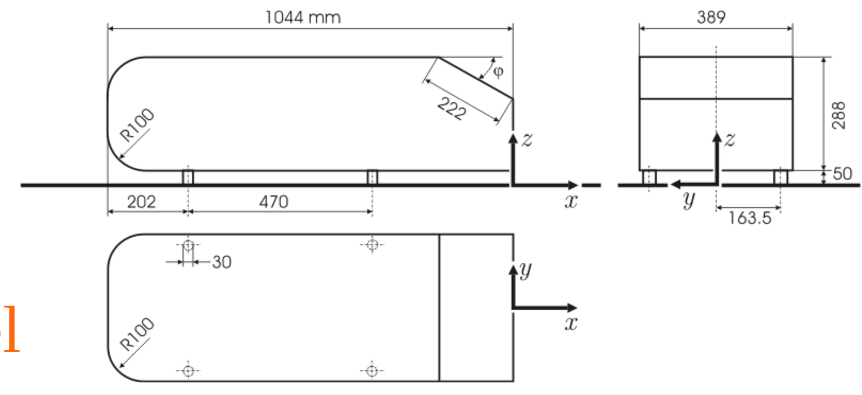


Figure 4) Ahmed body schematic[5]

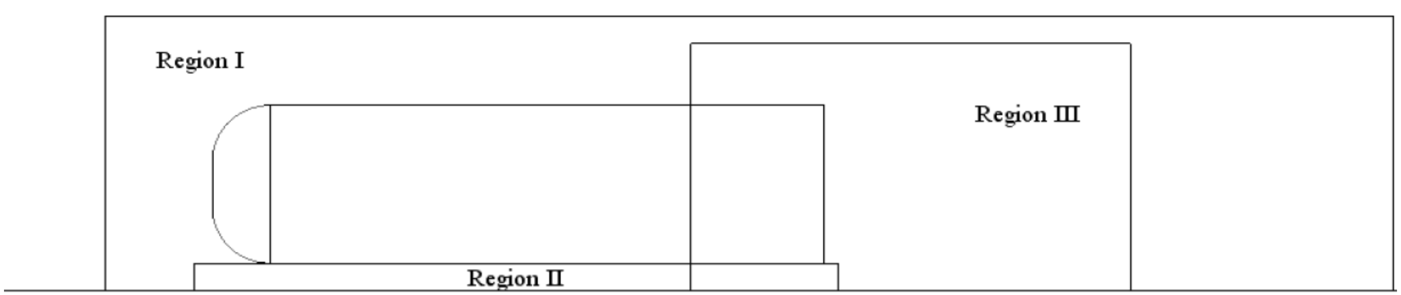


Figure 5) Diagram showing overall volume mesh refinements[6]

Ahmed Body Simulations

- Non-traditional grid independence study
  - Used as the basis for grid independence for the entirety of simulated cases
  - Single Ahmed body simulated with various minimum element sizes in each refinement region, and compared to experimental wind tunnel results

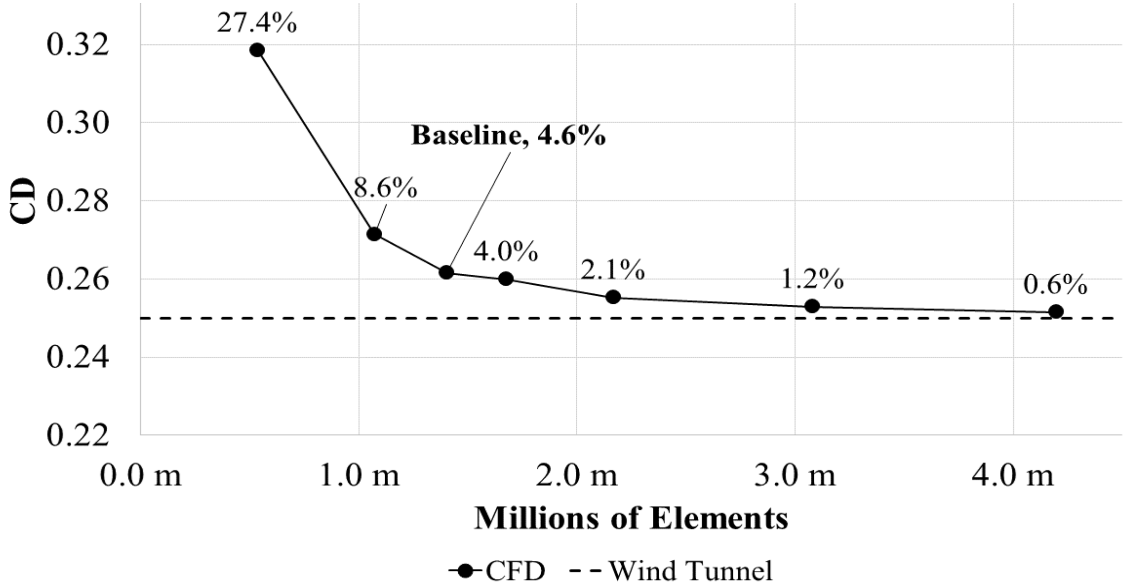


Figure 6) Error in simulation vs. elements – Ahmed body[6]

Ahmed Body Simulations

- Platooning validation – Goal to validate grid independence and turbulence model to well-researched results
  - RKE turbulence model used throughout simulations

- Compared to Pagliarella's platooned Ahmed body wind tunnel results[7]
  - Difference between the two believed to be caused by the difference in slant angle between simulated results and wind tunnel results[6]

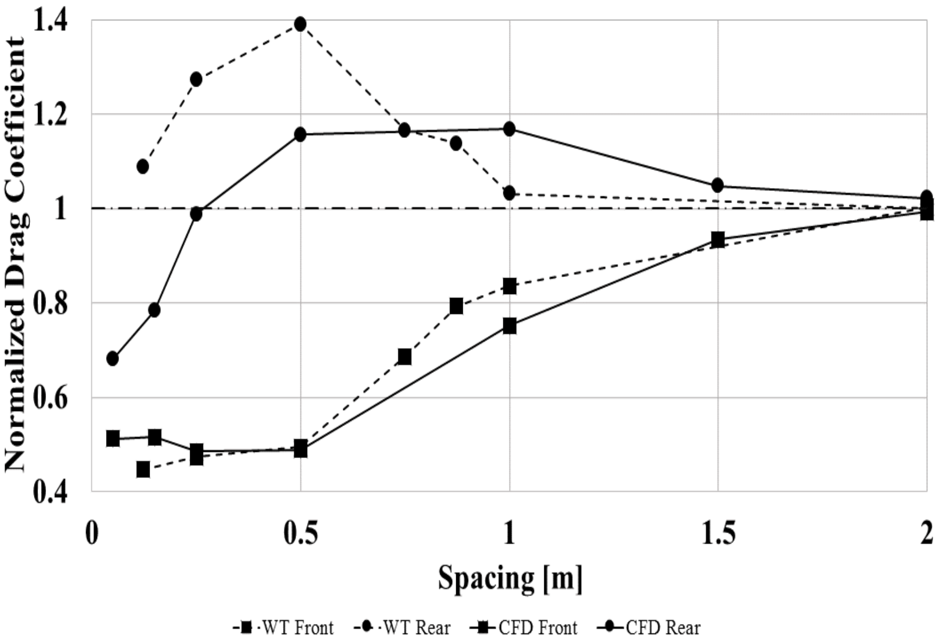


Figure X) Platooned Ahmed bodies simulation vs. wind tunnel results[6]

Single Truck Simulations

- Peterbilt 579 model chosen as basis for design
  - Two Peterbilt 579's leased for the duration of project for physical testing of DATP system

Figure 7 — Picture of Auburn 579

- 3D geometry simplified for meshing purposes
  - Any feature below a length scale removed
  - Wheels "stepped" to make flat contact with road

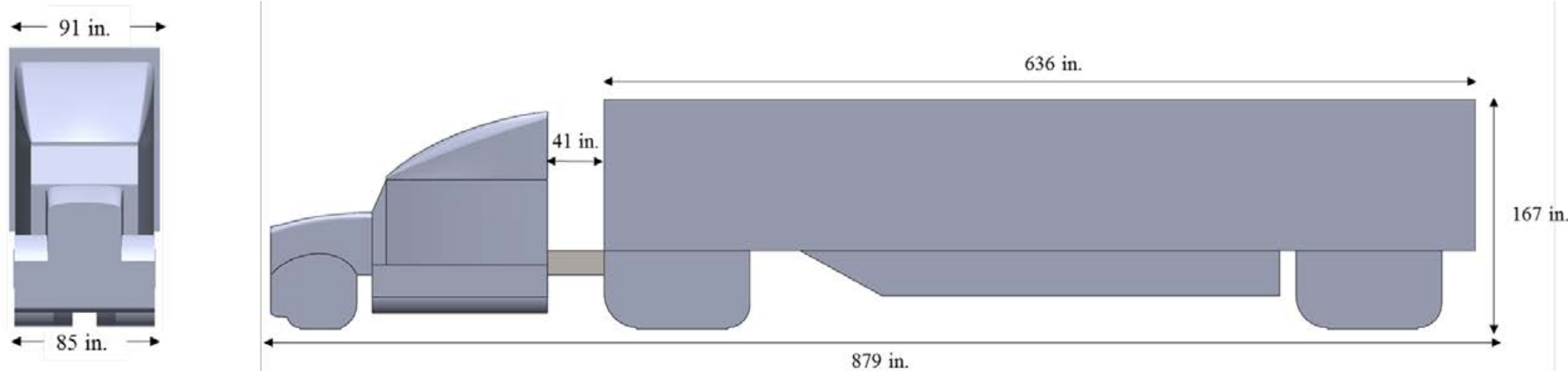


Figure 8 — 3-D Model for Peterbilt 579

Single-Truck Meshing and Simulation

- Similar Refinement Regions to Ahmed body

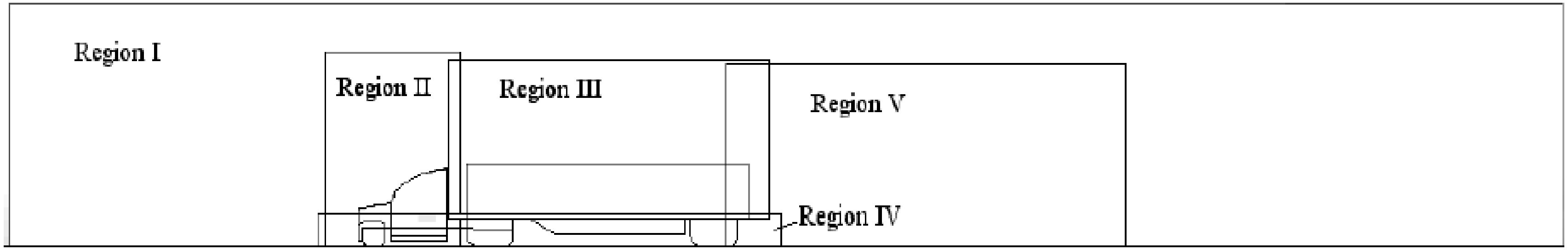


Figure 9) Diagram of volumetric refinement regions[6]

- Region I – Transition from near field to far field
- Region II – Cab region
- Region III – Trailer Region
- Region IV – Underbody Region
- Region V – Wake Region

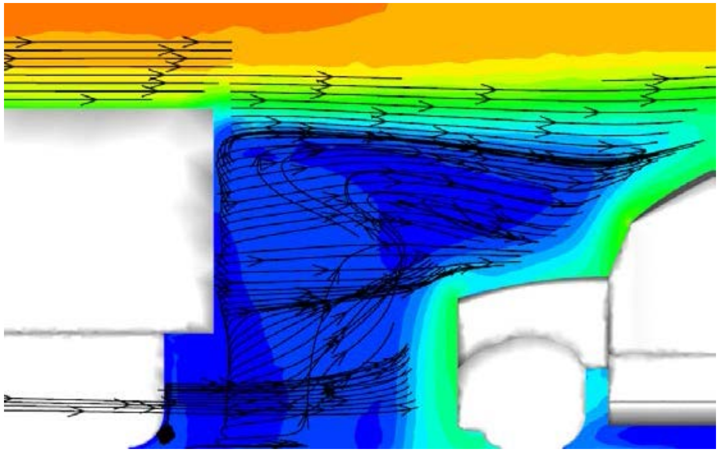


Figure 10) Depiction of streamlines

Surface Refinements

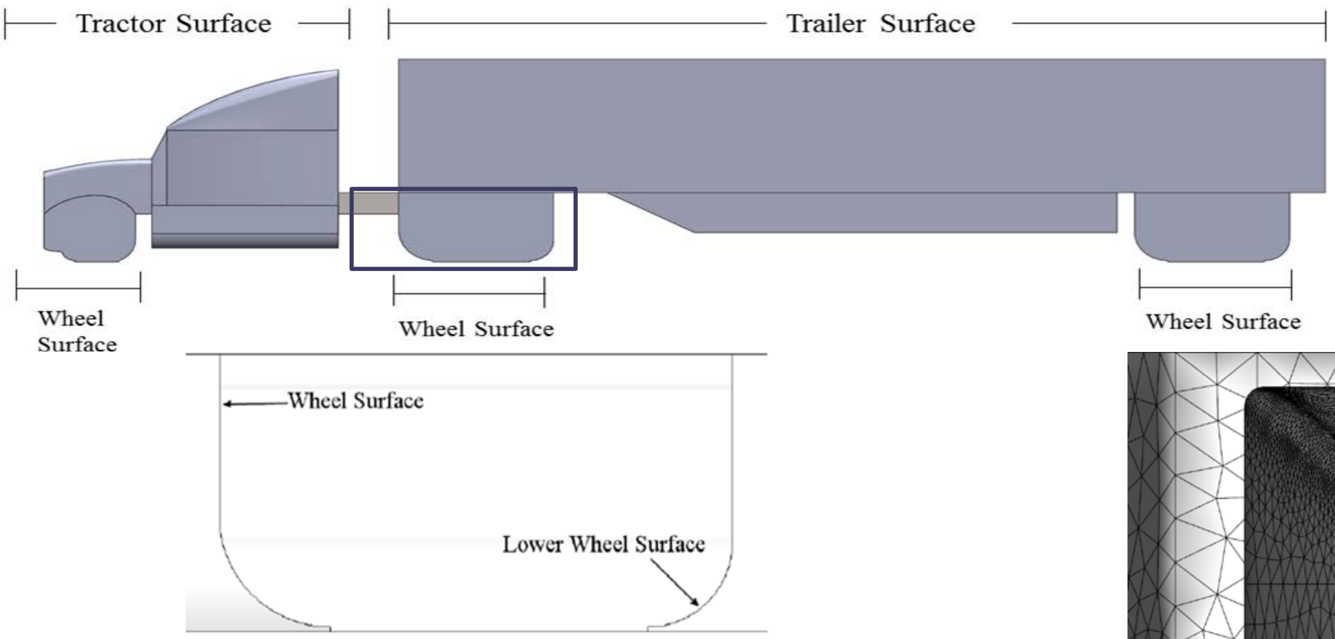


Figure 11) Diagram showing surface refinements

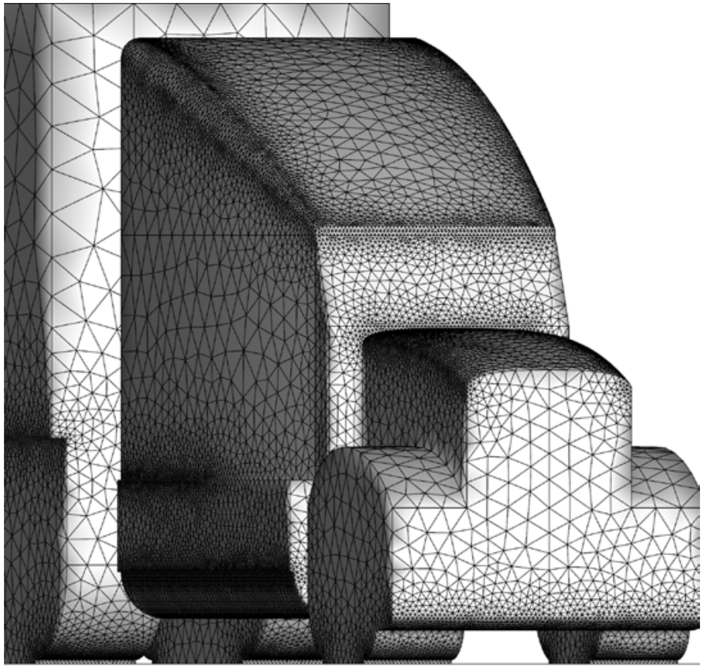


Figure 12) Example of mesh

- Additional surface refinements generated to help discretize the large areas of curvature on areas of the vehicle

Solution Parameters

- Boundary Conditions:
  - Velocity Inlet with far-field, fully developed flow assumptions
  - Pressure-Outlet with zero gauge pressure assumption
- Symmetry condition side-walls to approximate the far-field
- RKE turbulence model

Solution Methods	
Turbulence Model	Non-Transient RKE
Pressure-Velocity Coupling	Coupled
Pressure Solution Method	Standard
Momentum Solution Method	SOU
Boundary Conditions	
Velocity Magnitude Inlet Condition	29.0576 m/s (65 mph)
Pressure Outlet Condition	0 Pa Gauge Pressure
Turbulence Model Parameters	
Type	Realizable k-ε
Wall- Treatment	Non-Equilibrium Wall Treatment

Single Truck Simulation

- All simulations conducted using two simulation machines
  - 32 GB RAM, Intel 4790k using 7 cores at 4.0 GHz
  - 128 GB RAM, Dual E5620 processors using 15 cores at 2.53 GHz
- Typical solution times approximately 4.5 hours
- Yielded a coefficient of drag value of 0.52532
  - Used as baseline for comparison of drag reduction

Topics Covered

- Introduction & Motivation
- Validation Testing
  - Ahmed body meshing and solution
  - Single-Truck Solutions
- **Two-Truck Simulations and Fuel Economy Results**
- Lateral Offset Results
- Crosswind Results
- Conclusions & Future Work

Meshing and Simulation Setup

- Meshing incorporated two sets of single-truck meshing refinements
  - New dynamic definition of transition region
- Solution parameters left the same as single truck solutions

Separation Distance (ft.)	Number of Elements
10	4684539
20	4742006
30	4748209
40	4792167
50	4821888
60	4864276
70	4894380
80	4909448
90	4941851
100	4958136

Volume Refinement Region I

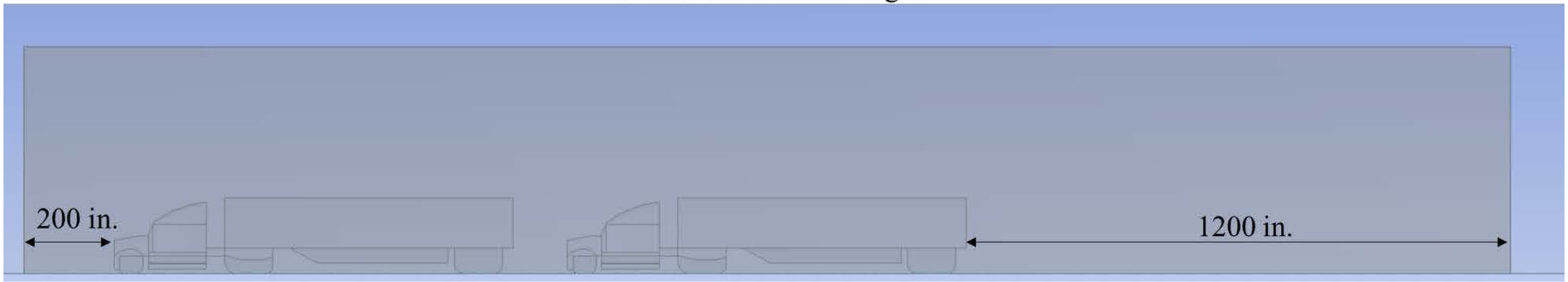


Figure 13) Dynamic definition of volume refinement region I

Two-Truck Solution

- Using same computers as single-truck, typical run-time increased to approximately 9.5-10 hours
- Drag reduction vs. separation trend developed

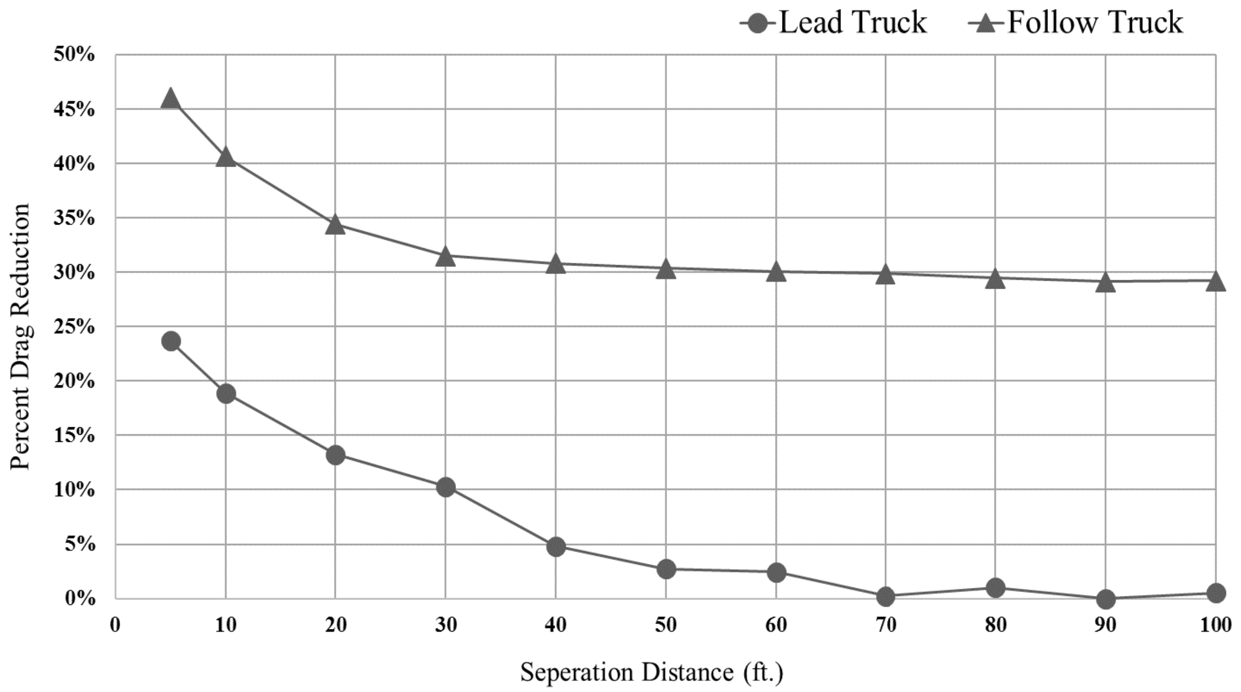


Figure 14) Two truck simulation drag results vs. separation distance

  - Monotonically increases as the separation distance diminishes

Two-Truck Results

- Mechanisms for drag reduction:
  - Lead Vehicle – Sees drag reduction due to the presence of the follow vehicle in the recirculation zone, raising the pressure on the rear surface of the trailer
  - Follow vehicle – Sees drag reduction due to a decrease in the velocity realized on the front surface of the cab, yielding a lower stagnation pressure

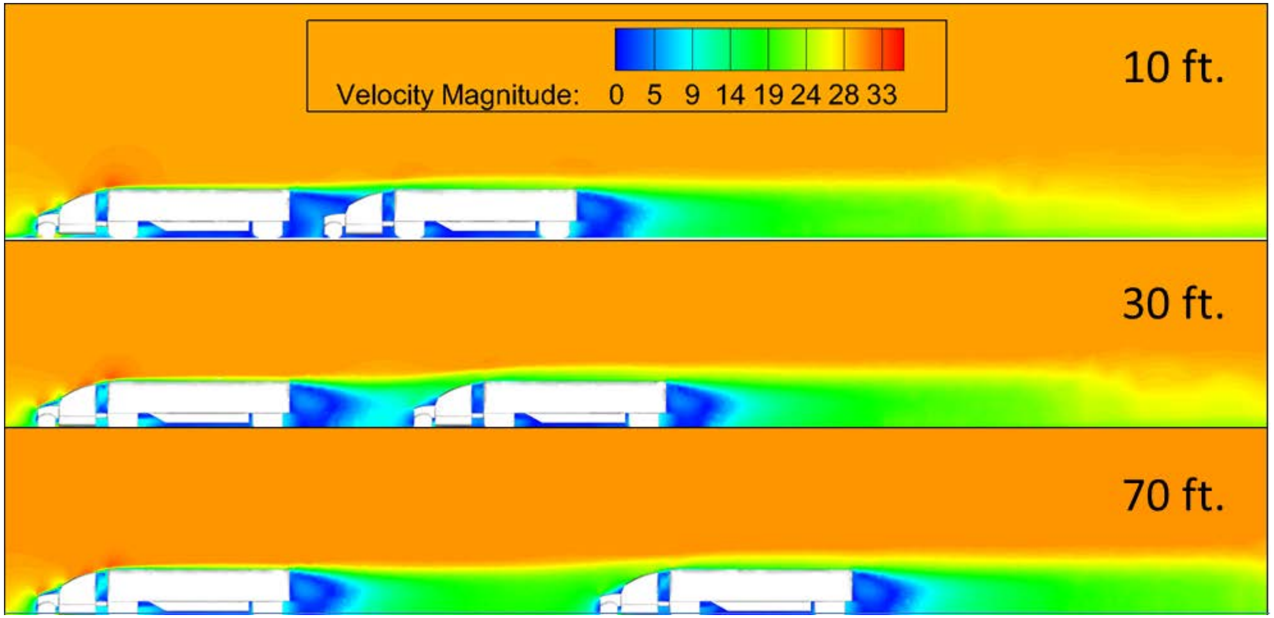


Figure 15) Comparison of drag mechanisms for lead and follow vehicles

Comparison to Previous Work

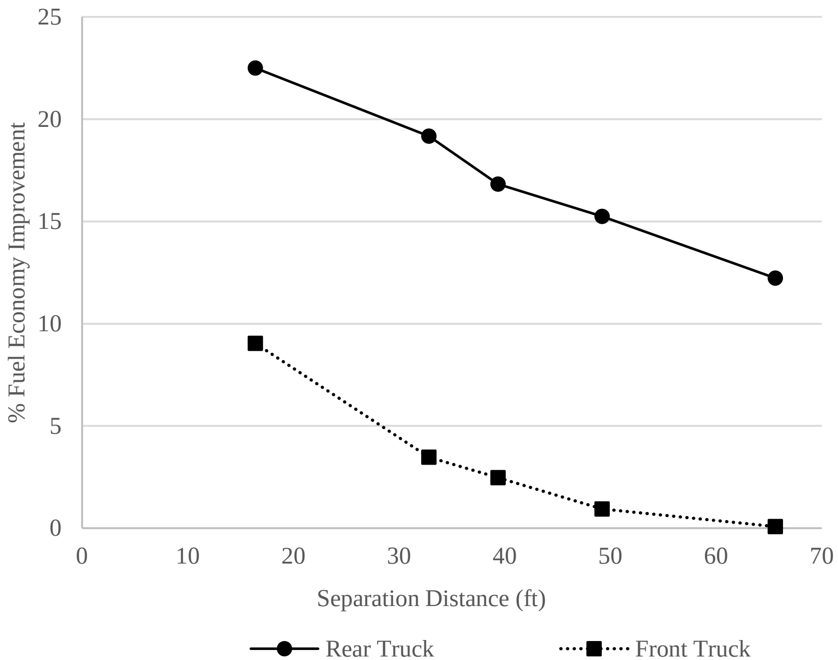


Figure 16) Energy ITS results[8]

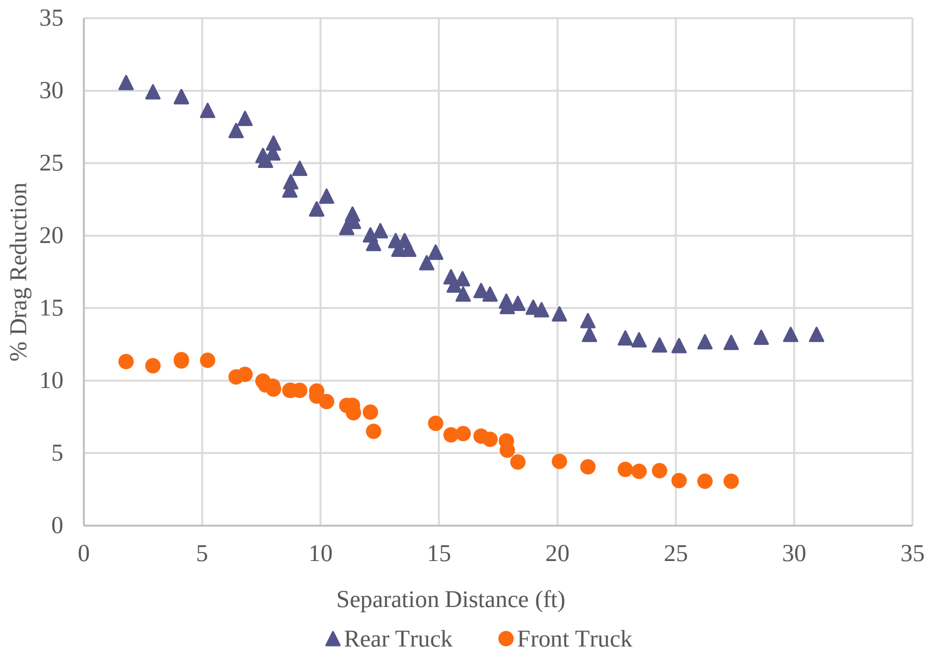


Figure 17) California PATH project wind tunnel results[9]

- Both wind tunnel results and fuel economy results show similar trends
  - ITS Results heavily caveated since they used unloaded trailers

NREL Fuel Economy Results

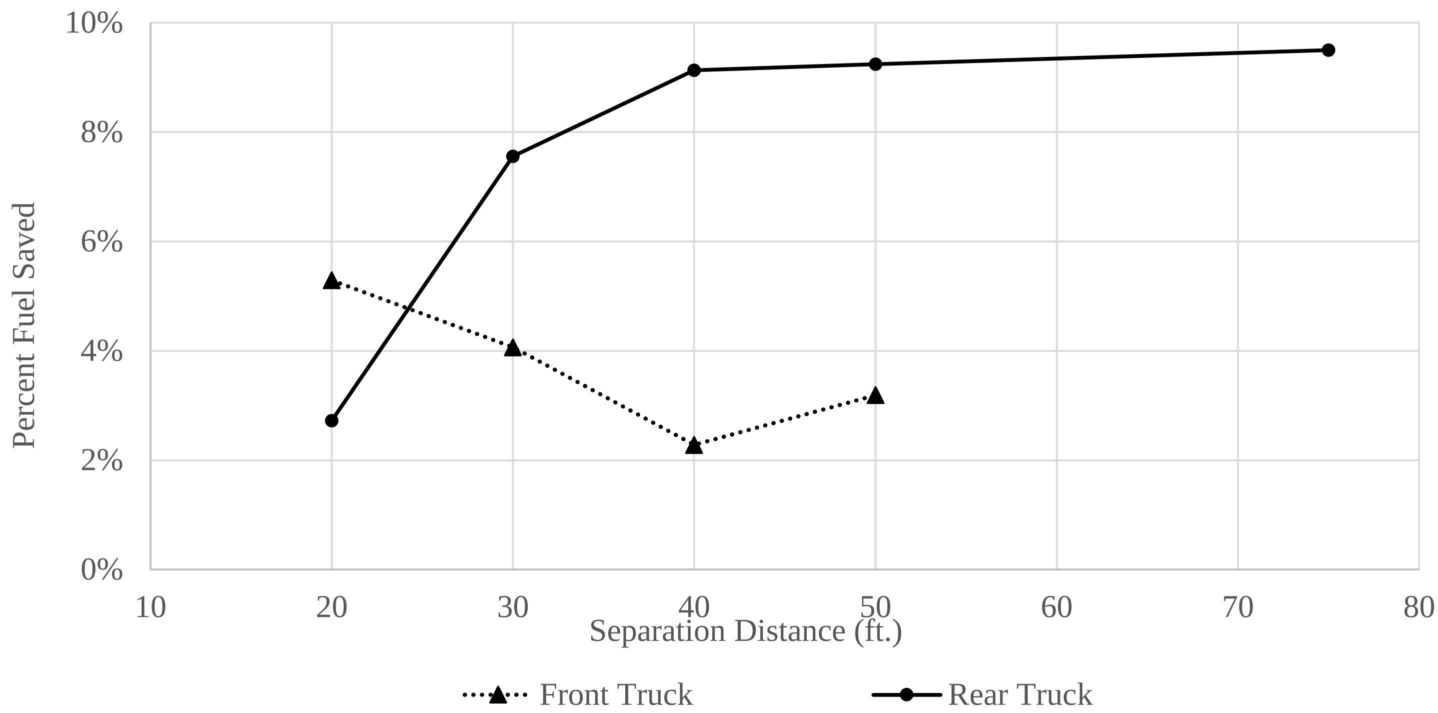
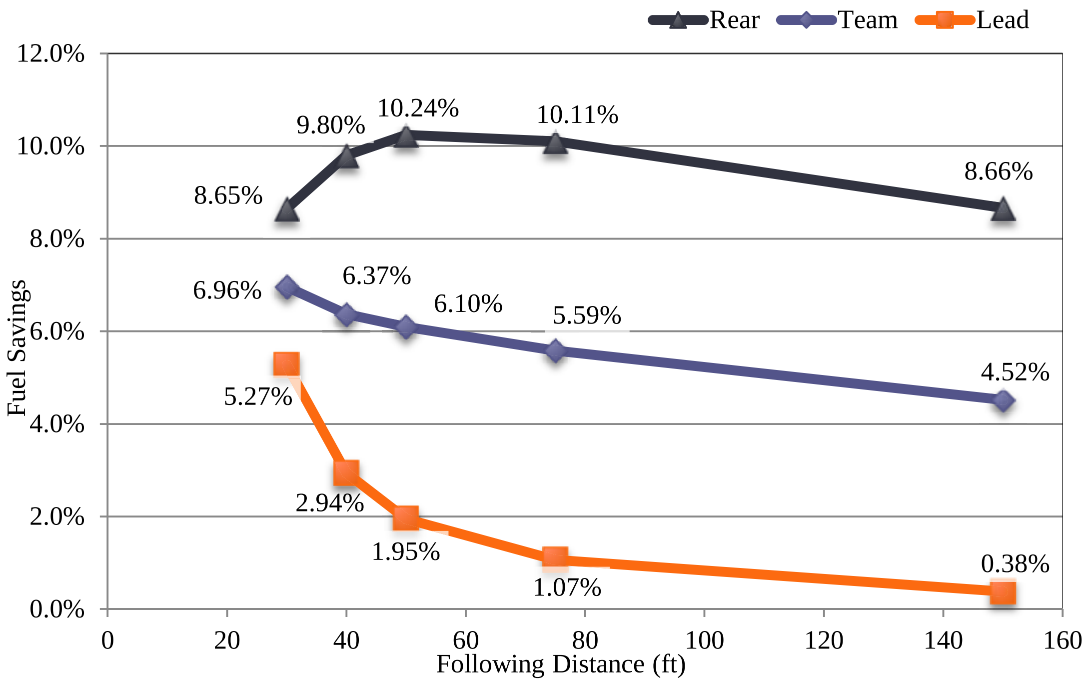


Figure 18) Selected runs from NREL study on DATP systems[10]

- Shows similar trend for selected runs
  - Decreasing fuel economy for rear truck at close separation distances
  - Several test cases had indications of high engine temperatures with engine fan duty cycle being present

Auburn Fuel Economy Results

- Trucks taken to large test track in Ohio
- SAE Type II Fuel Economy test using SAE J1321 standard



- Follow truck sees significantly different trend – Requires explanation
  - Local maximum at 50 ft. following distance
- Lead vehicle's CFD trend seems to predict fuel economy trend

Controller Dither

- There is a potential that as the separation distance diminishes, the control algorithm monitoring the distance becomes more aggressive in its control
  - This leads to controller "dither" where there are rapid changes in the acceleration of the vehicle

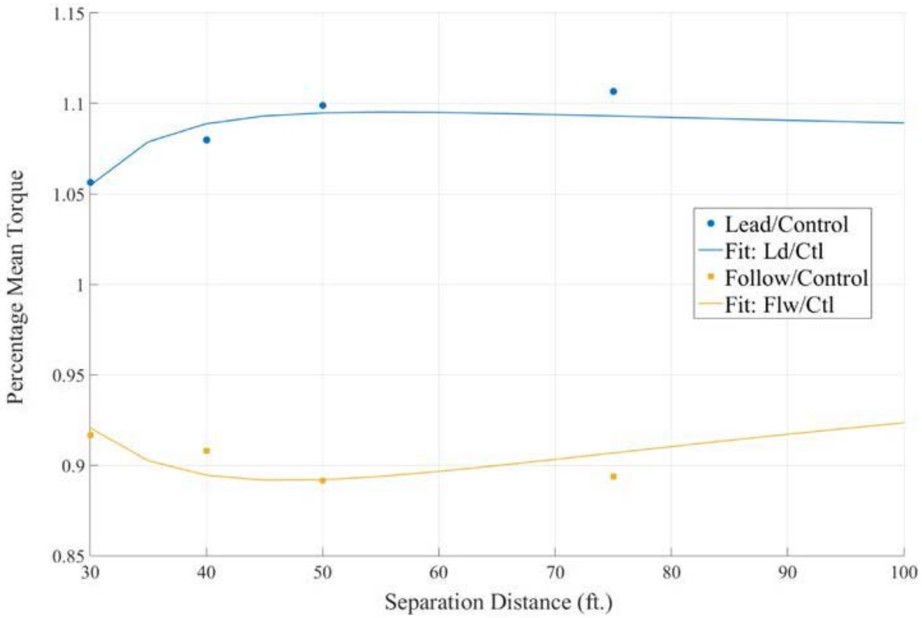


Figure 19) Mean Engine Percent Torque

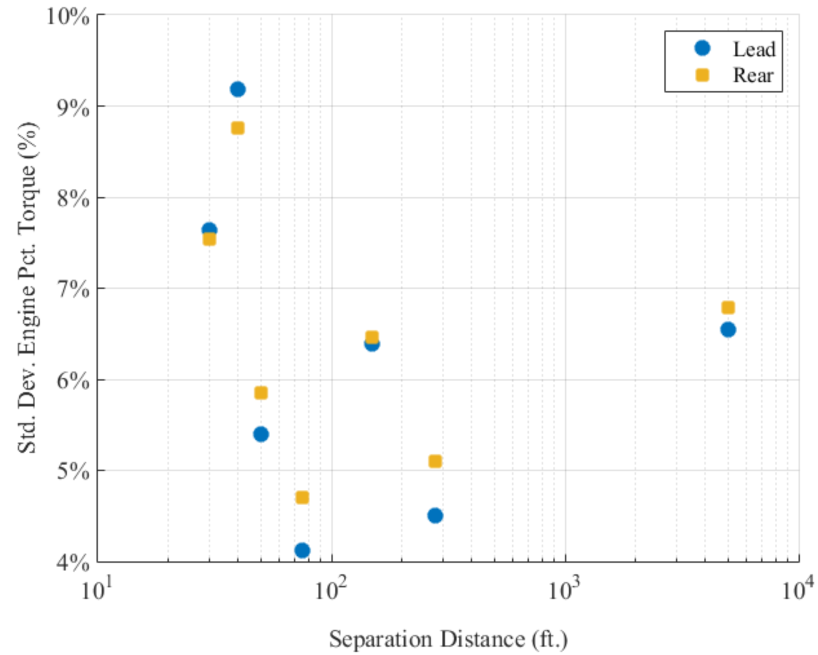


Figure 20) Standard Deviation of Engine Torque

Excess Temperature Gradients

- Similar to NREL – Possibility follow vehicle sees higher temperatures
  - Lower velocity across the engine block results in less convective heat transfer

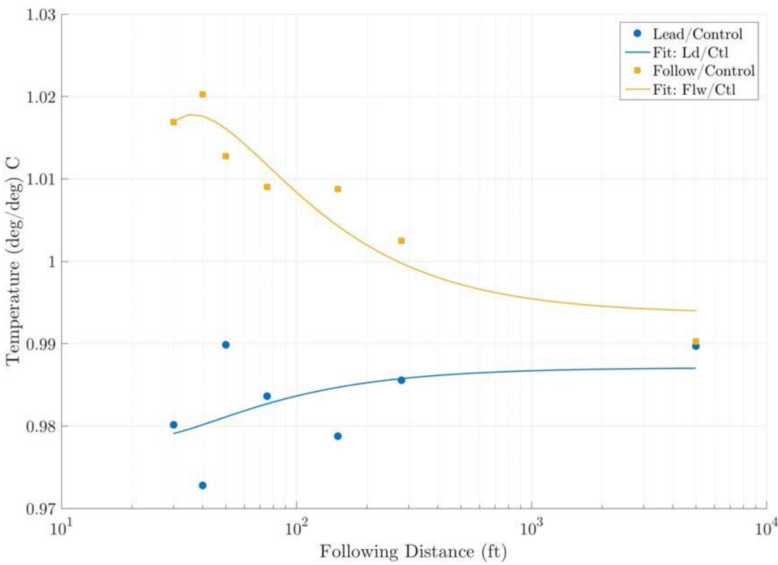


Figure 21) Normalized temperature vs. separation distance

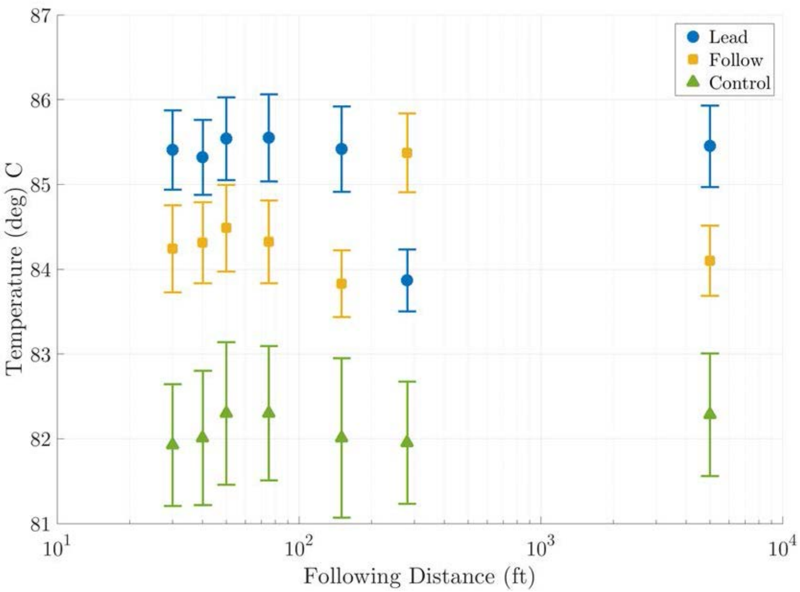


Figure 22) Ttemperature vs. separation distance

- Maximum temperature rise of approximately 2%
- Very little correlation separation distance and temperature
  - Temperature differences more likely to be related to fuel consumption or engine differences rather than lack of heat transfer

Topics Covered

- Introduction & Motivation
- Validation Testing
  - Ahmed body meshing and solution
  - Single-Truck Solutions
- Two-Truck Simulations and Fuel Economy Results
- **Lateral Offset Results**
- Crosswind Results
- Conclusions & Future Work

Lateral Offset Results

- Rear truck sees significant losses
- Marginal loss from centered case increases as the separation distance diminishes
  - At long separation distances (>40 ft.) the trend is similar, at a lower magnitude
- Losses increase as lateral offset increases

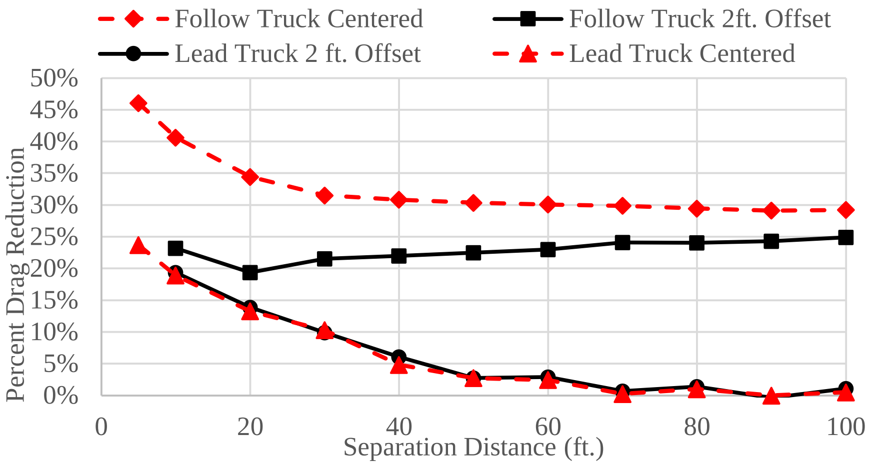


Figure 23) Comparison of 2ft. offset to centered cases

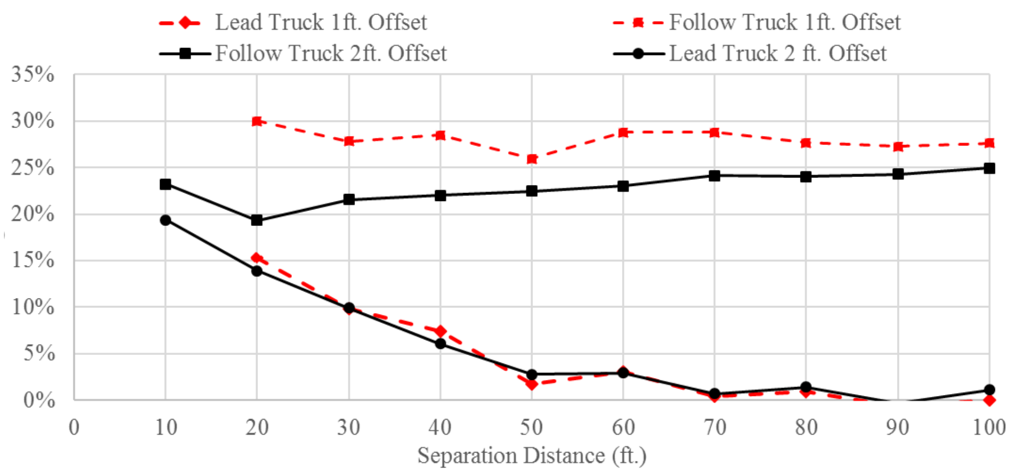


Figure 24) Comparison of 2ft. offset to 1ft. offset cases

Lateral Offset Results

- Wake behind lead vehicle is degraded
  - Region of recirculation and low velocity is now asymmetric
  - Higher velocities in the wake region

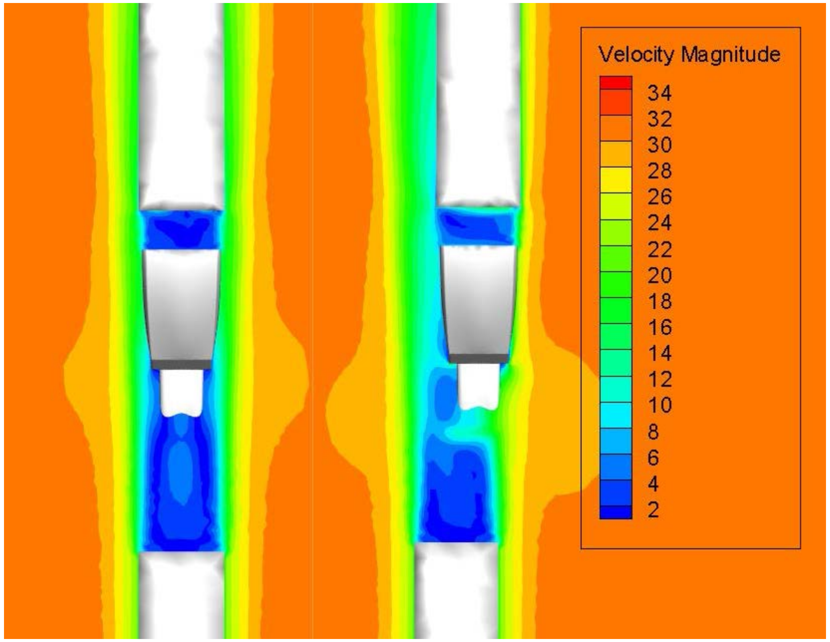


Figure 25) Comparison of wake structure for centered vs. offset flow for 10 ft. separation distance

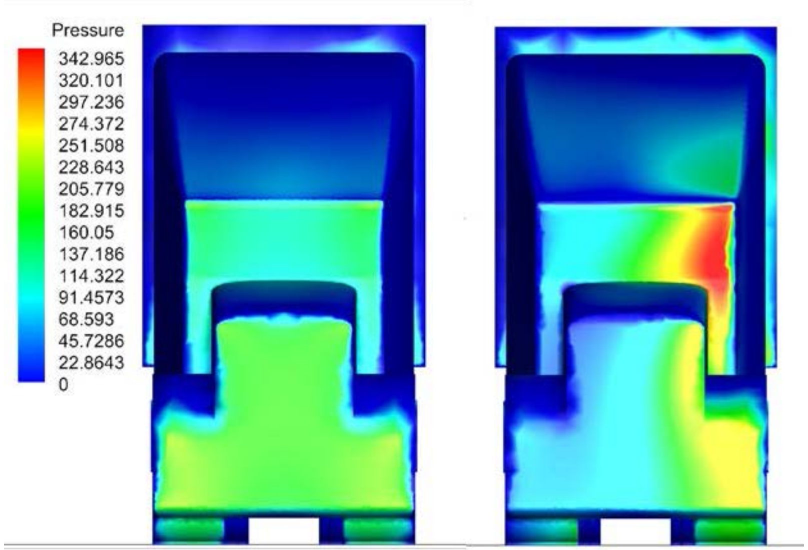


Figure 26) Pressure contour on follow vehicle front surface

- Rear truck exposed to higher velocity, free-stream flow
  - Results in much higher pressure on the front surface of the follow vehicle
- Side force induced tends to attempt to re-center the follow vehicle

Small Lateral Offset Results

- Performance losses not restricted to large offsets
  - Even at an 8 inch offset, the follow vehicle sees diminished drag reduction at close separation distances

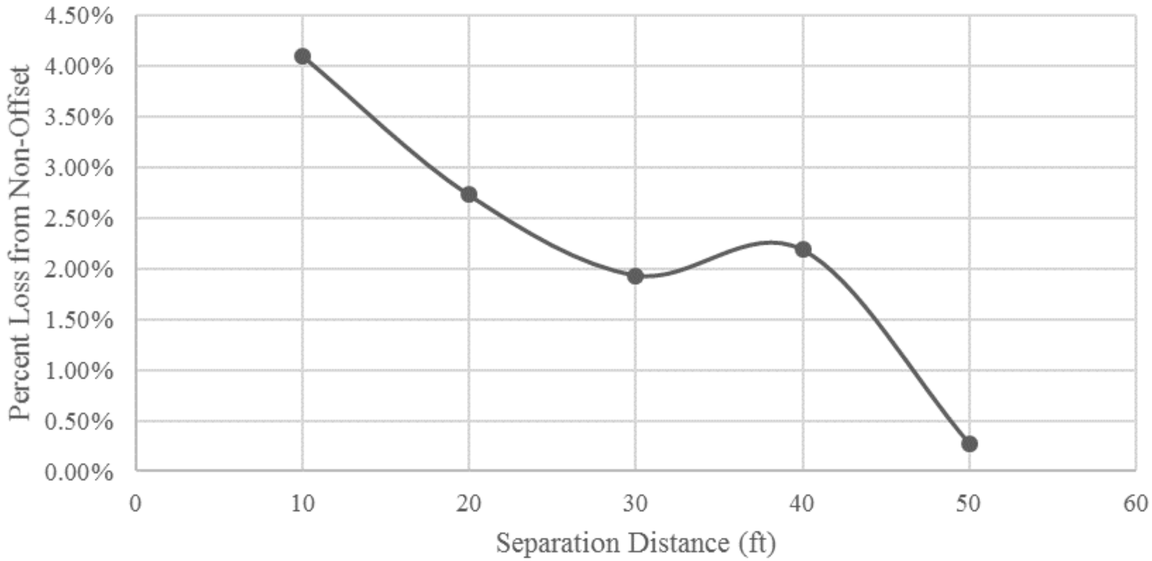


Figure 27) Percent loss from centered case for follow vehicle in two truck platoon for close separation distances

- Effect of small offsets diminishes rapidly
  - While 4% loss from centered gains may not seem significant, the large number of miles travelled by heavy vehicles makes it more significant

Topics Covered

- Introduction & Motivation
- Validation Testing
  - Ahmed body meshing and solution
  - Single-Truck Solutions
- Two-Truck Simulations and Fuel Economy Results
- Lateral Offset Results
- **Crosswind Results**
- Conclusions & Future Work

Crosswind Simulation Setup

- Same as two-truck, however one sidewall was changed to a velocity-inlet
- Both velocity-inlets now component rather than normal definition
  - Using component definitions prevents unphysical pressure gradients where inlets meet
  - 65 mph travelling speed, 5mph crosswind
- Opposite wall now simulated as a pressure- outlet
- Bounding volume extended in lateral direction to accommodate boundary conditions

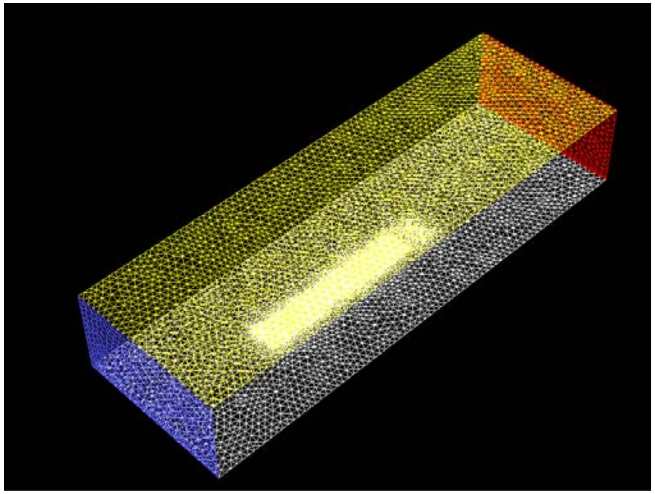


Figure 28) Bounding box in FLUENT setup

Crosswind Results

- New single truck simulation used as baseline
  - Single Peterbilt 579, 5mph crosswind – Cd value of 0.62591
    - Significantly higher than no crosswind
- New centered drag reduction vs. separation distance trend developed with single crosswind truck as normalization
  - Two-truck 579 platoon, centered, with 5mph crosswind

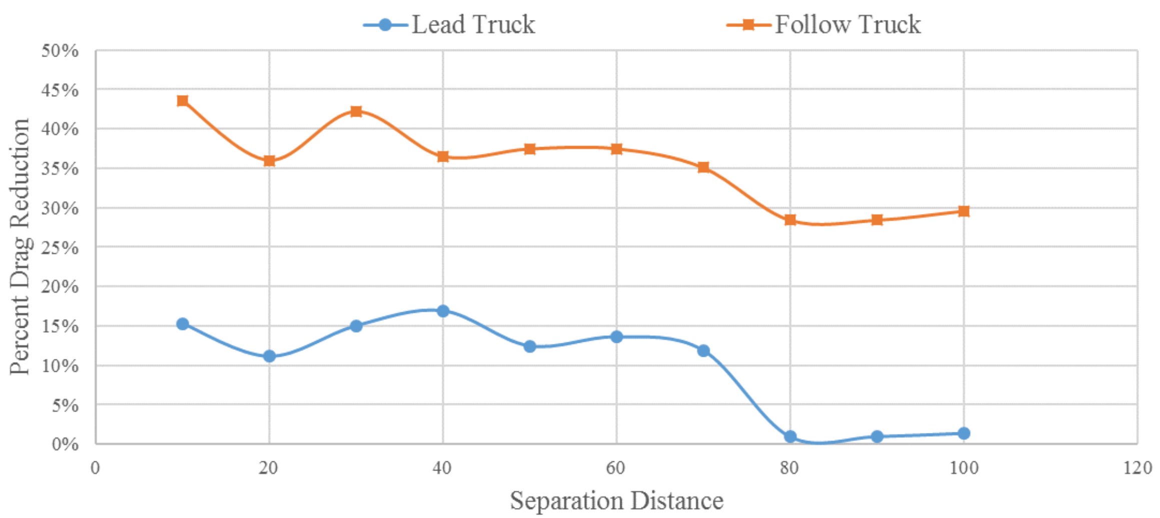


Figure 29) Centered crosswind results for various separation distances

Crosswind with Lateral Offset Results

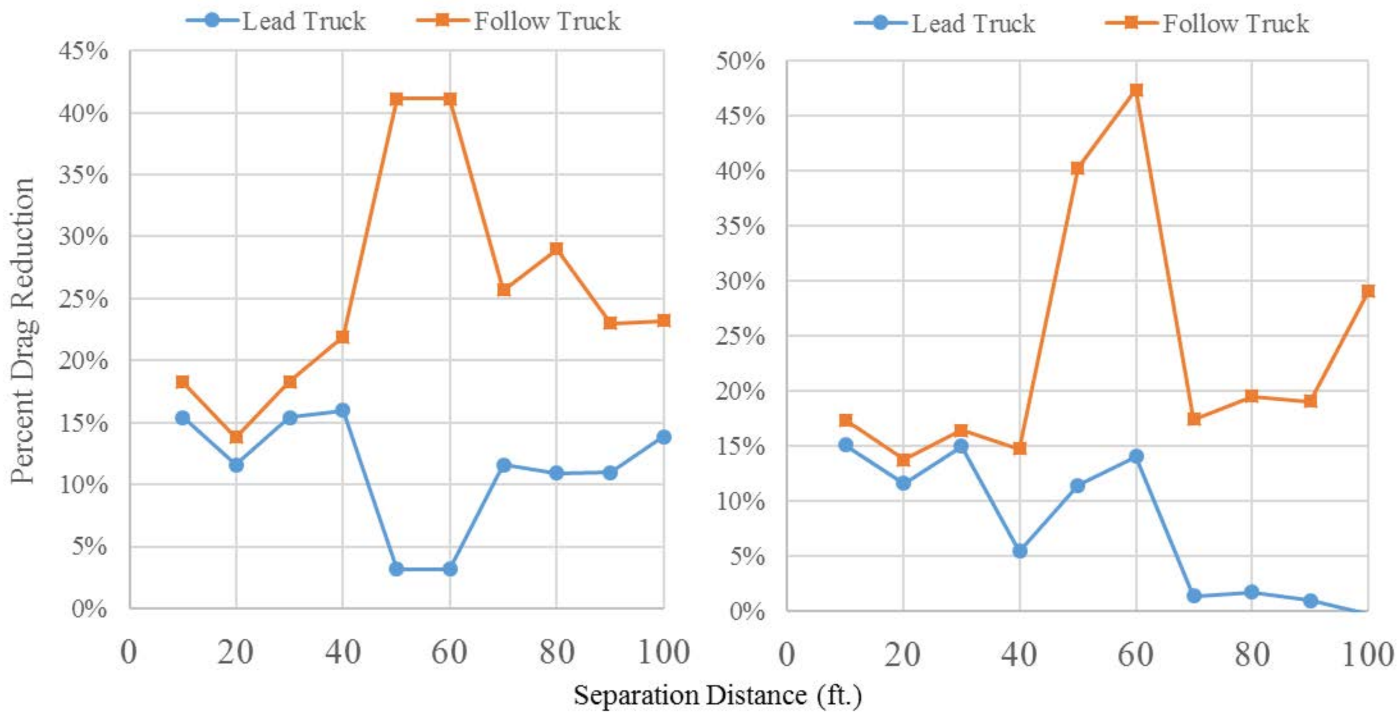
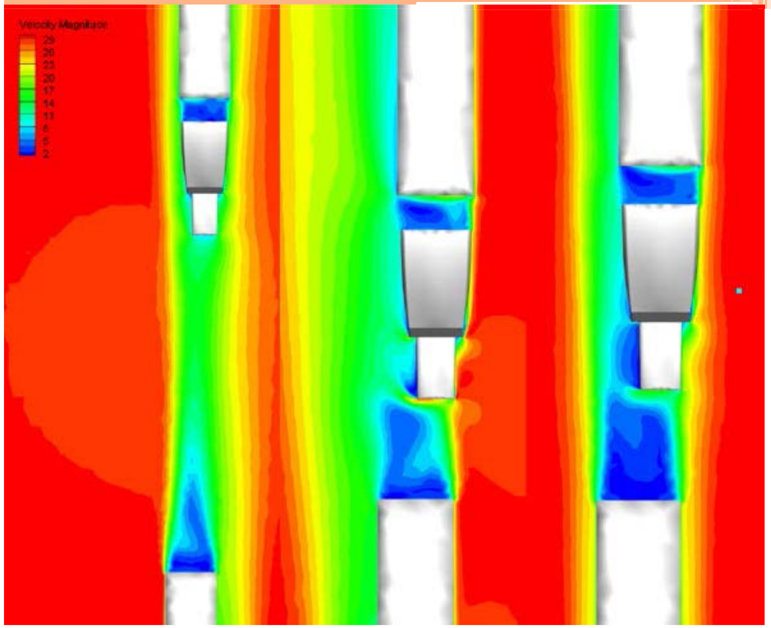


Figure 30) Percent drag reduction for crosswind in direction of offset results (left) and in opposite direction of offset (right)

- Overall, the trend is significantly more scattered
  - Very likely due to steady-state solution
    - Vortex shedding and crosswind are inherently time-dependent phenomenon, and are typically asymmetric in both time and space
- Comparatively much lower than the centered crosswind cases again
- Large rise in drag reduction at 50-60 ft.

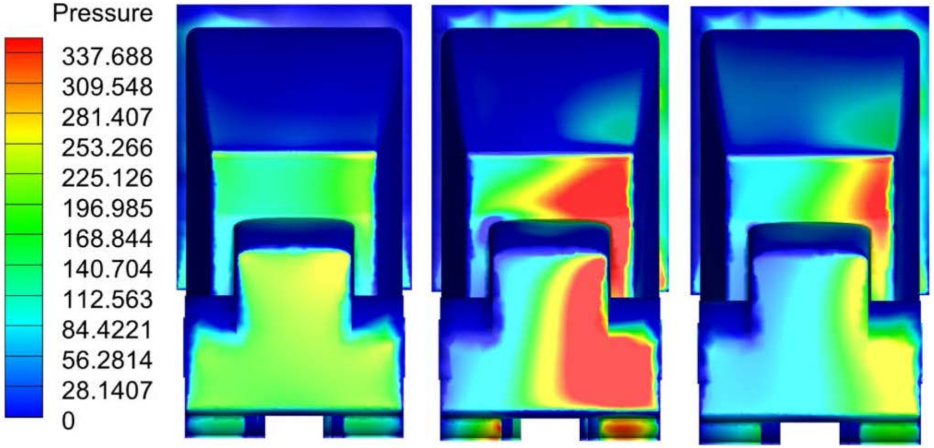
Crosswind Results

- Crosswind interacts with wake development of lead vehicle
  - Even higher velocities in wake region
  - Low pressure recirculation zone shifted away from crosswind



60 ft, 5mph, Opposite 10 ft, 5mph 10 ft

Figure 31) Velocity profile for various test cases



50 ft. 5mph 10 ft. 5mph 10 ft.

Figure 32) Comparison of pressure contour on follow vehicle front surface for various offset test cases

- At close separation distances – crosswind amplifies lateral offset's effect, causing
  - At 40-50 ft. there is an interesting increase in drag reduction on follow vehicle
    - Potentially due to resonance between vortex shedding and crosswind

Topics Covered

- Introduction & Motivation
- Validation Testing
  - Ahmed body meshing and solution
  - Single-Truck Solutions
- Two-Truck Simulations and Fuel Economy Results
- Lateral Offset Results
- Crosswind Results
- **Conclusions & Future Work**

Conclusions

- DATP systems predict a large gain in fuel economy for heavy vehicles
  - Both CFD and fuel economy results seem to corroborate this claim
- Lateral offset presents a potential reduction in the efficiency of DATP systems
  - Lateral control may enhance the efficacy of DATP systems if lateral offset presents as a problem during normal operation
- Crosswind effects may couple with lateral offset to further degrade the performance of the vehicles

Future Work

- Extend the analysis with more detailed turbulence models
  - LES or DES models, potentially even *k*-*w* models are more accurate in a wider range of scenarios
- Extend the analysis to fully time-resolved simulations
  - Many of the dynamic effects, such as vortex shedding, are asymmetrical in both space and time, resulting in potentially improper simulations when modeled steady-state
- Vary different geometric parameters
  - Trailer-gap has a large impact on the aerodynamic performance of vehicles
  - DATP systems may enhance or negate the impact of various geometric features, i.e. trailer gap, boat-tails, side-skirts.

Questions?

Citations

- [1] Peloton Technology, "*How It Works*", URL: http://peloton-tech.com/how-it-works/, Accessed 4/10/2017
- [2] Federal Motor Carrier Safety Administration (FMCSA) *"Large Truck and Bus Crash Facts (2015)"* URL: https://www.fmcsa.dot.gov/safety/data-and-statistics/large-truck-and-bus-crash-facts-2015, Accessed: 4/10/2017
- [3] Agogino, A., Goebel, K., and Alag, S., "Intelligent sensor validation and sensor fusion for reliability and safety enhancement in vehicle control," *Mech. Eng.* (November):1–56, 1995
- [4] Torrey IV, W.F. (ATRI) and Murray, D. (ATRI), "An Analysis of the Operational Costs of Trucking: A 2014 Update," 36, URL : http://www.atri-online.org/wp-content/uploads/2014/09/ATRI-Operational-Costs-of-Trucking-2014-FINAL.pdf, 2014.
- [5] Ahmed, S., Ramm, G., and Faltin, G., "Some Salient Features Of The Time-Averaged Ground Vehicle Wake," *SAE Tech. Pap.* 840300, 1984
- [6] Watts, A., "Computational Characterization of Drag Reduction for Platooning Heavy Vehicles," 2015
- [7] Pagliarella, R., Watkins, S., and Tempia, A., "Aerodynamic Performance of Vehicles in Platoons: The Influence of Backlight Angles," *SAE Tech. Pap.*, 2007
- [8] Yoshida, J., Sugimachi, T., Fukao, Y., and Suzuki, Y., "Autonomous Driving of a Truck Based on Path following Control," *10th Int. Symposium on Advanced Vehicle Control*, 2010
- [9] Browand, F., McArthur, J., and Radovich, C., "Fuel Saving Achieved in the Field Test of Two Tandem Trucks," (June), 2004, doi:UCB-ITS-PRR-2004-20
- [10] Lammert, M.P., Duran, A., Diez, J., Burton, K., and Nicholson, A., "Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass," *SAE Int. J.* 14, 2014, doi:10.4271/2014-01-2438