Lateral Offset and Its Potential Effects on Platooning

Prepared for 2016 SAE World Congress

Luke Humphreys – Auburn University
Joshua Batterson, David Bevly – Auburn University
Ray Schubert - Peloton Technology

04/12/2016

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Previous Results
- Lateral Offset
- Conclusions

Motivation: Improved Fuel Economy

- 2012 Transportation industry:
  - $1.33 Trillion
  - 8.5% national GDP
  - Extremely competitive
- Crude oil is a finite commodity
  - Highly variable market
- Improved fuel economy
  - Allows marketplace advantage
  - Complies with DOT / EPA regulations [2]
- If the FedEx fleet (25,000 tractors) improved gas mileage by 1% it would generate $20 million USD savings per year

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE OF ENGINEERING

Motivation

- Previously unfeasible due to human physiological limitations
  - Driver reaction time
  - Limited visibility
  - 80,000 lb loaded trailer requires ≈ 400-500 ft stopping distance
- Cooperative Adaptive Cruise Control (CACC) removes barriers
  - Offers longitudinal vehicle automation via throttle / braking control
  - Driver still controls lateral movement (steering)
- Research system being tested by Auburn-led FHWA project team
  - Grant awarded as part of the Exploratory Advanced Research Program under the Federal Highway Administration
  - Private sector team members providing trucks and research version of DATP platooning system
  - Partners include: Auburn University, Peloton Technology, Meritor Wabco, Peterbilt, and the American Transportation Research Institute

Motivation

- Why CFD studies?
  - Physical testing prohibitively expensive
    - Wind Tunnel testing requires large, expensive models to eliminate wall-effects
    - Direct observation of coefficient of drag requires large number of expensive sensors and testing facilities
  - Flexibility – Multiple scenarios
    - 2-4 Truck platoons, multiple geometries, various offsets, etc.

CACC

- Sensor and display package installed on existing tractor
- Automatically monitors and adjusts distance between vehicles via Dedicated Short Range Communication
- System recognition and response time orders of magnitude lower than human senses

Figure 1. Heavy Vehicle Platoon [1]

Driver-Assistive Truck Platooning (DATP)

- Platooning
  - A group of two or more aligned vehicles in a leader-follower configuration
  - Utilizes fuzed GPS-Radar for range measurement, DSRC for V2V communications
- Takes advantage of a phenomenon referred to as “drafting”

Figure 2: Auburn Peterbilt 579’s in Platoon

Topics Covered

- Introduction & Motivation
- Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Meshing
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Previous Results
- Lateral Offset
- Conclusions

Simplified Car Body

- First vehicle modeled, colloquially known as “Ahmed body,” after 1984 wind tunnel test [3]
- Designed to represent a simplified, generic bluff body
- 0° rear slant used to more closely represent tractor-trailer
- Used as validation case for one and two body simulations

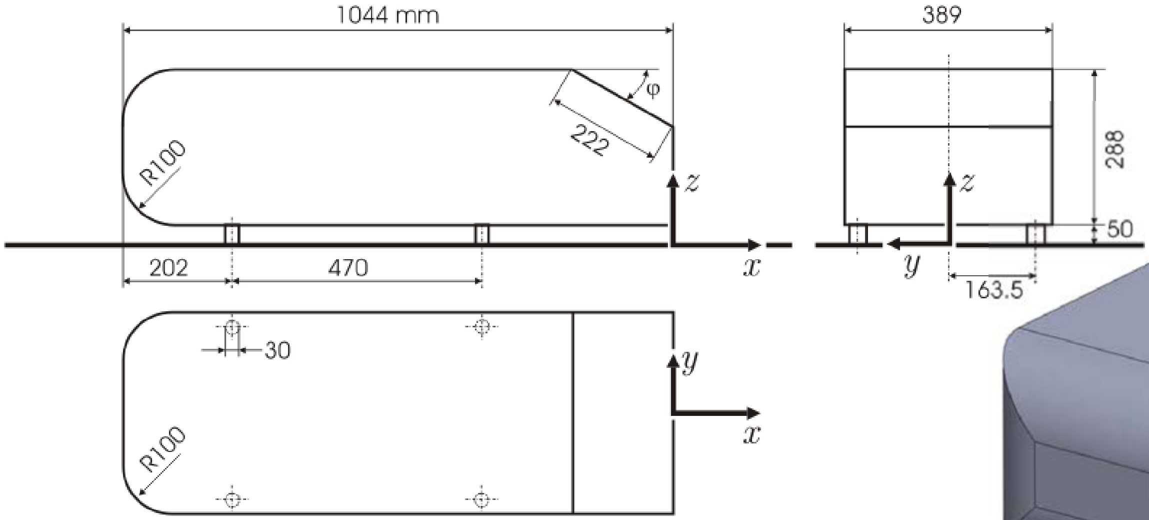


Figure 3. Ahmed body reference dimensions [6]

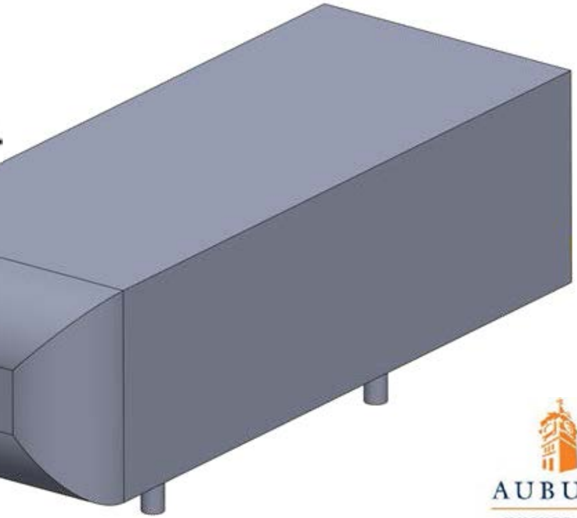


Figure 4. Ahmed Body Isometric View

Turbulence Modeling

- Turbulence is a phenomenon that occurs every day on a variety of scales
- Difficult to model
  - Irregular and chaotic in nature
  - Highly nonlinear
  - Adds several variables to the Navier-Stokes equations
- Two models considered herein:
  - Realizable k-ε
  - Detached Eddy Simulation

Turbulence Modeling Flaws

- RKE cannot return to laminar flow once turbulent
- Does not terminate wake
- Poor prediction at large distances
- LES Based models more accurate
- RKE still valid from 0-300ft
- Indicates RKE performs poorly in low TKE situations
- Consistent with knowledge about RKE

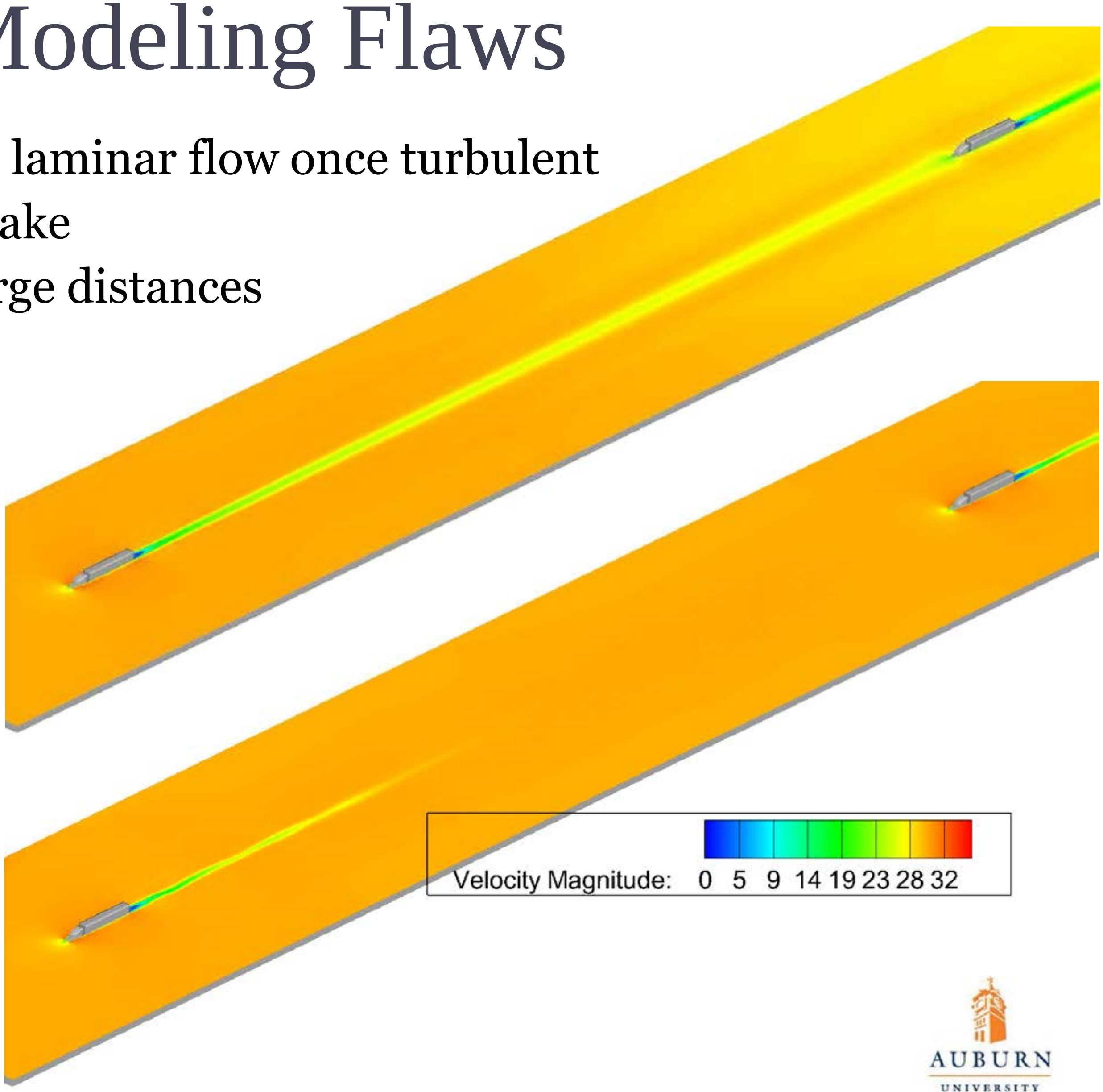


Figure 13. Two vehicle 1000 ft spacing: RKE (top) vs. DES (bottom)

Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Previous Results
- Lateral Offset
- Conclusions

AUBURN
UNIVERSITY
Samuel Ginn
College of Engineering

Mesh Size Variation

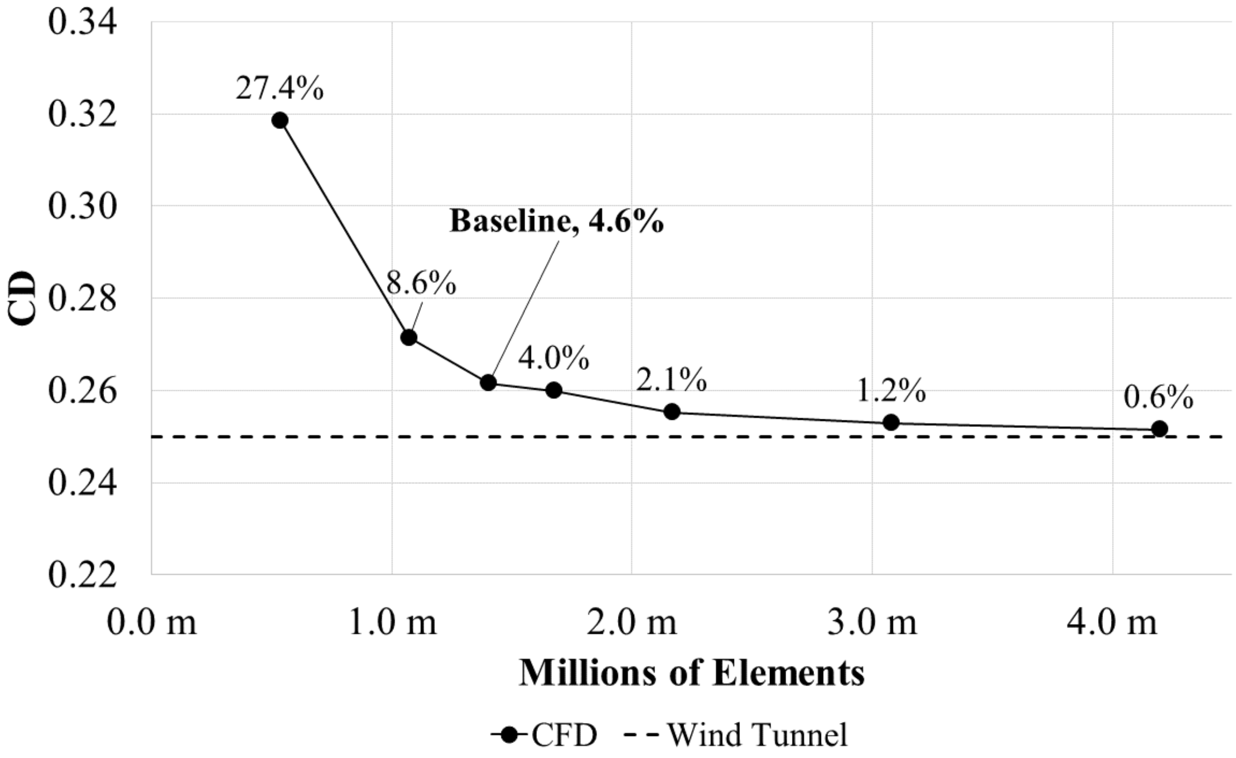


Figure 5. Error vs. mesh size variation

- Asymptotically approaches wind tunnel data
- Highly nonlinear error reduction
- Mesh size largely dependent on local refinement
  - 1mm reduction in body surface element resulted in 1.1M more elements

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

Simulation vs. Wind Tunnel

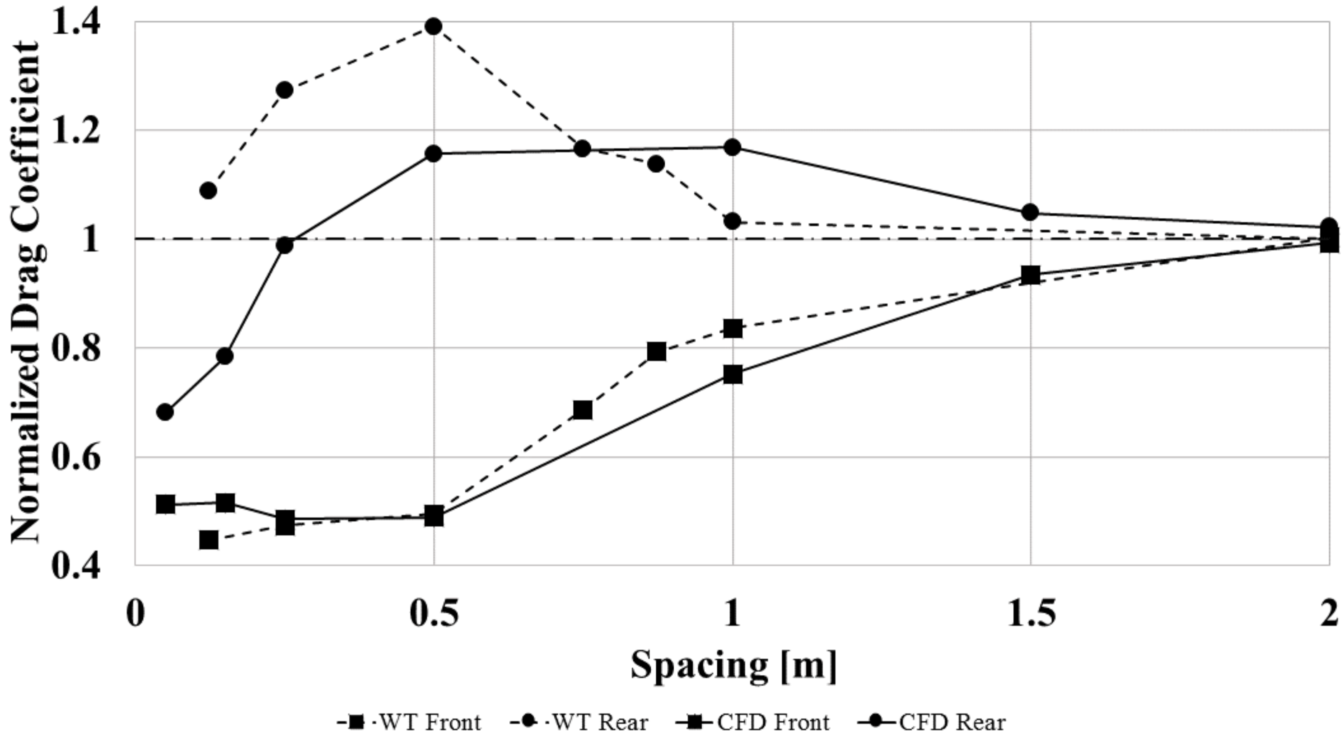


Figure 7. Two Ahmed CFD vs. Wind Tunnel [8]

- Trend captured
- Validates simulation increase prediction
- Difference due to rear slant variation (25°)
  - Shows tighter wake increases rear body drag
  - Analogous to aerotail on a trailer

Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Previous Results
- Lateral Offset
- Conclusions

Single Vehicle Simulations

- Performed to gain a baseline drag force
- Allowed detailed surface analysis to determine primary contributing drag surfaces
- 53 ft trailer simulated – Industry Standard

Figure 8. P579 [4]

Peterbilt 579 CAD Model

- Peterbilt 379 simplified CAD modified to create Peterbilt 579 model
    - Sloped hood
    - Aerodynamic fairing
- Primary test model
    - For future comparison to experimental data

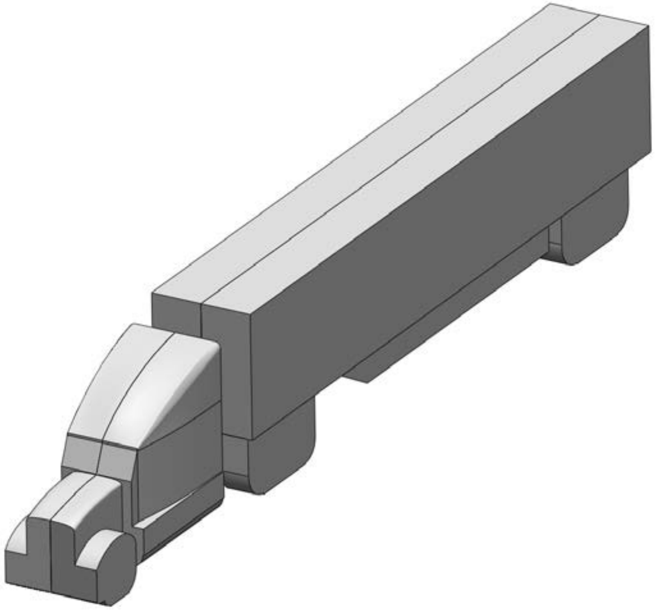


Figure 9. P579 CAD

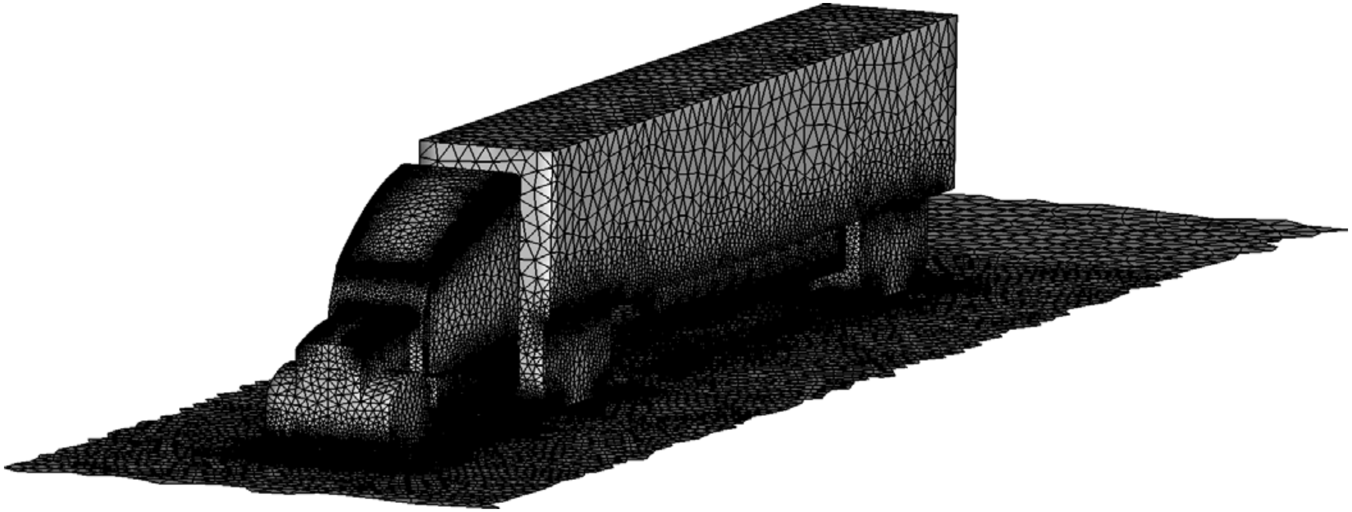
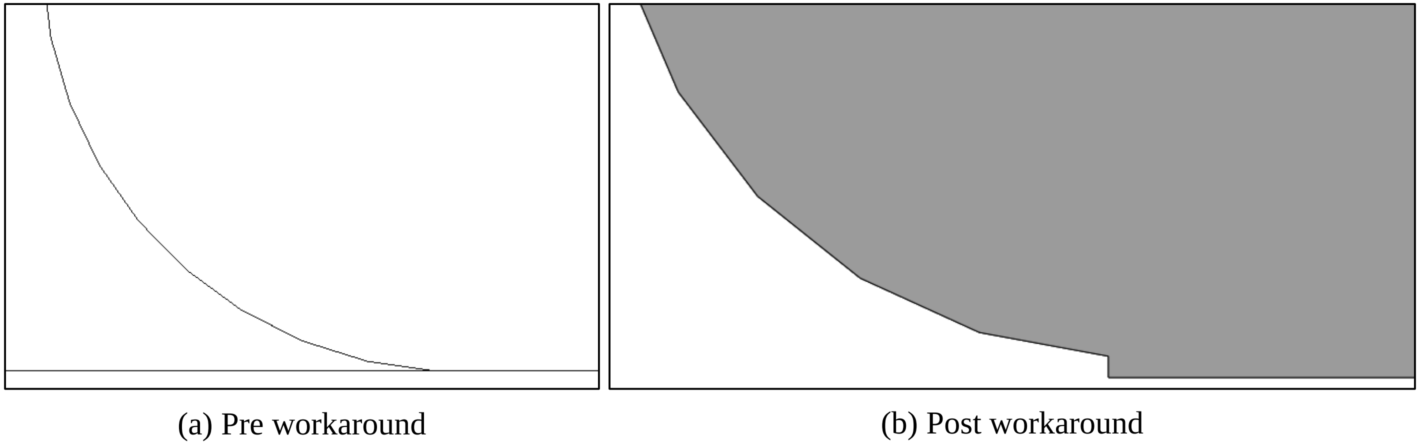


Figure 10. P579 Surface Mesh

Workaround Features

- Due to complex nature of tractor geometry additional modifications were required
- Nonphysical regions that cannot be discretized exist in mesh
  - Sharp curves that meet with near tangent surfaces
  - Meshing algorithm attempts to create a volume mesh on a point, results in error
- Example
  - Intersection of wheel curve and flat ground
  - Add 1” buffer region so there is a finite end to air region


(a) Pre workaround

(b) Post workaround

Figure 11. Workaround feature example

Two Vehicle

- Primary focus of study
  - Developed drag vs. vehicle spacing trend
- Peterbilt 579 geometry
- Simulated at many distances
  - Small separation: < 100 ft between vehicles
  - Large separation: > 100 ft between vehicles

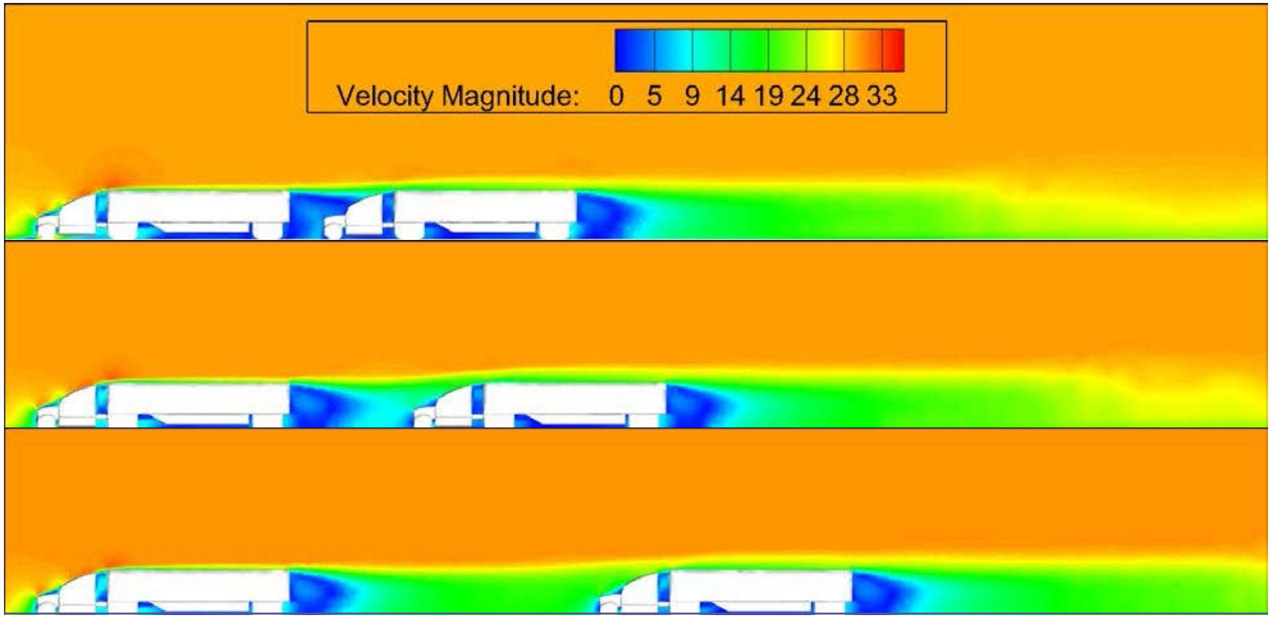


Figure 12. Two vehicle velocity profile, top to bottom: 10 ft, 36 ft, 90 ft spacing

Two Vehicle Simulation Results

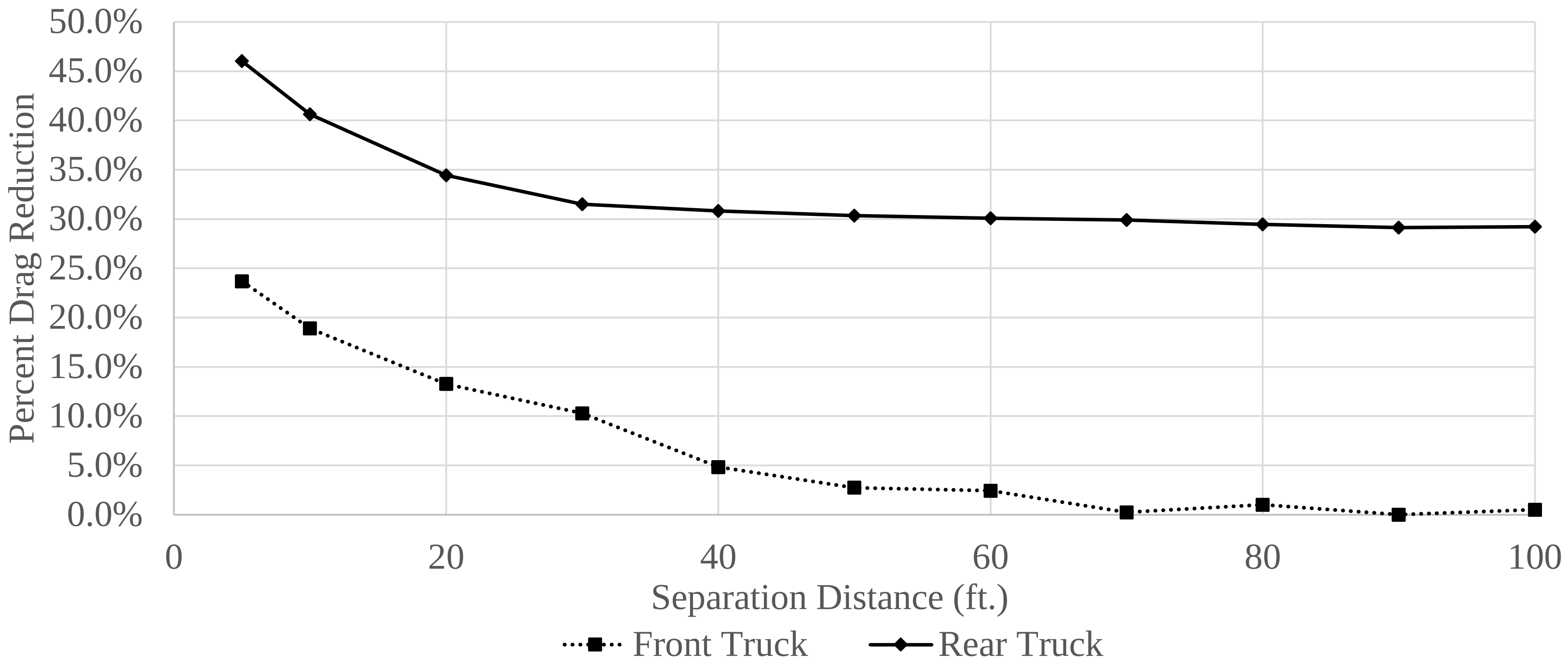


Figure 14. Two vehicle drag vs spacing

- Important Takeaways
  - Drag reduction monotomically improves as separation distance diminishes
  - Drag reduction corresponds to fuel-consumption
  - Rear truck sees benefit even at relatively high distances
  - Front truck benefit diminishes rapidly

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

Previous Experimental Results

- PATH Project – Wind Tunnel Results

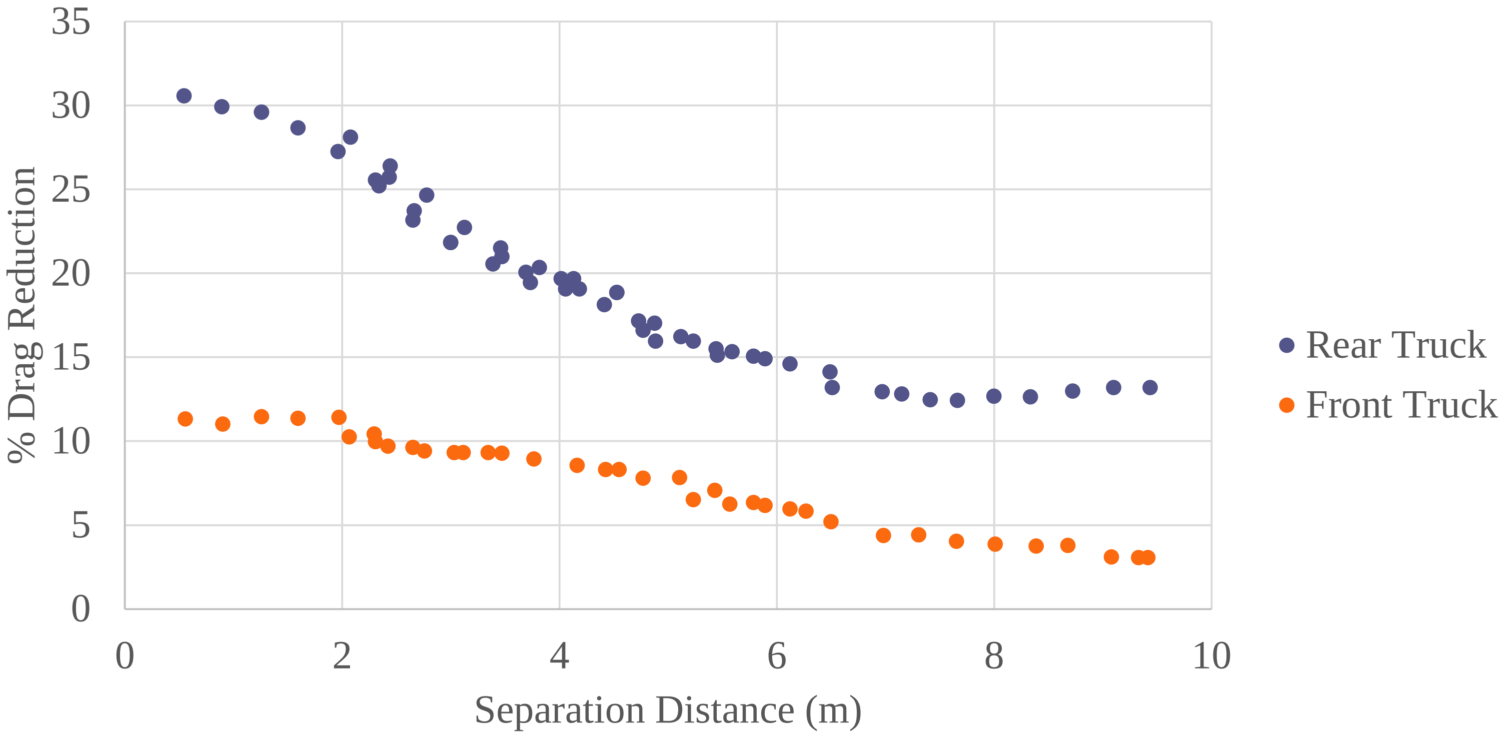


Figure 15: Path Project Wind Tunnel Results [5]

- Follows similar overall trend to simulated data

Energy ITS Results

- Energy ITS – Fuel Economy Results

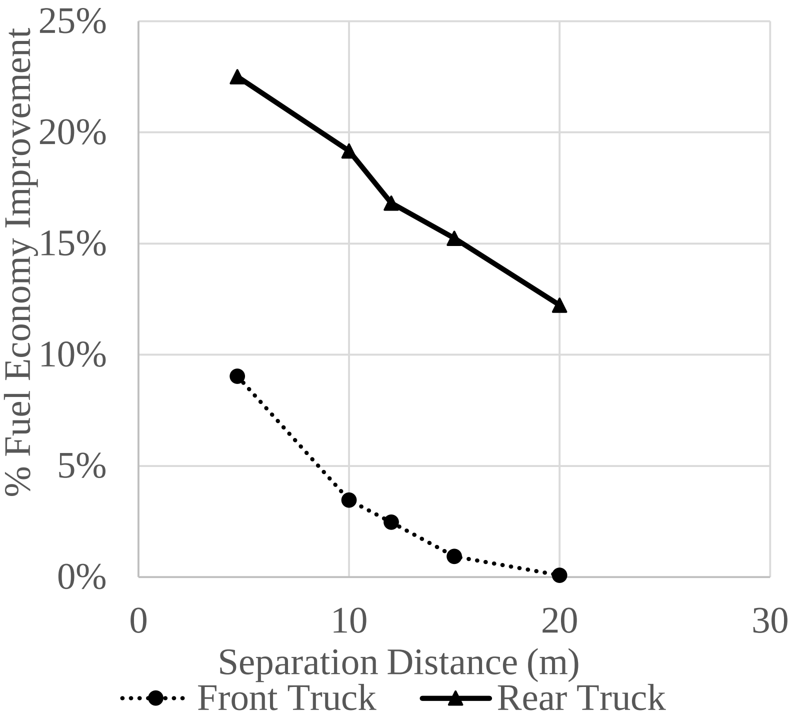


Figure 16: Energy ITS Fuel Economy Results [6]

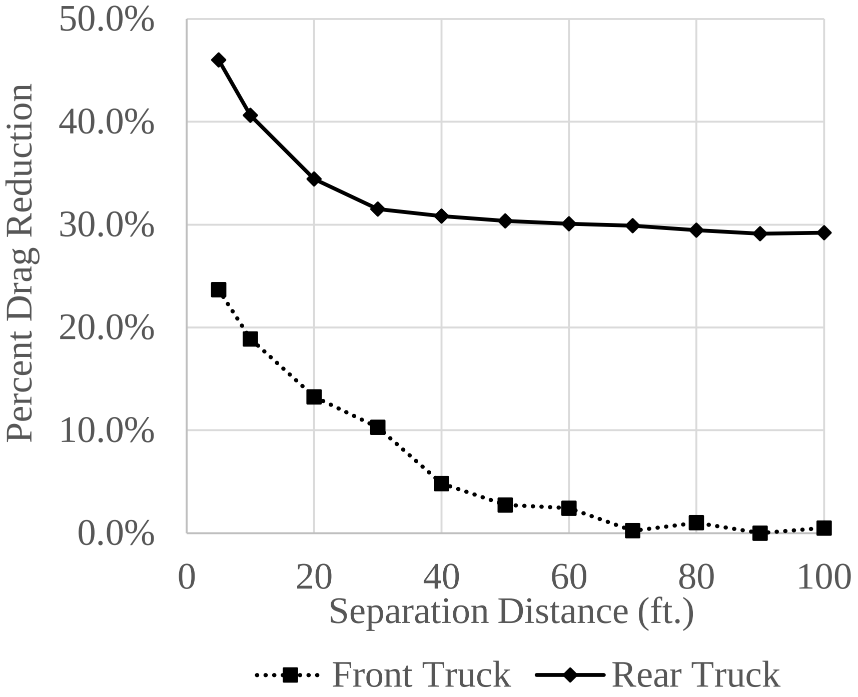


Figure 17: Simulated Two vehicle drag vs spacing

- Similar Results – Laterally Controlled

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

NREL Results

- National Renewable Energy Laboratory – Fuel Economy Results

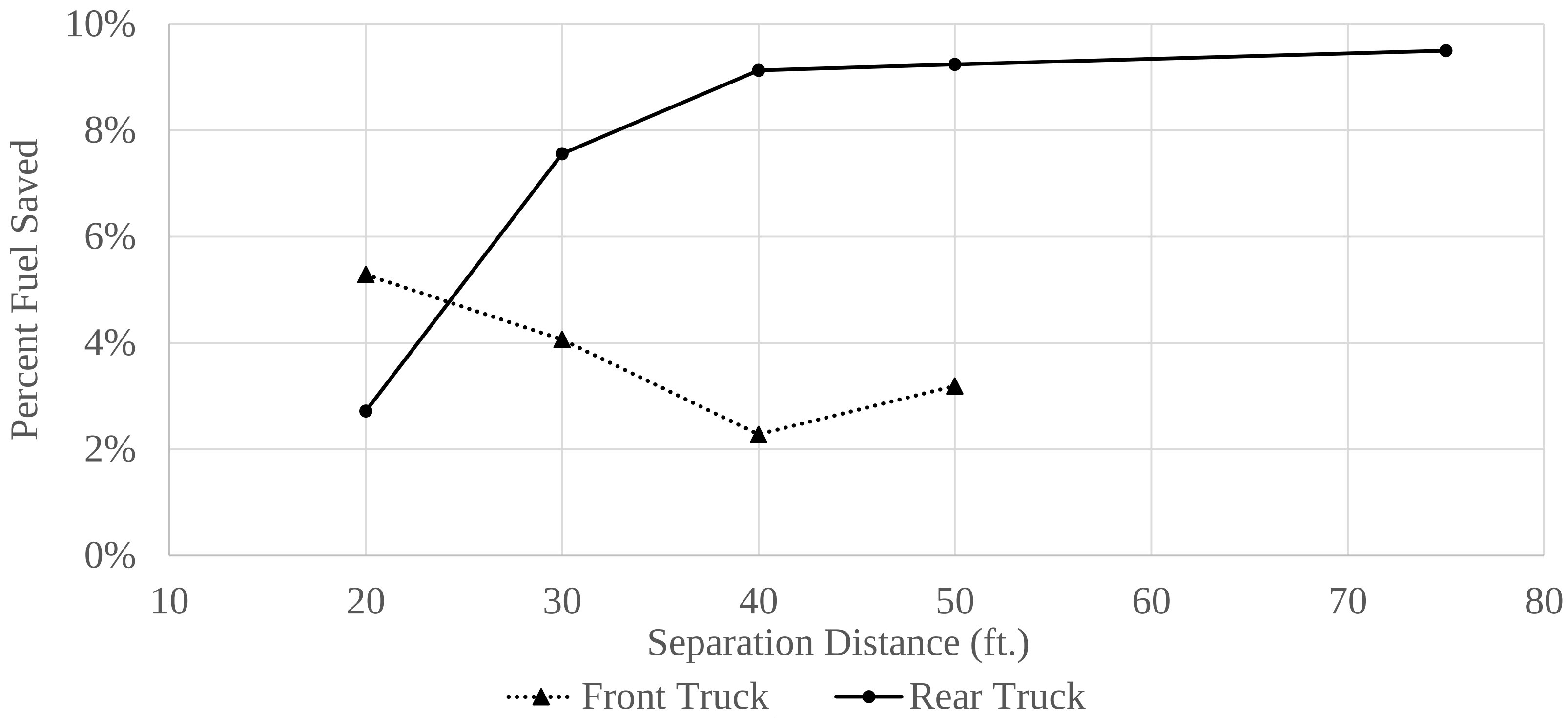


Figure 18: Percentage Fuel Saved for NREL Tests, 65 mph, 65K lbs/ Loaded Weight [7]

- Drastically different trend than simulated data
  - Engine fan duty-cycle much higher at close separation distances

AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

Possible explanations

- Engine Temperatures
  - As separation distance diminishes, less convective heat transfer for rear truck engine
- Controller Dither
  - As spacing diminishes, more aggressive controller behavior
- Previously non-captured aerodynamic effects

Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Fuel Economy Testing
- **Lateral Offset**
- Conclusions

AUBURN UNIVERSITY
SAMUEL GINN COLLEGE OF ENGINEERING

Lateral Offset – Potential Culprit

- Previous testing indicates most likely explanation is an aerodynamic effect
- Lateral offset – More likely to occur at close following distances
  - Vortex shedding off front truck coupled with lack of visual cues to center the rear truck
- Second set of simulations conducted to investigate

Laterally Offset Platooning

- Lateral offset negatively effects the drag reduction on rear truck
  - No longer drafting optimally
  - Asymmetrical pressure distribution
- More pronounced at smaller spacings

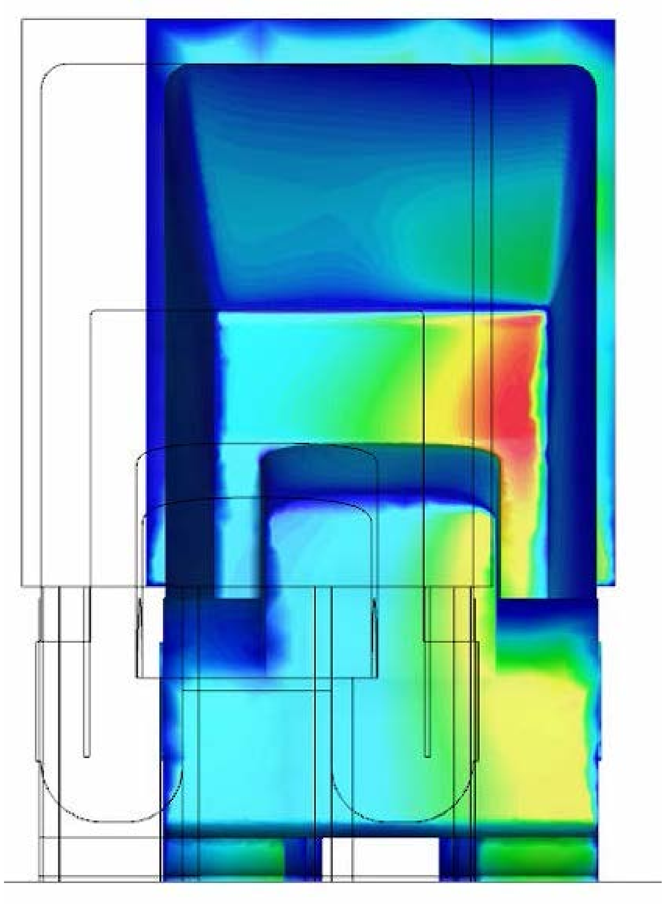


Figure 22: Pressure Contour on the Front Surface of the Rear Truck with Outline of Front Truck

Lateral Offset Simulation Results

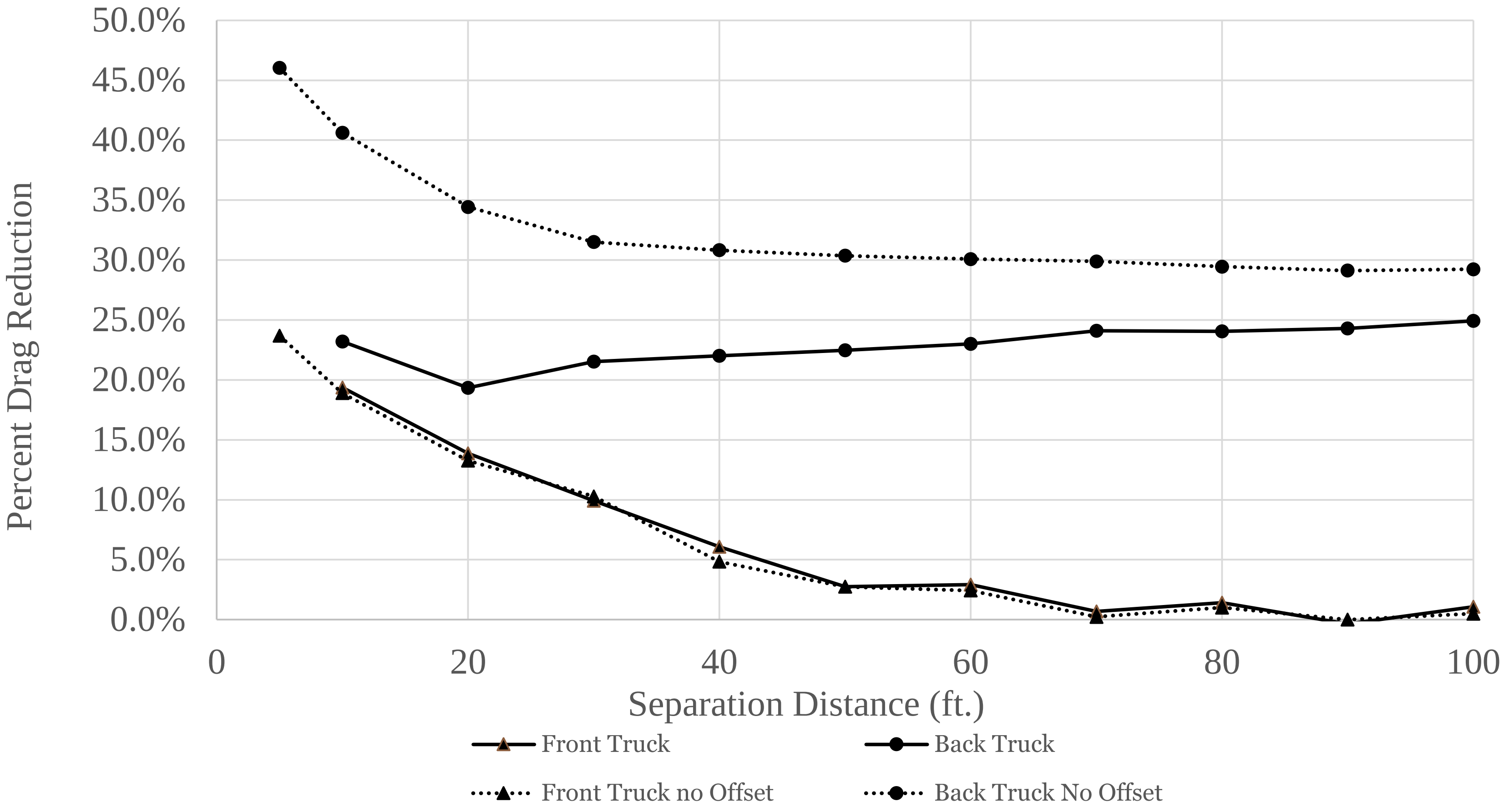


Figure 23: CFD Results including 2 ft. Lateral Offset

Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - Two body
- Single Heavy Vehicle
  - Baseline model
- Multiple Heavy Vehicle
  - Two vehicle
- Fuel Economy Testing
- Lateral Offset
- Conclusions

AUBURN
UNIVERSITY

SAMUEL GINN
COLLEGE OF ENGINEERING

Conclusions

- New trend matches experimental data more closely
  - Lateral offset most likely to occur at close spacings
  - Largest difference between ideal and offset drag reduction also at close distances
- Verification of lateral offset during testing in progress

Implications

- Lateral control a potential way to improve efficacy of DATP systems
  - Despite this, DATP still provides large benefit to fuel consumption without lateral control ~10%
- Implies optimal spacing of platoon is non-uniform
- Further research shows that offset platoons vary even more drastically with ambient conditions
  - Cross-winds and other potential phenomena affect offset platoons differently from controlled platoons

Questions

References

[1] www.bbc.com

[2] www.epa.gov/otaq/climate/regulations.htm

[3] S. Ahmed, G. Ramm, and G. Faltin, \Some Salient Features Of The Time-Averaged Ground Vehicle Wake," tech. rep., Feb. 1984.

[4] http://www.peterbilt.com/products/on-highway/579/

[5] C. Nowakowski, S.E. Shladover, X.-Y. Lu, D. Thompson and A. Kailas,“Cooperative Adaptive Cruise Control (CACC) For Truck Platooning:Operational Concept Alternatives”, California PATH Research ReportUCB-ITS-PRR-2015-05.

[6] J. Yoshida, T. Sugimachi, T. Fukao, Y. Suzuki, and K. Aoki, Autonomous Driving of a Truck Based on Path Following Control,” Proc. 10th Int. Symposium on Advanced Vehicle Control (CD-ROM), 2010.

[7] M. P. Lammert, A. Duran, J. Diez, K. Burton, and A. Nicholson, “Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass,” SAE Int. J. Commer. Veh., vol. 7, no. 2, pp. 2014–01–2438, 2014.

[8] R. M. Pagliarella, S.Watkins, and A. Tempia, \Aerodynamic Performance of Vehicles in Platoons : The Influence of Backlight Angles Reprinted From : Vehicle Aerodynamics 2007," vol. 2007, no. 724, 2014.