Drag Reduction Achieved through Heavy Vehicle Platooning

Thesis Defense

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04/15/2015

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Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - One body
  - Two body
- Single Heavy Vehicle
  - Baseline model
  - Three vehicle geometry
- Multiple Heavy Vehicle
  - Two vehicle
  - Three vehicle
  - Multiple geometry two vehicle
- Conclusions & Future Work

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Introduction to Platooning

- What is a heavy vehicle?
  - A large tractor-trailer combination vehicle that is used for goods transportation
  - Primary focus of this research
- What is platooning?
  - A group of two or more aligned vehicles in a leader-follower configuration
- Takes advantage of a phenomenon referred to as “drafting”
  - Also known as “slipstreaming”
  - Reduces aerodynamic drag, saves fuel

Figure 1. Heavy Vehicle Platoon [1]

Drafting

- Drafting provides aerodynamic drag reduction for follower vehicle
- Lead vehicle encounters "wall of air," follow vehicle encounters highly disrupted flow
  - Fluid dynamics perspective: lower mean flow velocity
- At highway speeds, aerodynamic drag accounts for over 70% of total drag force
  - Aerodynamic force scales with speed squared

$$F_D = C_D \left(\frac{1}{2}\rho_\infty v_\infty^2\right) A$$

- Benefits well-known and utilized in real world scenarios
  - Geese in V formation
  - Cyclists
  - NASCAR Drivers
- Reduced drag translates directly to improved fuel economy

Figure 2. Geese in V formation [1]

Figure 3. Cyclists drafting [2]

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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
  - Continually rising prices
  - Primary fuel for foreseeable future
- Improved fuel economy
  - Allows marketplace advantage
  - Complies with DOT / EPA regulations [3]
- If the FedEx fleet (25,000 tractors) improved gas mileage by 1% it would generate $20 million USD savings per year

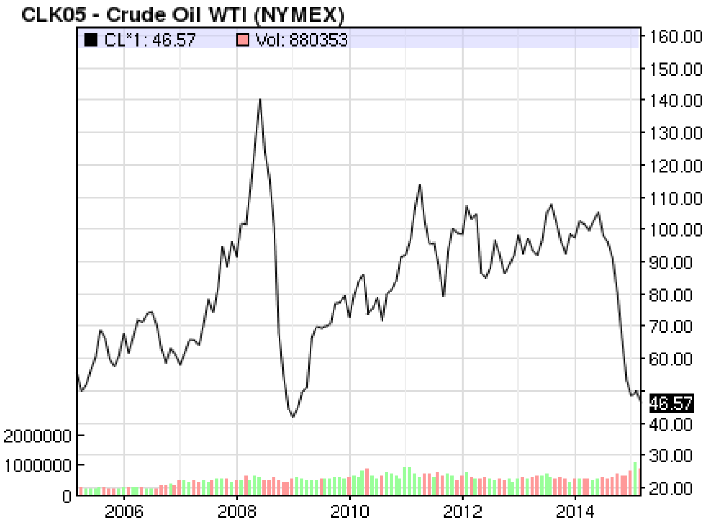

Figure 4. Crude Oil Price – 10 yr [4]

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Motivation

- Previously unfeasible due to human physiological limitations
  - Driver reaction time
  - Limited visibility
  - 80,000 lb loaded, 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)
- Under development by Auburn University
  - Grant awarded as part of the Exploratory Advanced Research Program by the Federal Highway Administration

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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
- Allows driver to observe metrics and roadway ahead of lead vehicle

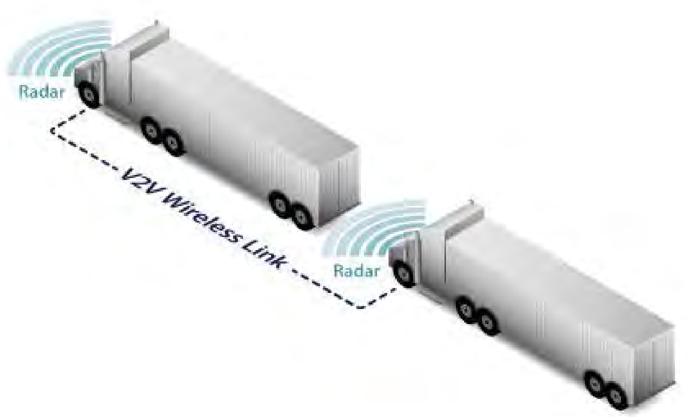

Figure 5. CACC Communication [5]

Existing Literature

- S. Ahmed, “Some Salient Features Of The Time-Averaged Ground Vehicle Wake”
  - 1984 wind tunnel tests of simplified car body
  - Well-known, common reference for validation of bluff body analysis
- Surprisingly limited research done on vehicle platooning
  - Particularly limited computational work
- Society of Automotive Engineers published the majority of platooning work
- Interesting problem but previously no practical applications
  - Manual platooning unsafe
  - Illegal in many states, “tailgating”

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Aerodynamic Force Modeling

- Two types of aerodynamic forces
  - Normal force resulting from pressure on the surface
  - Shear force from viscosity (skin friction)
- Determining force requires knowledge of velocity and pressure fields
- Navier-Stokes equations govern these variables
  - Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

  - Conversation of Momentum

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

- Low speed, incompressible flow negates requirement for use of conservation of energy and equation of state
- No closed form analytic solution
- Discretize and numerically solve, known as Computational Fluid Dynamics (CFD)

Simplified Car Body

- First vehicle modeled, colloquially known as “Ahmed body,” after 1984 wind tunnel test [10]
- 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

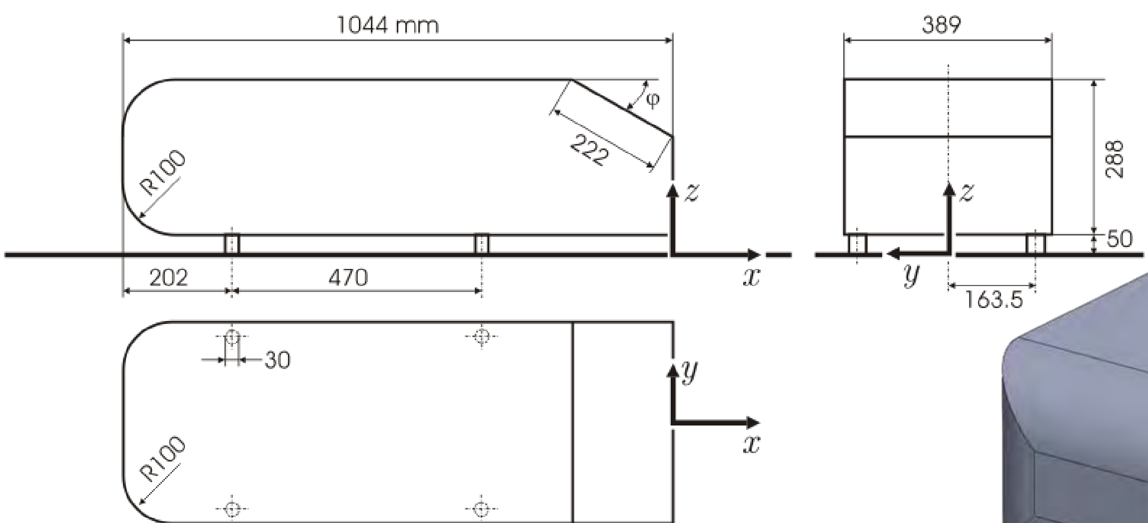

Figure 6. Ahmed body reference dimensions [6]

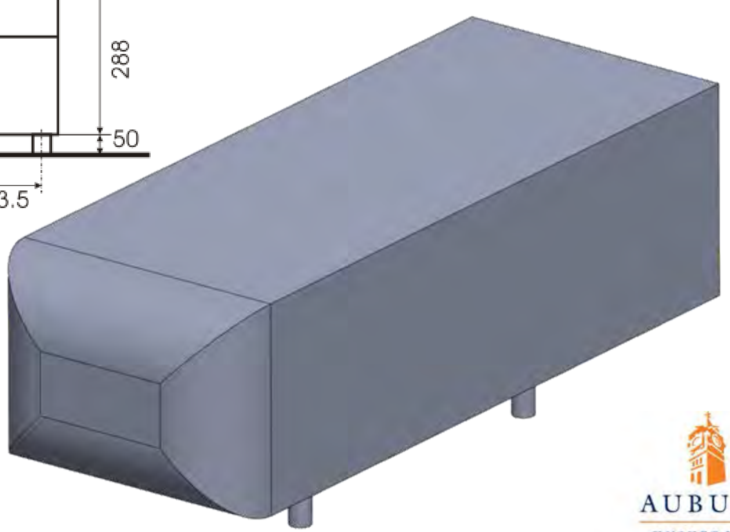

Figure 7. Ahmed Body Isometric View

Meshing

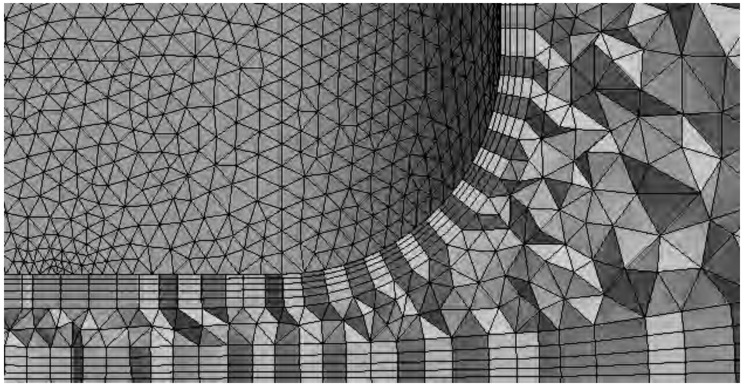

Figure 6. Ahmed body inflation layer

- A continuous domain cannot be used
  - Navier-Stokes equations are numerically solved
  - Discretize volume around structures
  - Treat each discretized cell as a control volume
- Unstructured gridding to better capture the complex nature of the tractor-trailer
- Global parameters
  - Parameters that apply to the entire domain, particularly relevant in the far field
- Refinement zones
  - Near body regions have large property gradients and must be properly resolved to maintain solution fidelity
- Inflation layer
  - Quasi-Cartesian elements in near surface regions that are used to resolve boundary layers

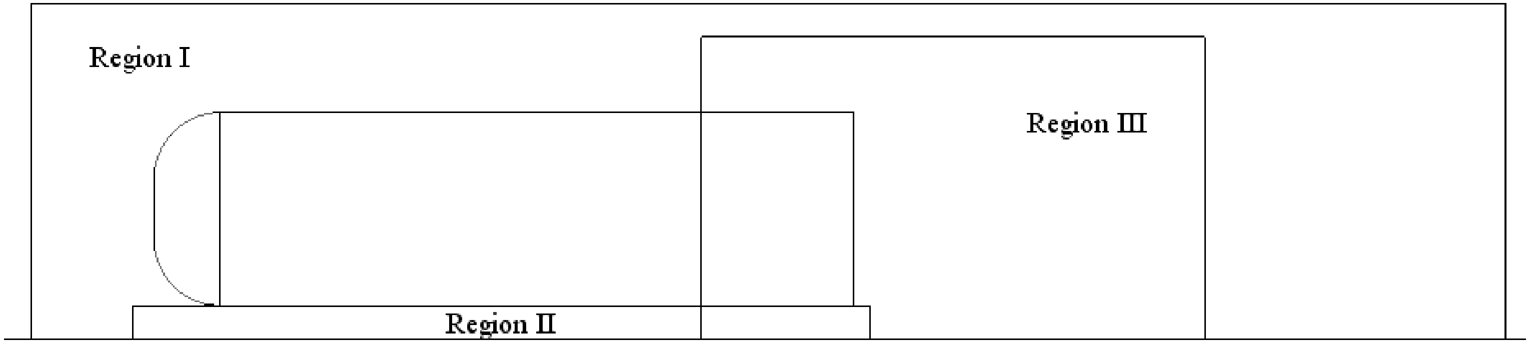

Figure 8. Ahmed body refinement zones

Meshing Metrics

- Number of elements
  - Used to determine fineness or coarseness of mesh
  - Only limited by hardware (RAM available)
- Skewness
  - Measure of deviation from equiangular polyhedron
  - High skewness causes interpolation error
  - Average skewness
    - Represents overall element quality
    - Desired average: 0.25
  - Maximum skewness
    - Represents worst element quality
    - Elements with too large skewness unsolvable
    - Maximum allowable: 0.90

Table 1. Element Quality [7]

Skewness	Element Quality
0	Ideal
0.01 – 0.25	Excellent
0.26 – 0.50	Good
0.51 – 0.75	Fair
0.76 – 0.90	Poor
0.91 – 0.99	Bad (Sliver)
1	Degenerate

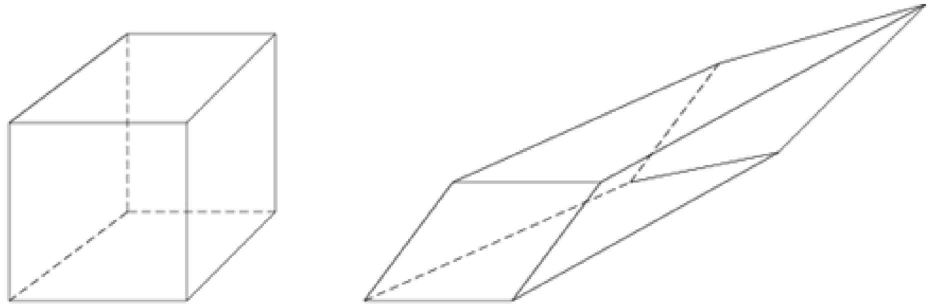

Figure 9. Low skew vs. high skew element

Flow Simulation

- Unstructured CFD solver Fluent used for simulations
  - Version 15.0, Produced by ANSYS Inc.
- Pressure-based solver used (incompressible flow)
- Second Order Upwind method preferred
  - Faster convergence, more complex computation
- Cell face pressure calculated using weighted average of cell center values
- Pressure-Velocity solved using "coupled" algorithm
  - Does not use predictor-correction scheme
  - Allows a single matrix which can be solved through Algebraic Multigrid
- Relaxation factors
  - Introduced to account for the fact that the non-linear Navier-Stokes are being modeled linearly
  - Directly effects rate of convergence / convergence ability
  - Explicit – direct variable manipulation
  - Implicit – introducing selective amounts of variables into equations
  - A low relaxation parameter represents a tightly controlled variable / equation
  - Complex bluff body geometry generates local high skewness regions, which requires low explicit relaxation to achieve convergence

Boundary Conditions

- Velocity inlet
  - Very far away from bodies – considered "freestream"
  - Incompressible flow allows only a velocity to be specified
  - 30 m/s (67.1 mph) for most simulations
- Pressure outlet
  - Freestream assumption allows 0 gauge pressure
  - Reference pressure is 1 atm
- Solid Wall
  - Solid surfaces in the domain
  - No slip condition: flow cannot move relation to wall
  - No tangential velocity
- Symmetry Wall
  - Can be used to represent far field parallel boundary condition
  - "Slip wall"
  - No tangential velocity

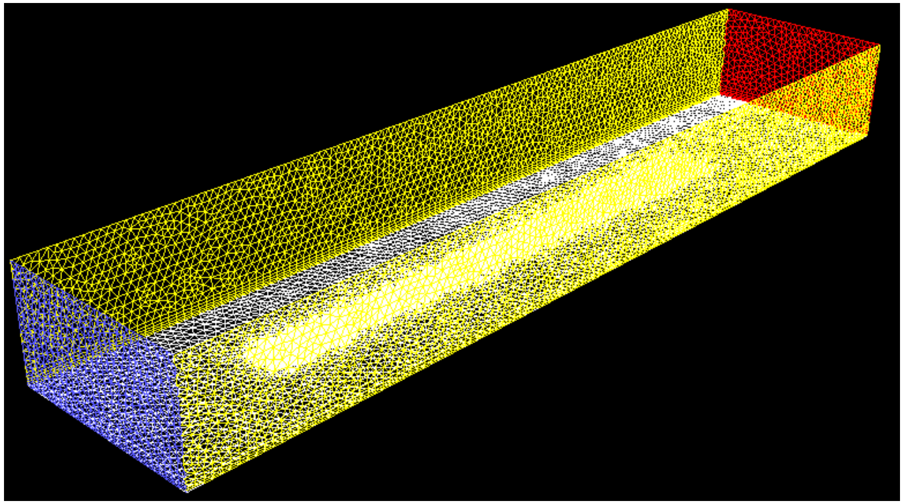

Figure 10. Boundary conditions for two vehicle simulation

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

Figure 11. Wingtip vortex turbulence [8]

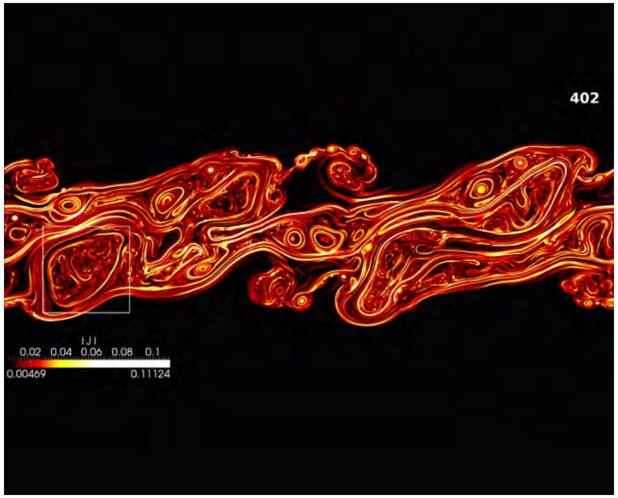

Figure 12. Solar wind turbulence [9]

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Realizable k-ε (RKE)

- Reynolds-averaged Navier-Stokes (RANS) based approach
  - Assumes any variable can be decomposed into a fluctuation and an average
- Two equation model: adds two transport differential equations
- Turbulent Kinetic Energy

$$k \equiv \frac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right)$$

- Turbulent Dissipation

$$\varepsilon \equiv \nu \overline{\frac{\partial v_i{}'}{\partial x_k} \frac{\partial v_i{}'}{\partial x_k}}$$

- Realizable
  - Satisfies physical constraints not applied in the standard k-epsilon to model turbulent viscosity μ_t
  - A constant is replaced with a variable that is dependent upon the strain rate tensor
- Used for steady state analysis in this work

Detached Eddy Simulation (DES)

- Based on Large Eddy Simulation (LES)
  - Operates on the principle that large eddies are geometry dependent and small scale structures are universal
  - Uses a resolved (large) scale and a sub-grid scale (SGS)
  - Solves resolved scale equations using input from SGS model
  - Shown to be more accurate than the RANS approach
  - Extremely high computational cost due to SGS
- DES is a hybrid approach
  - Combines LES and RANS techniques
  - LES in far field regions
  - RANS in near wall regions because the SGS computational cost is astronomical due to the highly refined mesh
- RKE used as RANS model
- Designed for transient analysis

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Single Ahmed Results

- Predicted $C_D = 0.26150$, wind tunnel: $C_D = 0.250$
- 4.6% relative error
- Over predicts
- Medium-Coarse grid
- 90% pressure drag, < 10% viscous
- Two main contributor surfaces: front and rear

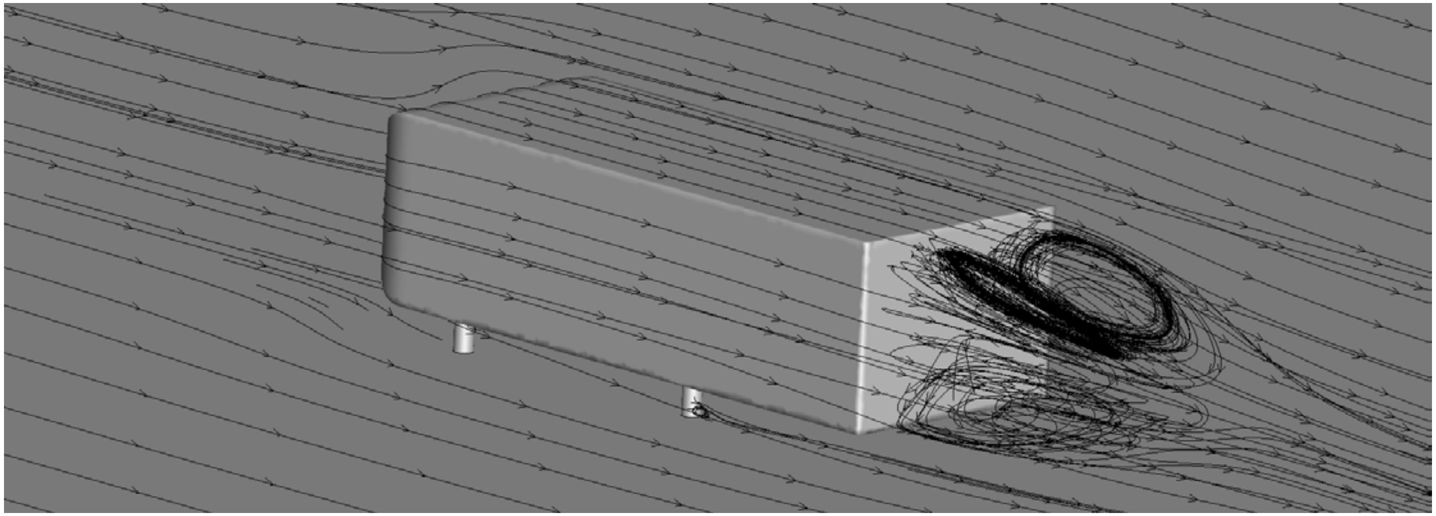

Figure 13. Ahmed body streamlines

Mesh Size Variation

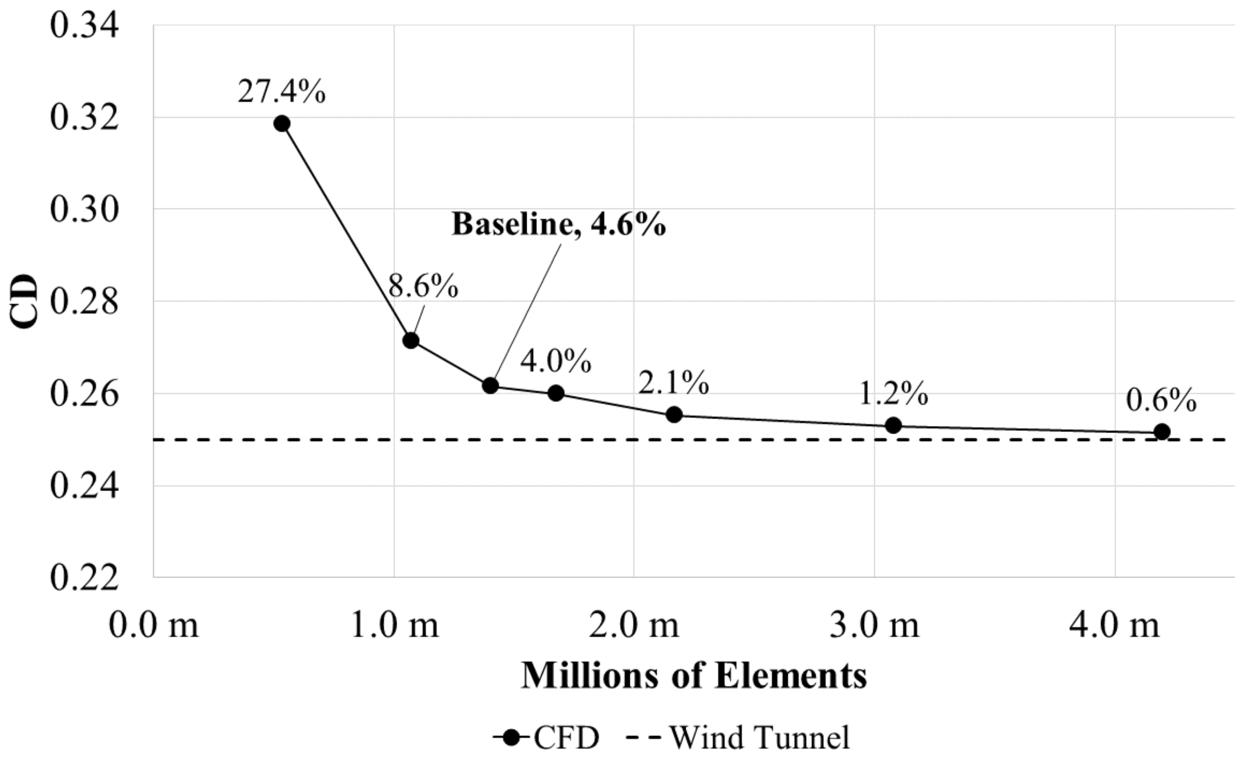

Figure 14. Error vs. mesh size variation

- 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

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Turbulence Model Comparison

- DES average slightly closer than RKE
- Highly variable
  - Largely dependent on range selected for average
  - Error reduction likely statistically insignificant
- Under predicts
  - Due to under estimation of skin friction
  - Result of the RANS-LES transition

Table 2. Turbulence model drag

Model	Drag	Error
RKE	0.26150	4.6%
DES-RKE	0.23899	4.4%

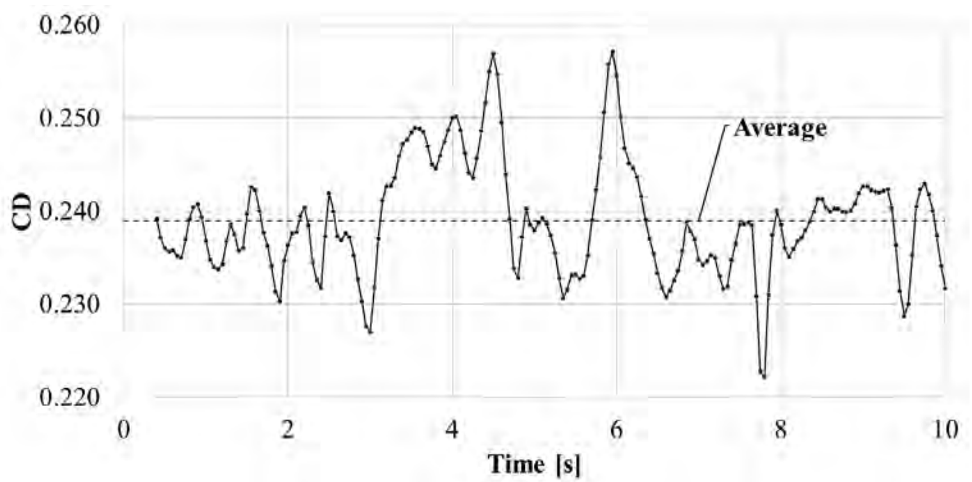

Figure 15. DES drag prediction over time

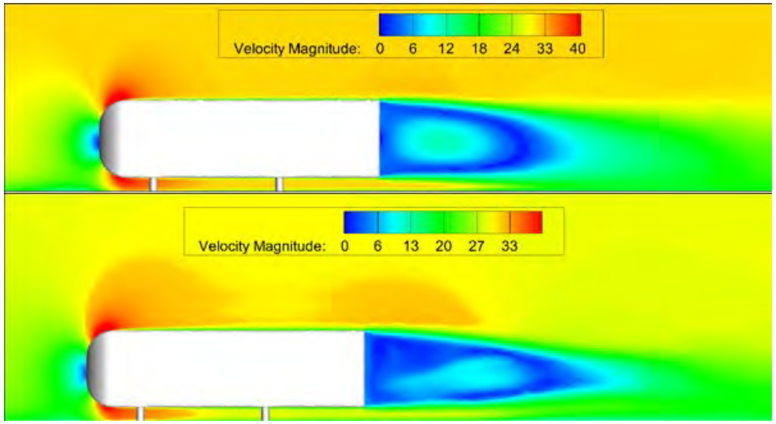

Figure 16. RKE (top) and DES velocity profiles

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Two Ahmed Simulation

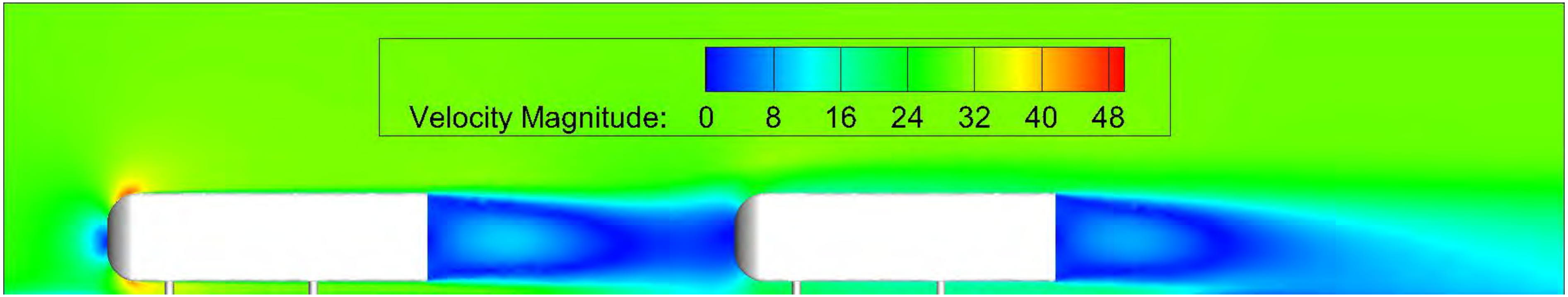

Figure 17. Two Ahmed velocity profile – 1 m separation

- Examine two body interactions for a simplistic model
  - Low surface count
  - Flow is well defined
- Wind tunnel data available for validation [11]
  - Multi Ahmed body experiments
  - Performed to test slant angle effect

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Two Ahmed Results

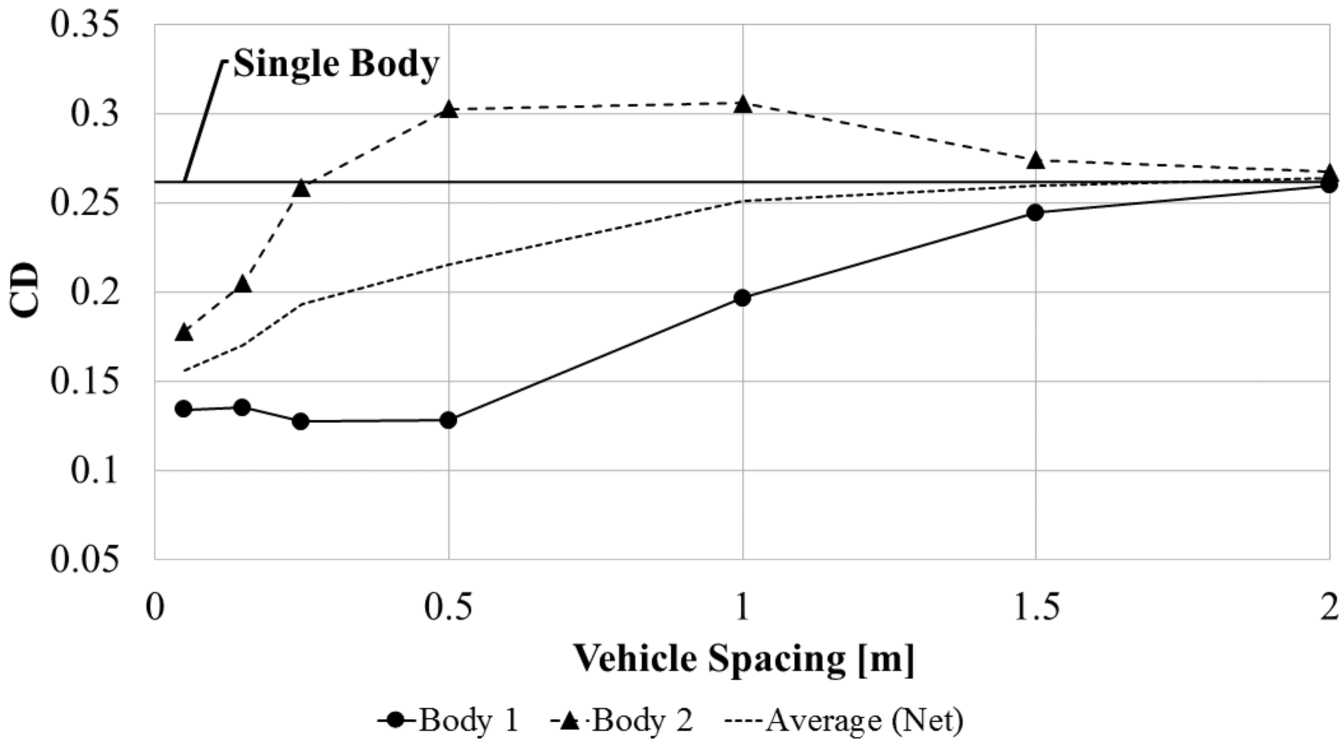


Figure 18. Two Ahmed drag coefficient

- Unexpected result: drag increases on follow body until very close distances
- Front body always sees drag reduction
- Net drag is always reduced

Simulation vs. Wind Tunnel

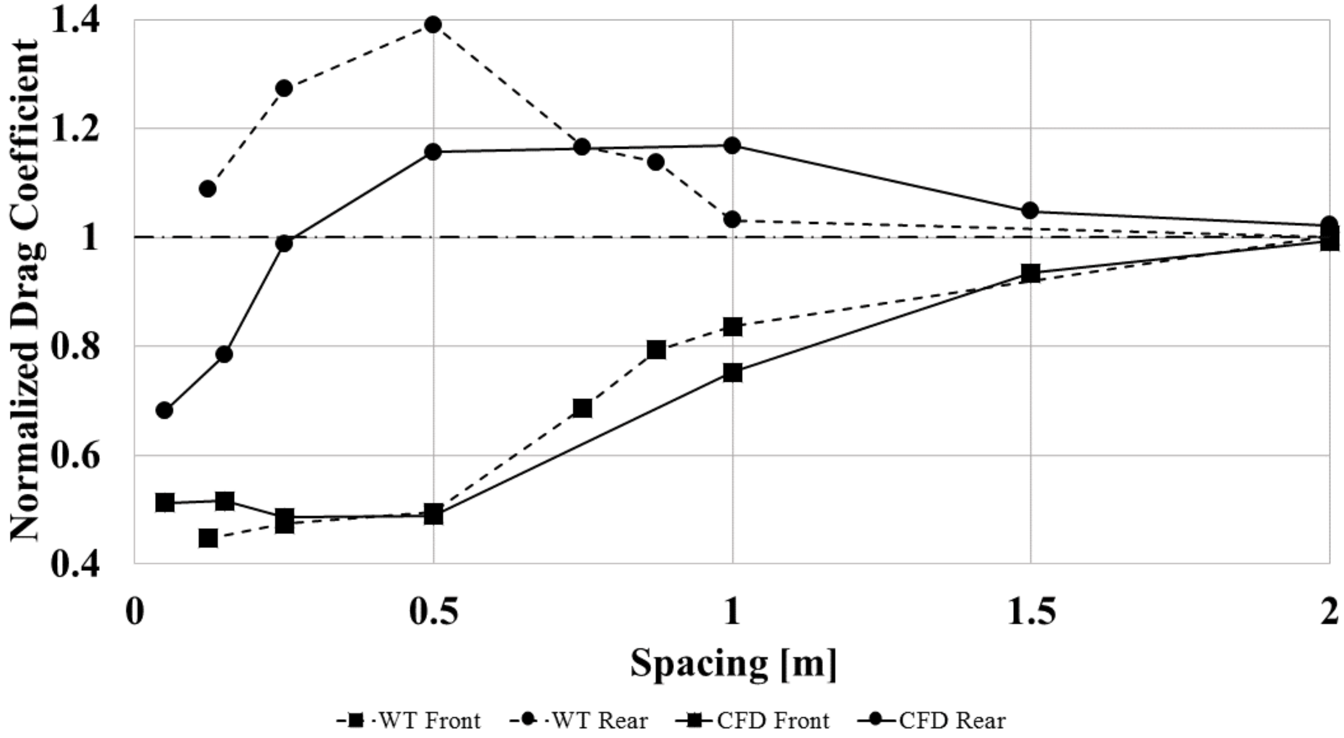
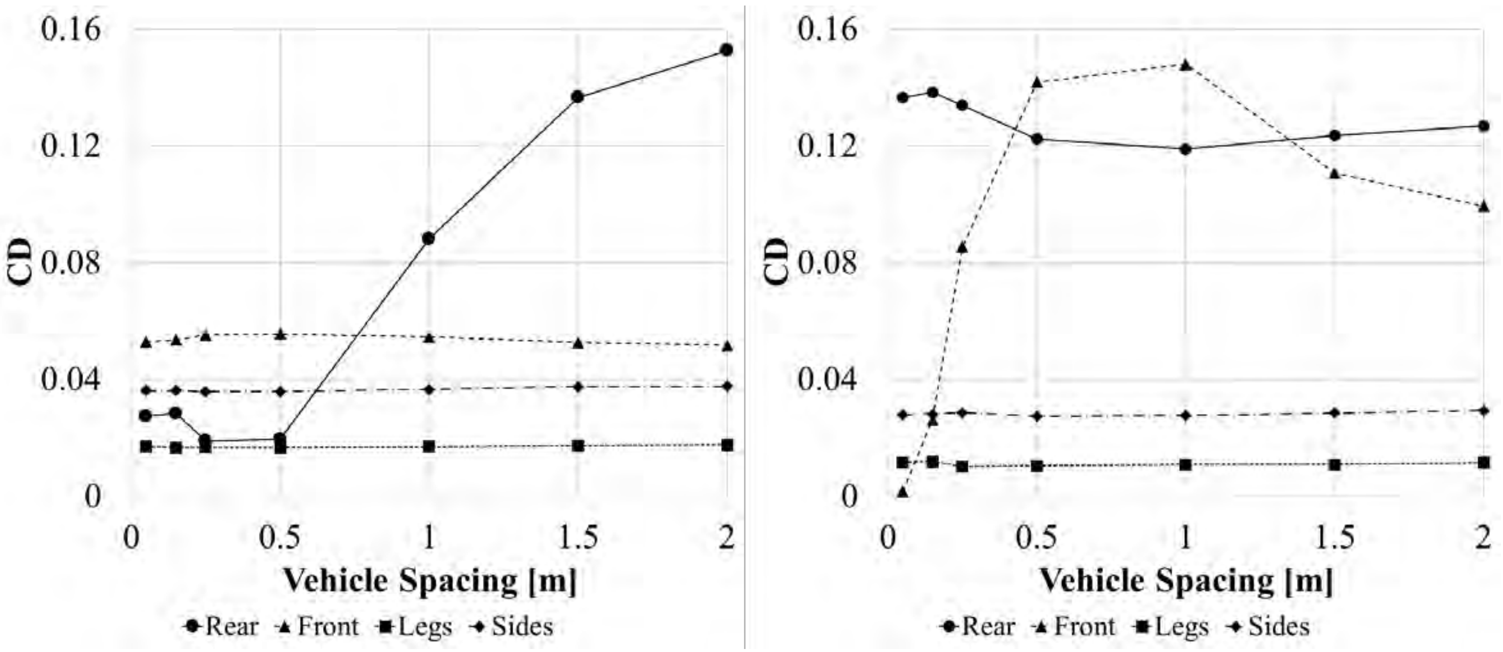


Figure 19. Two Ahmed CFD vs. Wind Tunnel

- 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

Surface Drag Analysis

- Examine drag by surface to determine why rear body sees more drag
- Only one region on each body saw major changes
  - Lead body: rear surface
  - Follow body: front surface
  - “Region of Influence”
- Follow body front surface drag larger than lead body



(a) Lead body (b) Follow body

Figure 20. Two Ahmed surface drag

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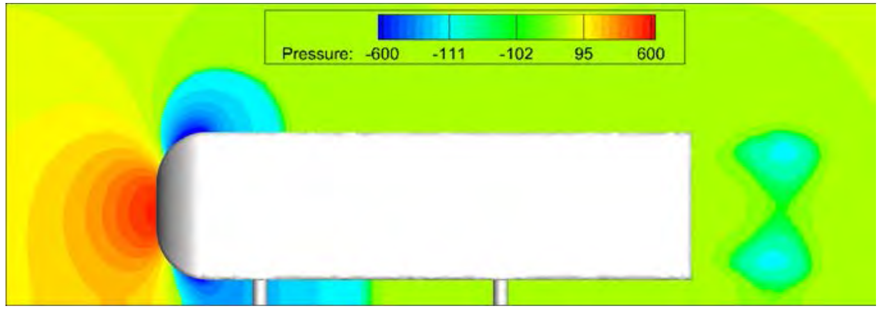
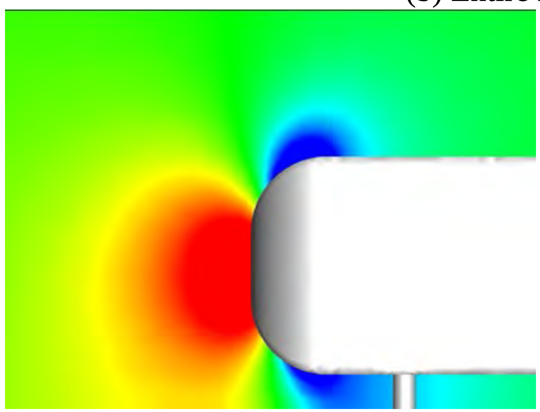
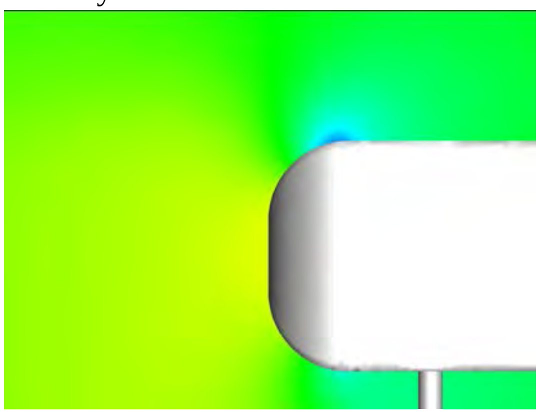
Pressure Distribution



(b) Entire lead body



(b) Lead body



(c) Follow body

Figure 21. Two Ahmed surface drag

- Gradient is much higher on front body
  - “Pull” region counters “Push” region, despite surface normal
  - Results in lower pressure force
- Large transverse surface area is detrimental

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Single Vehicle Simulations

- Performed to gain a baseline drag force for each geometry
- Allowed detailed surface analysis to determine primary contributing drag surfaces
- Three tractor geometries
  - Peterbilt 579 (P579)
  - Peterbilt 379 (P379)
  - Mercedes-Benz ACTROS (MBA)
- Identical 53 ft trailers

Figure 22. P379 [12]

Figure 23. MBA [13]

Figure 24. P579 [14]

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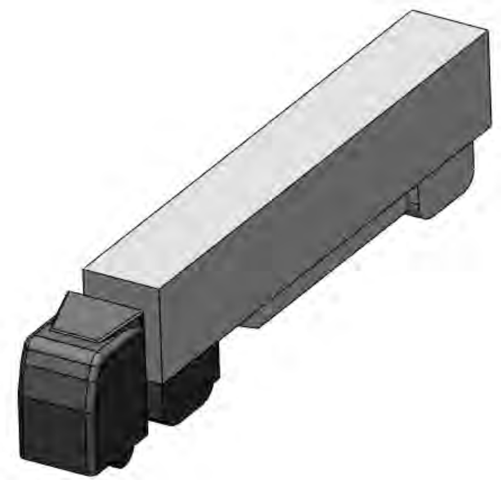
CAD Model Development

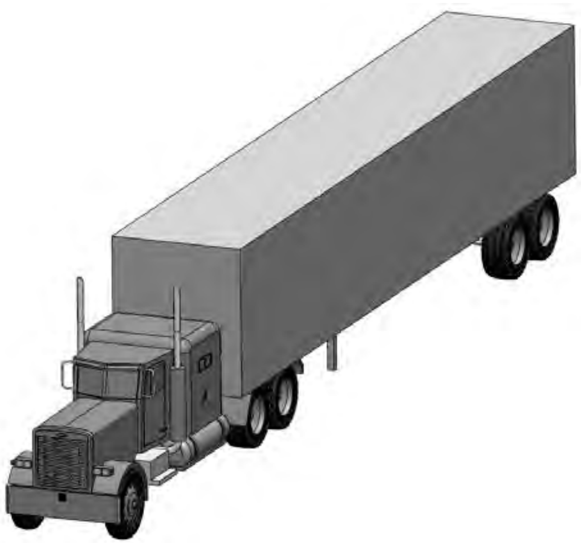
- CAD models acquired from GrabCAD community
- Simplified for simulation
  - Small, noncritical vehicle features removed
    - Side mirrors, grill, etc.
  - Length scale disparity
    - Small features on a large body
    - Requires fine meshing
    - Rapidly grows mesh size
    - Unfeasible
  - Does not reduce solution accuracy
    - Features do not have significant impact on overall flow or aerodynamic forces

(a) Original

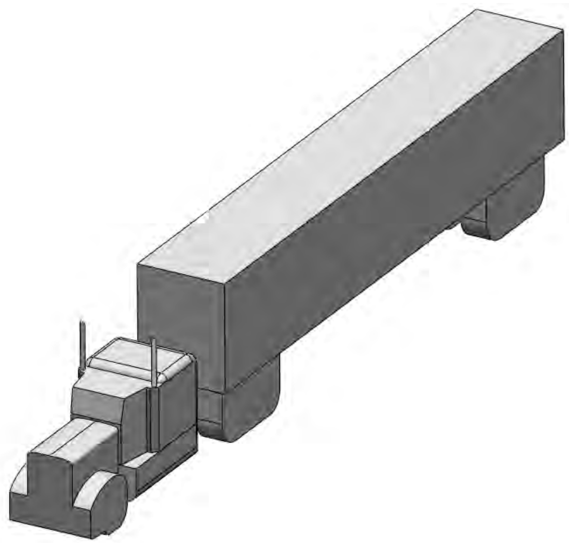


(b) Simplified

Figure 25. MBA CAD



(a) Original



(b) Simplified

Figure 26. P379

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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

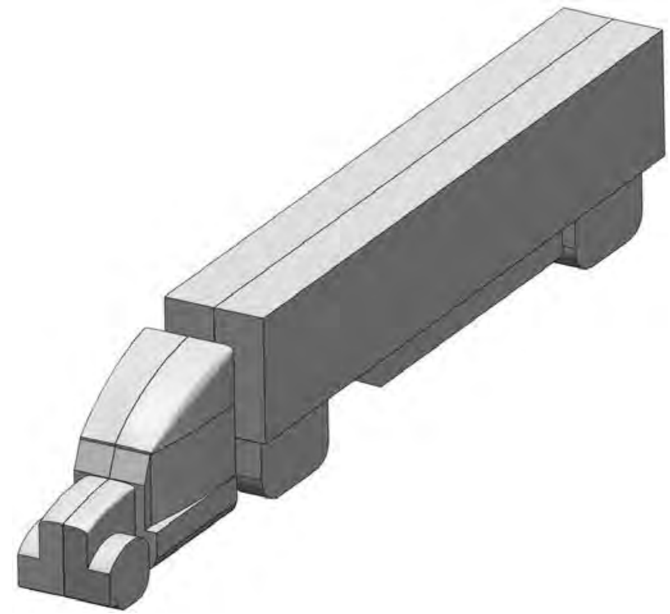


Figure 27. P579 CAD

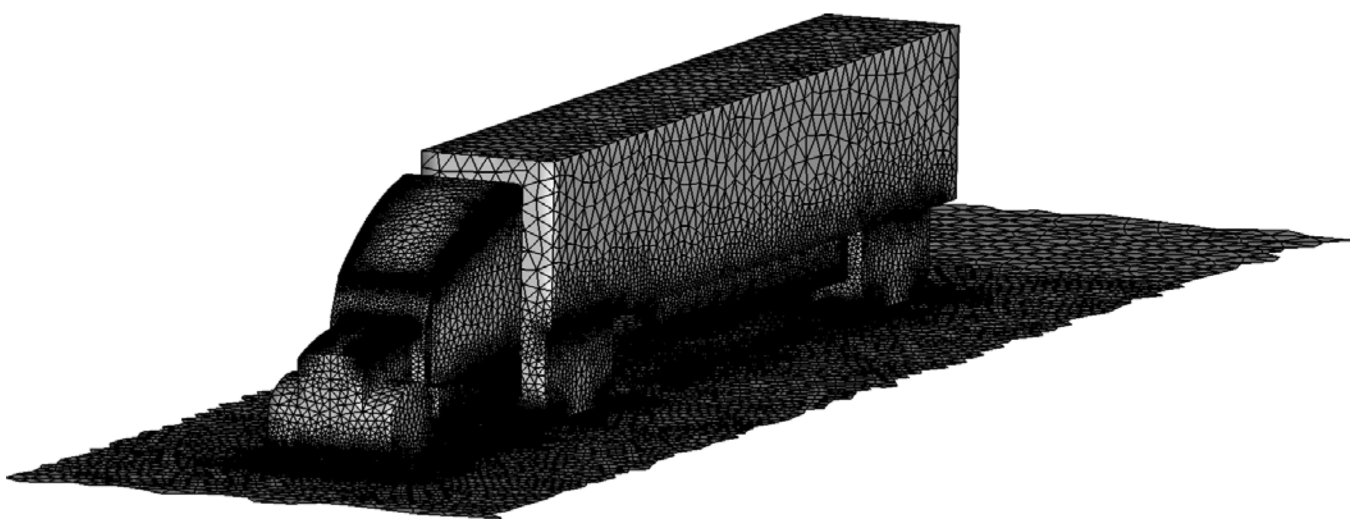
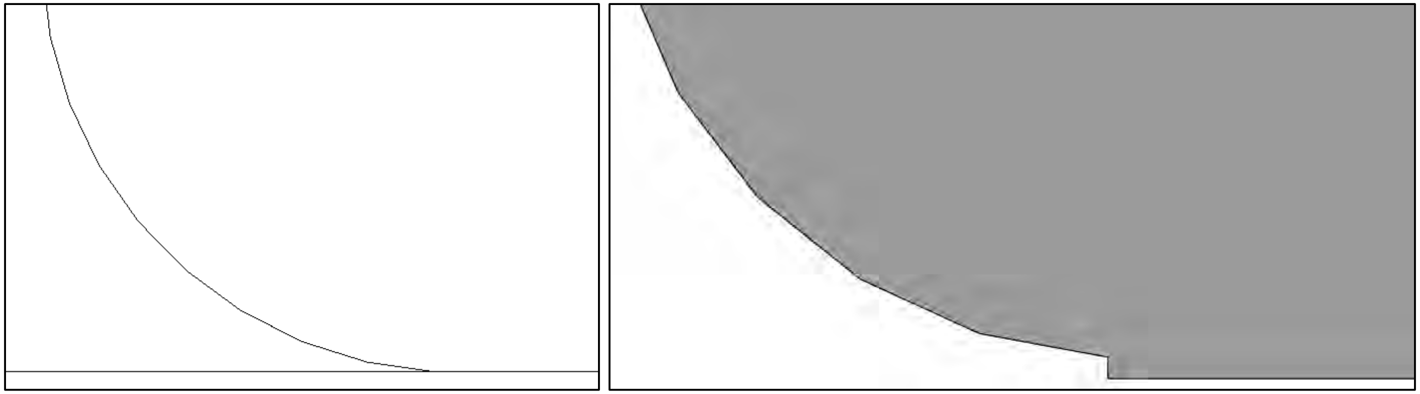


Figure 28. P579 Surface Mesh

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 29. Workaround feature example

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Single Vehicle Results

- Viscous drag approx. 5%
- P379 experiences larger drag because there is no aerodynamic hood fairing
  - High speed flow impacts transverse wall

Table 3. Single vehicle drag

Model	Drag
P579	0.5271
P379	0.8766
MBA	0.5078

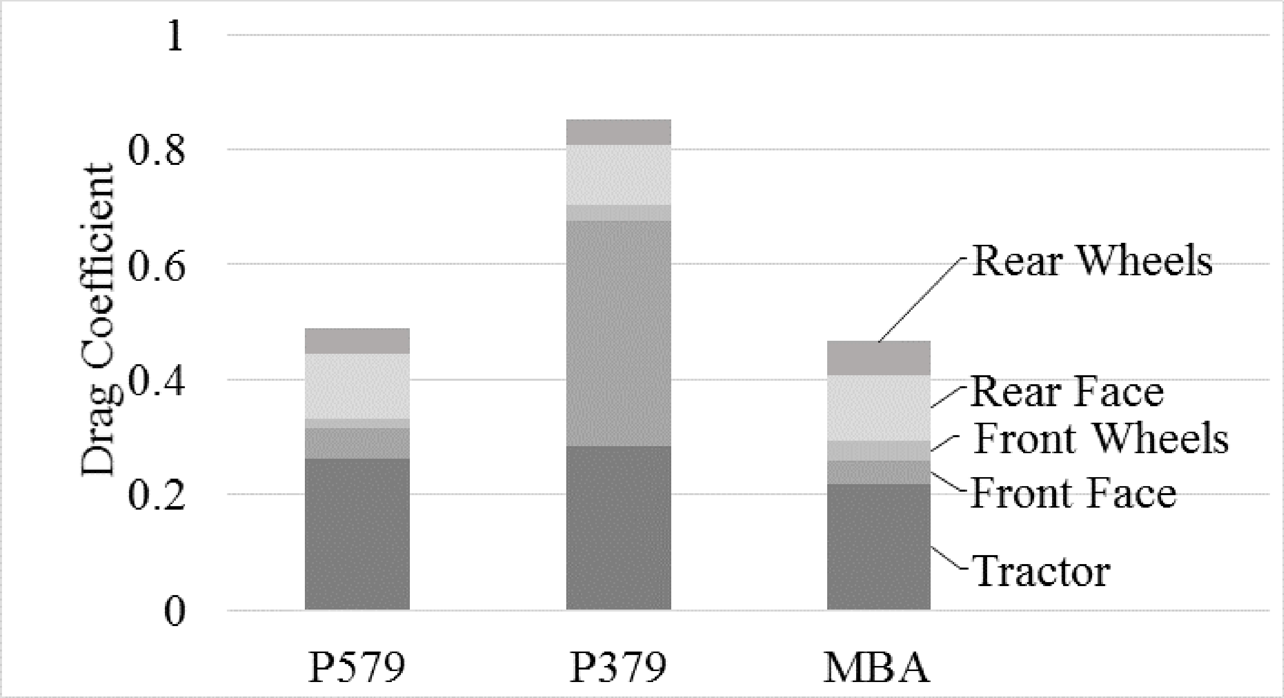

Figure 30. Single vehicle drag composition

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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
- Presented as percentage of single vehicle drag

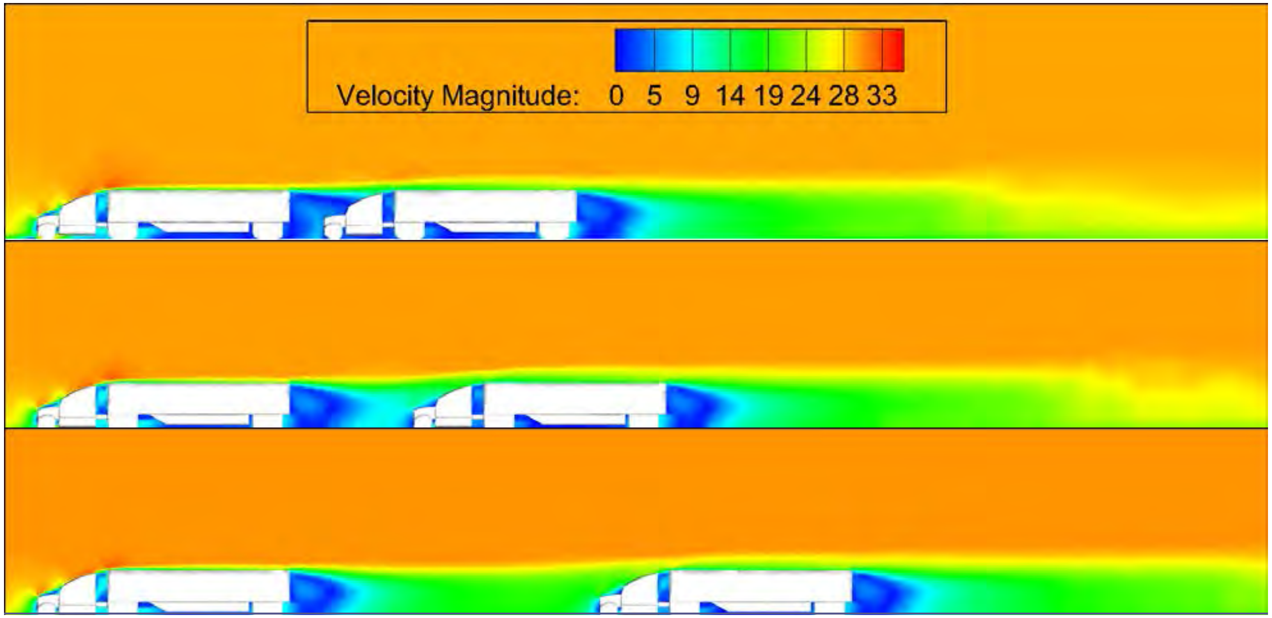

Figure 31. Two vehicle velocity profile, top to bottom: 10 ft, 36 ft, 90 ft spacing

Two Vehicle Results

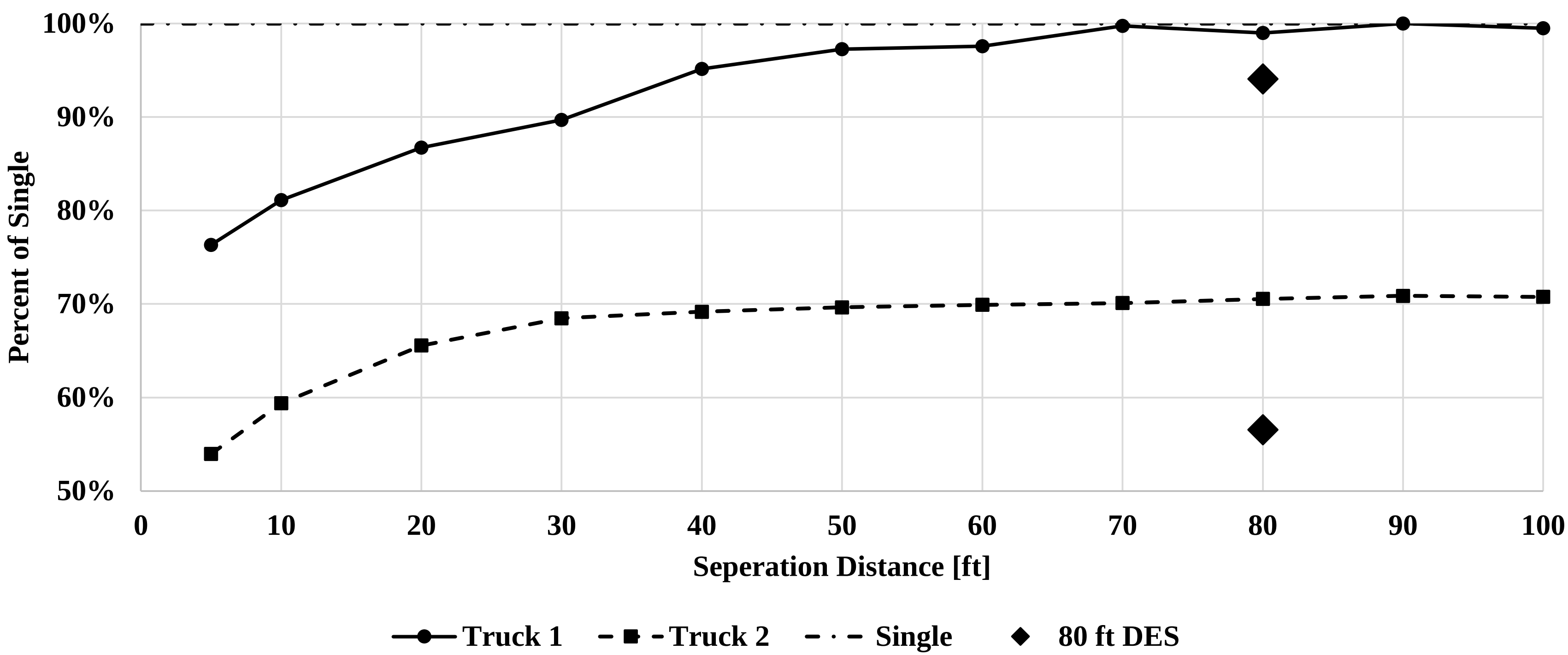

Figure 32. Two vehicle drag vs spacing

- Simulation suggests 3 distinct regions:
  - Inner Wake – rapid decrease in both vehicles drag
  - Outer Wake – Vehicle 1 still sees wake interference, Vehicle 2 in slipstream region
  - Slipstream – nearly constant, reduced drag for Vehicle 2, no benefit for Vehicle 1

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Turbulence Model Flaw

- RKE cannot return to laminar flow once turbulent
- Does not terminate wake
- Poor prediction at large distances
- Must use LES-based model DES
- Does not invalidate close distance RKE
- RKE does not become incorrect until wake terminates (350-400 ft)
- Indicates RKE performs poorly in low TKE situations
- Consistent with knowledge about RKE

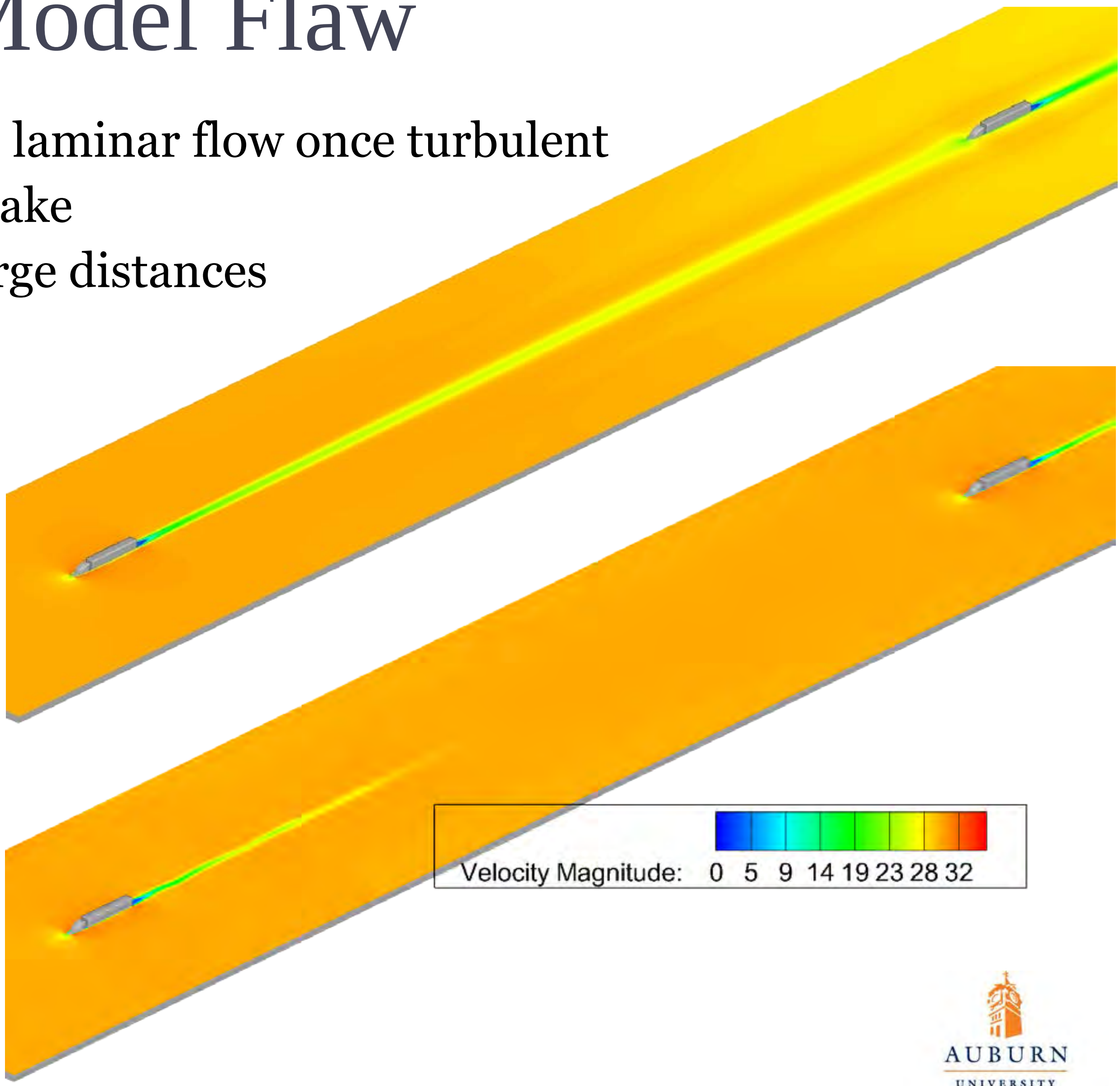

Figure 33. Two vehicle 1000 ft spacing: RKE (top) vs. DES (bottom)

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Two Vehicle – Large Distance

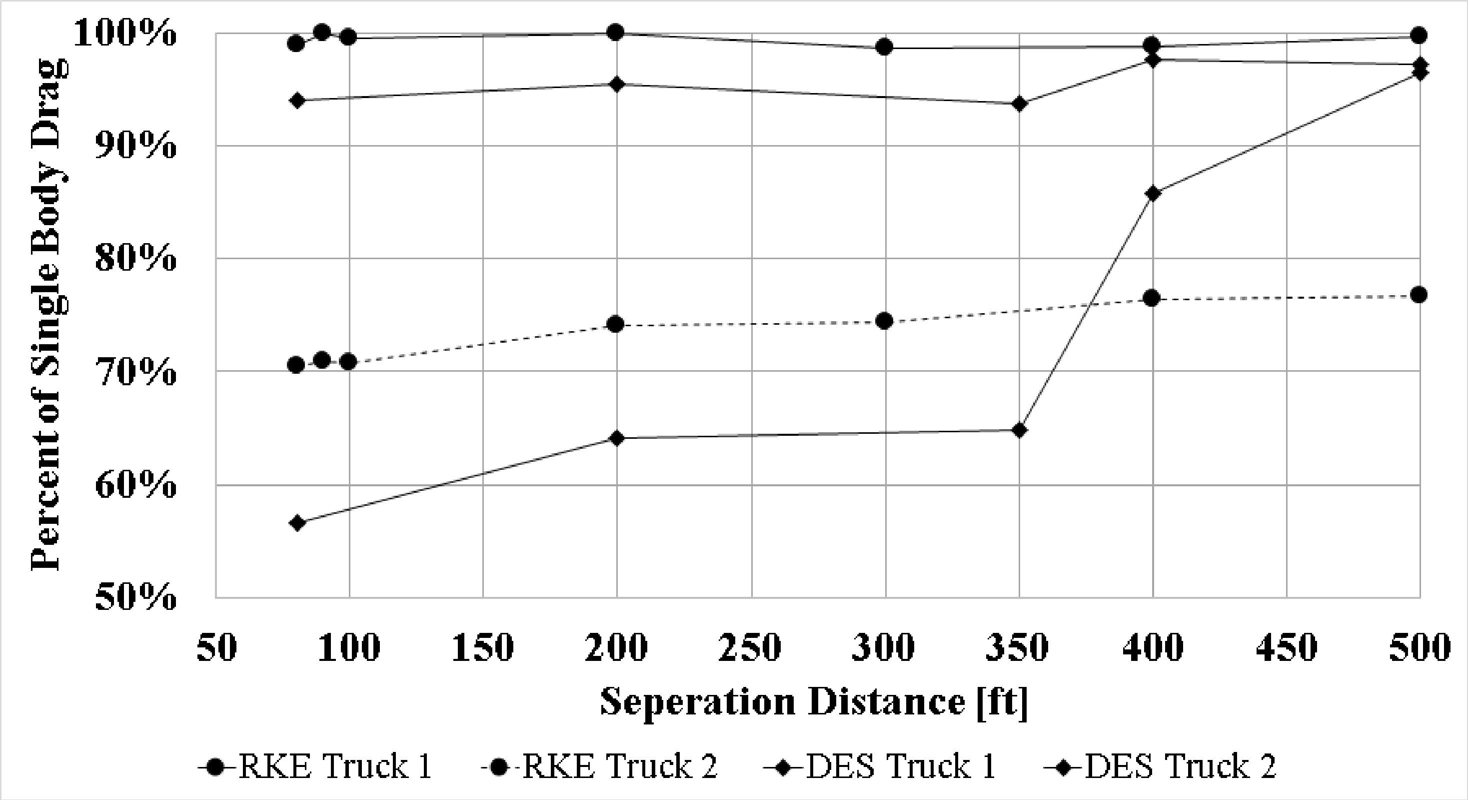

Figure 34. Two vehicle drag vs spacing – large distance

- RKE over-predicts, DES under-predicts
- RKE and DES diverge significantly between 350 and 400 ft
- Three regions apparent in DES:
  - Slipstream – near constant, reduced drag
  - Slipstream-freestream – rapid transition from slipstream to freestream, occurs at end of Vehicle 1 disturbance
  - Freestream – neither body sees any benefit, equivalent to single vehicle

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Drag Composition by Surface

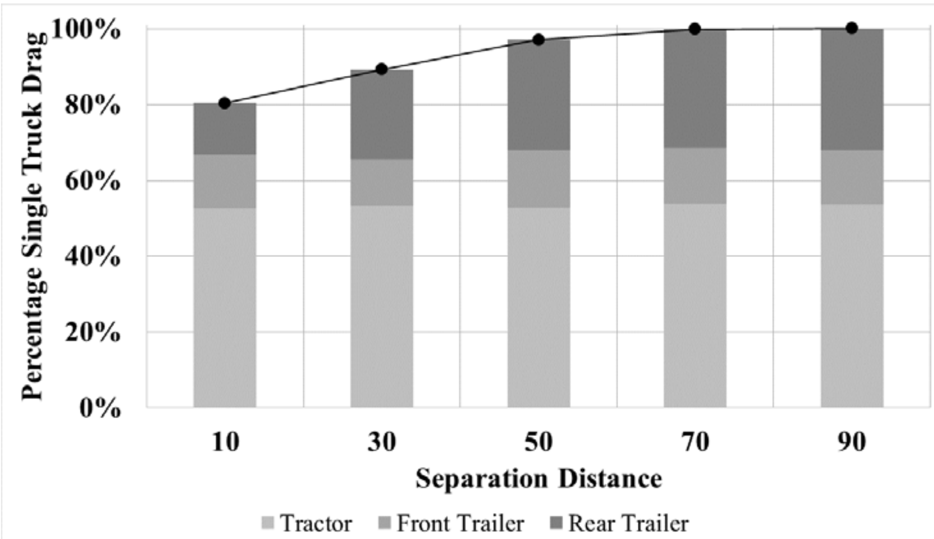

Figure 35. Vehicle 1 drag vs spacing

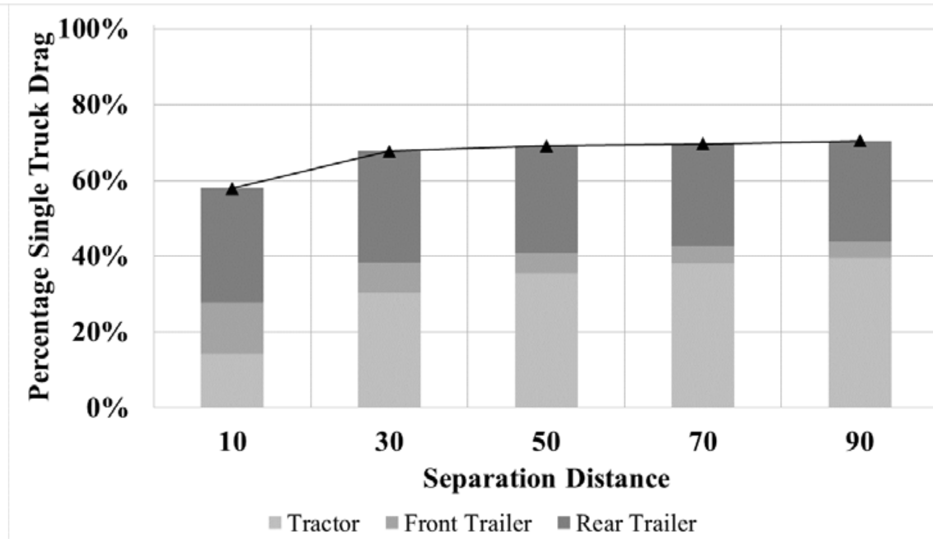

Figure 36. Vehicle 2 drag vs spacing

- Vehicle 1
  - Reduction on trailer rear surfaces only
  - Front surfaces identical to single vehicle drag
- Vehicle 2
  - Large tractor drag reduction
  - Increase in trailer front drag
    - Still reduced from single vehicle values

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Trailer Front Surface

- Anomaly: Pressure drag increases as distance between vehicles decreases
- Flow is highly turbulent with large amounts vorticity between
- Flow over vehicle acts as a solid wall
  - Flow from undercarriage is pulled into cavity and is buffeted
  - Flow cannot escape via lateral movement because air is being pulled in to create strong counter-rotating vortices
  - Creates multi-directional vortex
    - Upward inner vortex, downward stronger outer
- Relate pressure to velocity and vorticity via Crocco's theorem:

$$\vec{v} \times \omega = \frac{\nabla p}{\rho} + \frac{\nabla v^2}{2}$$

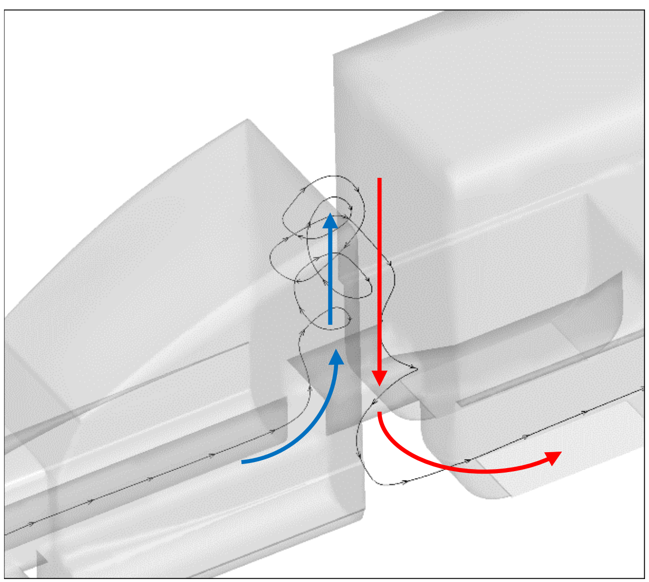
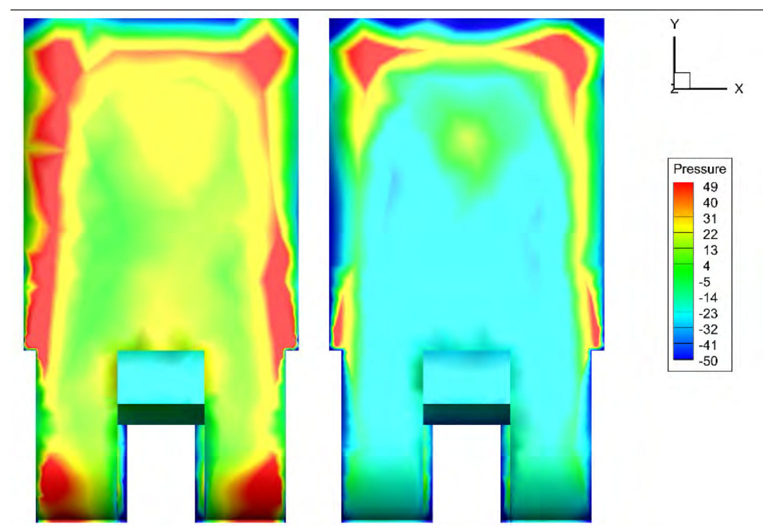


Figure 37. Tractor-trailer gap streamline



(a) 10 ft (b) 90 ft

Figure 38. Rear vehicle trailer front pressure distribution

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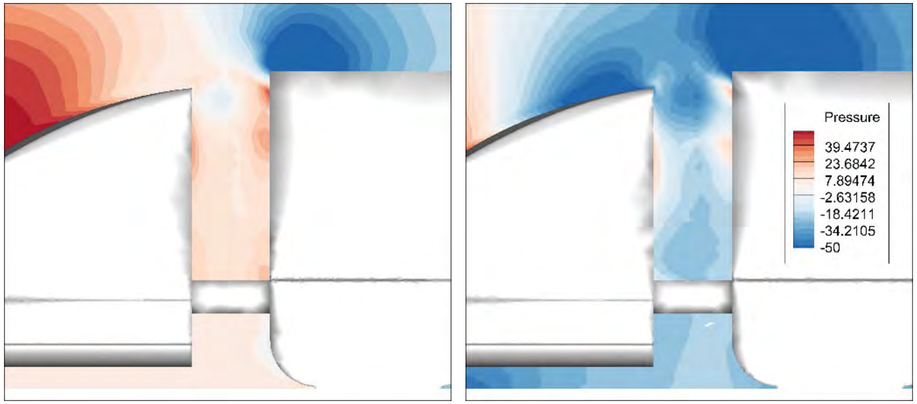
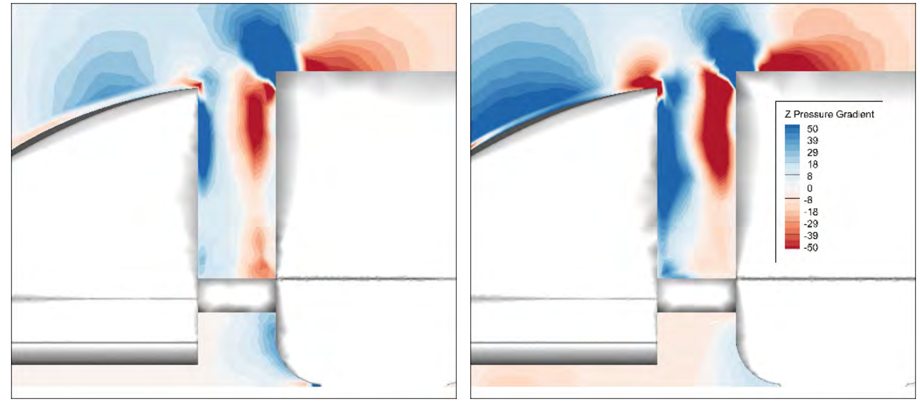
Trailer Front Surface Pressure



(a) 10 ft (b) 90 ft

Figure 39. Rear vehicle tractor-trailer interface pressure



(a) 10 ft (b) 90 ft

Figure 40. Rear vehicle tractor-trailer interface pressure gradient

- High velocity field yields:
  - High vorticity (which is the curl of velocity)
  - Low pressure distribution
  - High pressure gradient
  - Flow energy is kinetic instead of static
- 10 ft spacing
  - Lower mean flow velocity results in higher pressure in cavity
  - Lower Z direction gradient when nearing trailer surface
- 90 ft spacing
  - Higher mean flow results in lower pressure, higher gradient
- Z direction gradient not large enough to significantly increase pressure when approaching wall over the short distance

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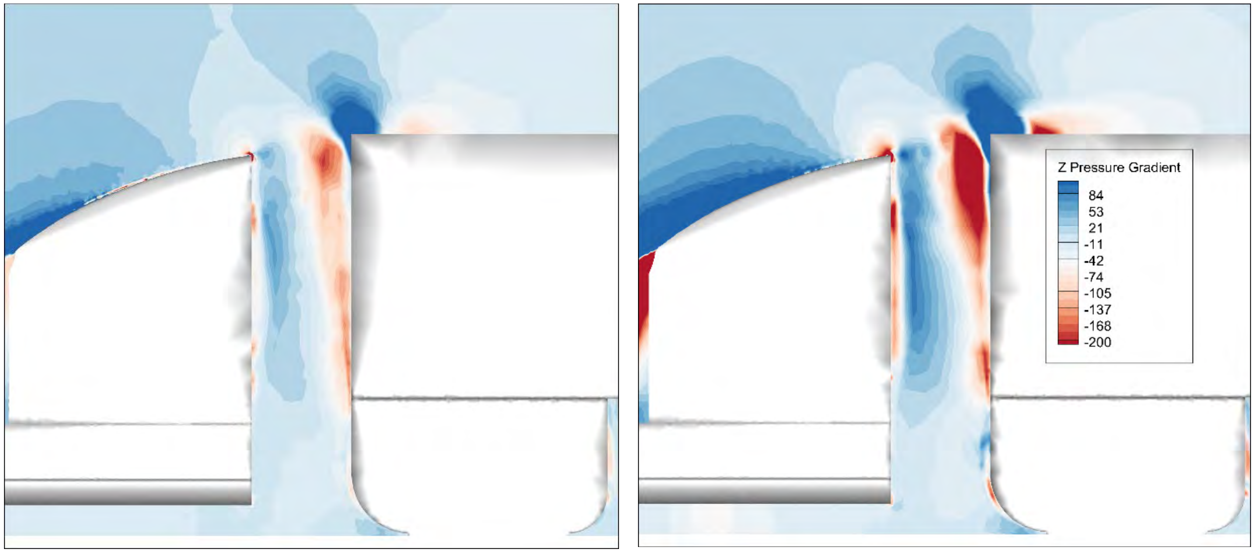
Single Vehicle Trailer Front Surface



(a) 90 ft

(b) Single

Figure 41. Tractor-trailer interface offcenter pressure gradient

- Apparent contradiction
  - In 90 ft case, the higher mean flow speed resulted in lower pressure force
  - Extrapolating this to the single vehicle would result in the lowest surface pressure when it actually has the highest
- Higher mean flow speed of single vehicle
  - Does result in increased vortex strength and lower pressure in the cavity region
  - Z direction pressure gradient is greatly increased
  - Much larger gradient translates to much larger pressure at surface
- Highlights the nonlinearity of the Navier-Stokes equations

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Three Vehicle

- Examined to determine if the influence of a vehicle extended beyond the immediate neighbors
- Both homogenous and heterogeneous distances tested
- Four equidistant cases: 20, 40, 60, 80 ft
- Two non-equidistant
  - Vehicle 1 and 2 spacing 20 ft, Vehicle 2 and 3 spacing 80 ft (20/80)
  - Vehicle 1 and 2 spacing 80 ft, Vehicle 2 and 3 spacing 20 ft (80/20)

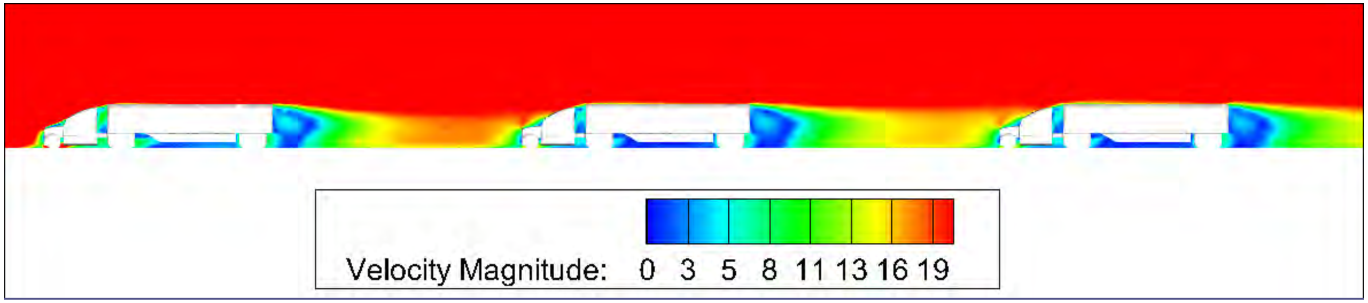

Figure 42. Three vehicle velocity profile, 80 ft spacing

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Three Equidistant Vehicle Results

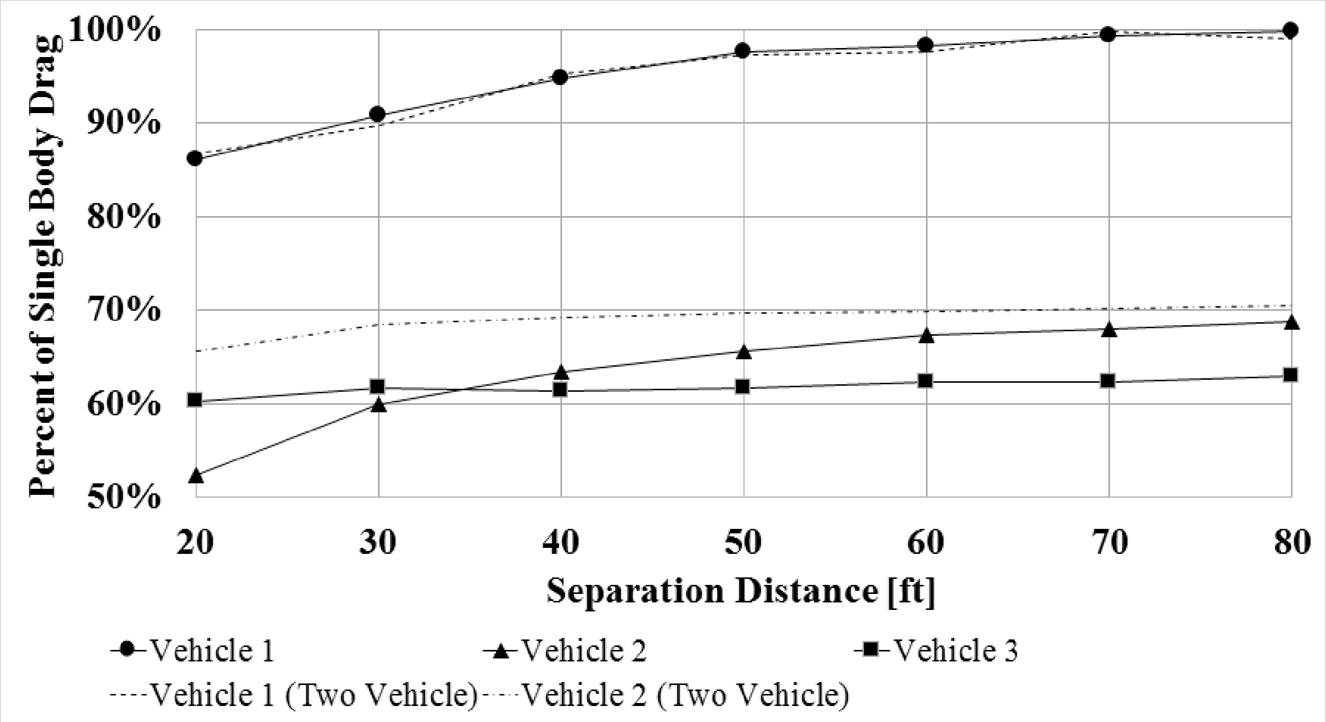

Figure 43. Three vehicle drag vs spacing

- Vehicle 1 nearly identical
  - Vehicle 3 has no influence
- Vehicle 2 reduced
  - Vehicle 1 drastically slows the flow in front of Vehicle 2
  - Vehicle 3 interferes with Vehicle 2 wake at close distances
- Vehicle 3 appears to be nearly constant
  - Vehicle 2 only slows the flow less than Vehicle 1 from a relative perspective
  - Has more drag than Vehicle 2 at very close spacings

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Three Vehicle Surface Drag Reduction

- Tractor surfaces on Vehicle 2 and 3 saw very close tractor drag reduction percentage between 20 ft and 80 ft
  - Indicates flow is similarly structured, magnitudes causing proportional amounts of drag
- Vehicle 1 saw a larger percentage reduction than Vehicle 2
  - Shows that the higher speed flow behind Vehicle 1 has more potential for pressure reduction via wake interference
- Sharp tractor drag reduction from Vehicle 1 to 2, less between 2 and 3 at 20 ft spacing
  - Illustrates force-velocity squared relationship
  - Large mean flow speed reduction from 1 to 2 results in large decrease, mean flow reduction
  - "Diminishing returns"
- Trailer rear drag increases from Vehicle 2 to 3 at 20 ft
  - Confirms Vehicle 3 wake interference hypothesis and explains why Vehicle 2 has lower total drag

Table 4. Vehicle Surface Drag reduction between 20 ft and 80 ft

Tractor	
Vehicle 2	37.6%
Vehicle 3	35.2%
Trailer Rear	
Vehicle 1	43.6%
Vehicle 2	36.1%

Table 5. Inter Vehicle Surface Drag – 20 ft

Surface	Vehicle 1 to 2	Vehicle 2 to 3
Tractor	55.5%	8.2%
Trailer Front	24.4%	5.1%
Trailer Rear	9.7%	-68.8%

Table 6. Inter Vehicle Surface Drag – 80 ft

Surface	Vehicle 1 to 2	Vehicle 2 to 3
Tractor	29.0%	11.6%
Trailer Front	68.1%	8.7%
Trailer Rear	20.2%	3.6%

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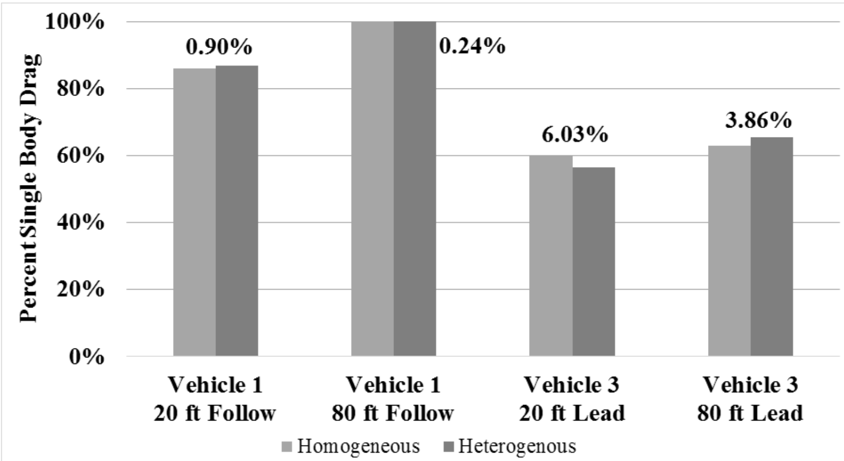
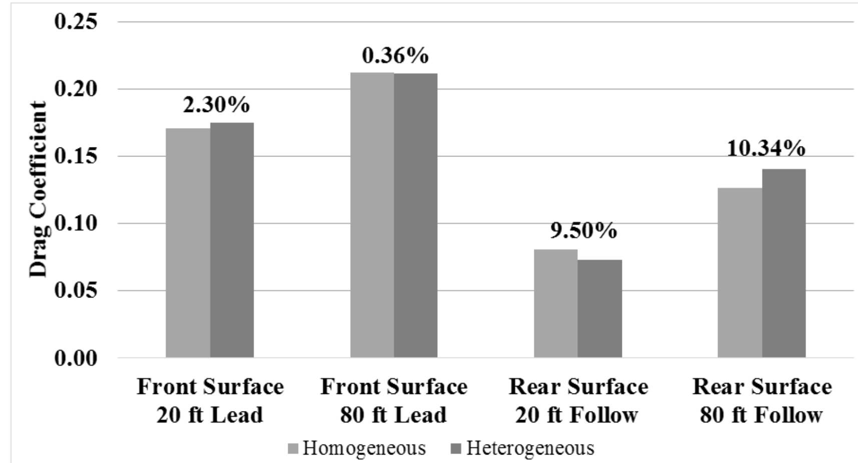
Three Vehicle Non-equidistant Comparison



(a) Vehicle 1 and 3



(b) Vehicle 2

Figure 44. Homogeneous and heterogeneous drag comparison

- Can directly compare homogeneous and heterogenous cases for Vehicle 1 and Vehicle 3
  - No other vehicle influencing front and rear surfaces, respectively
  - Vehicle 1 virtually indistinguishable
  - Vehicle 3 sees slight differences, not negligible
- Vehicle 2 must be analyzed by surface (front surfaces compared for identical frontal spacings, likewise for rear)
  - Frontal surface nearly identical, rear sees ~10% difference
- Following vehicle spacing can have no upstream effect beyond the immediate vehicle
- Leading vehicle spacing has an effect, albeit limited, on downstream vehicles beyond adjacent bodies
  - Vehicle 2 rear surface and Vehicle 3 saw less drag when Vehicle 1 was farther away
  - Cause can be related back to Crocco's theorem

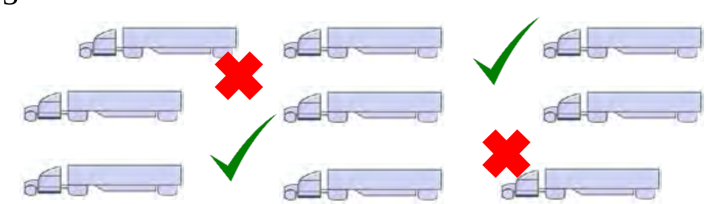


Figure 45. Vehicle 2 case comparison

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Multiple Geometry Two Vehicle

- Rear vehicle tractor geometry was varied to determine effect on savings
  - Peterbilt 579 – modern tractor designed for aerodynamic performance
  - Peterbilt 379 – traditional tractor
  - Mercedes-Benz ACTROS – flat-nose style tractor differing greatly from the P579 and P379
- Distances simulated: 20 ft, 40 ft, 60 ft, 80 ft
- Vehicle drag presented as a percentage of corresponding single vehicle drag

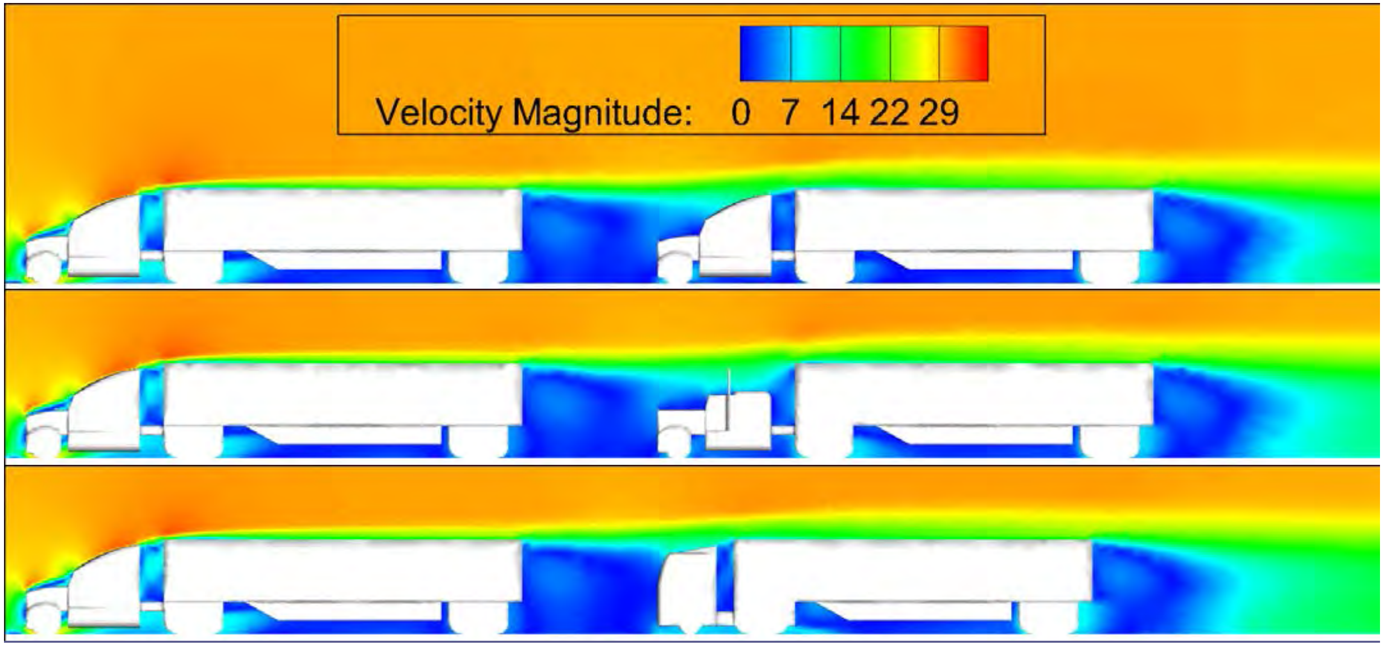

Figure 46. Multiple geometry velocity profile, 20 ft spacing – P579 (top), P379 (middle), MBA (bottom)

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Lead Vehicle Drag Reduction

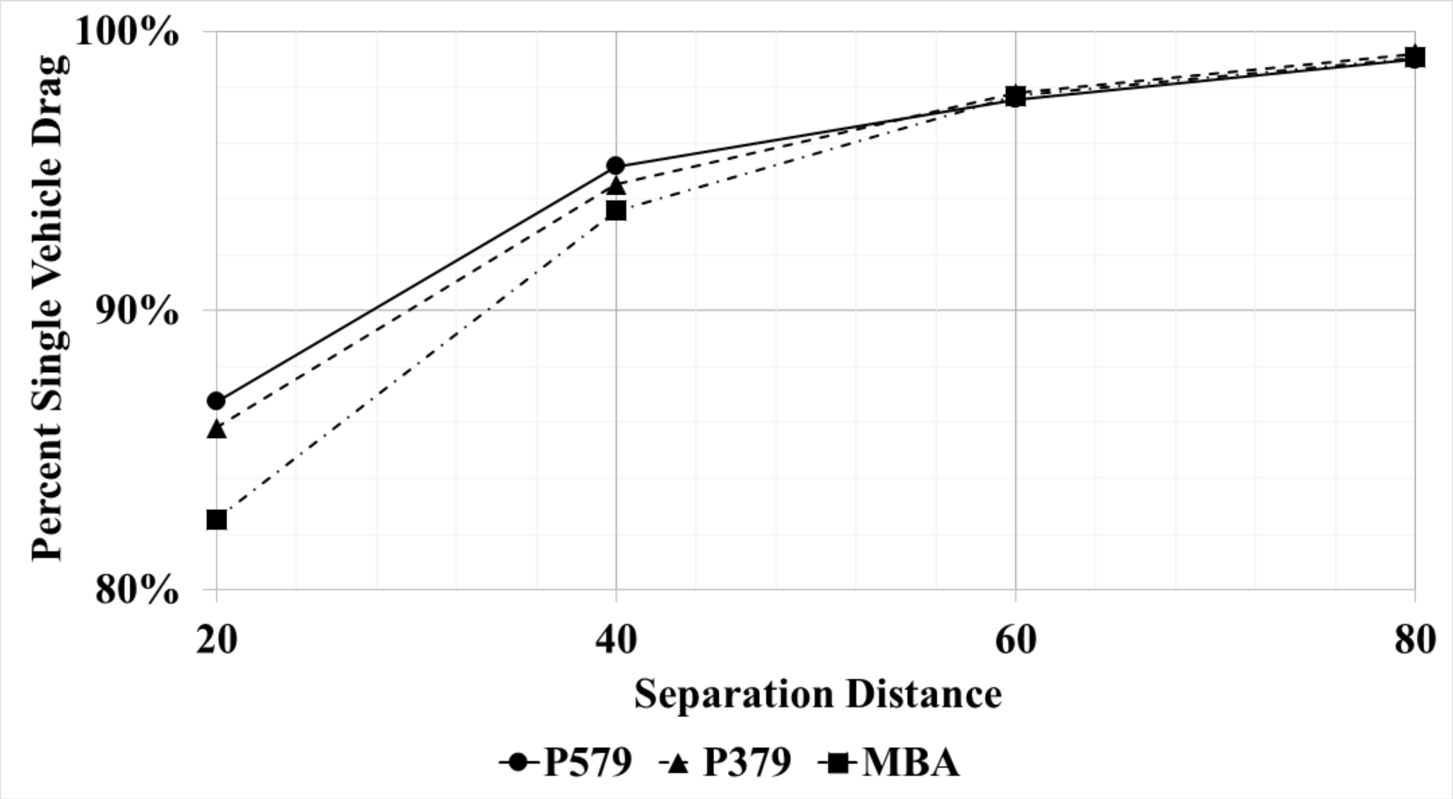

Figure 47. Multiple geometry lead vehicle drag reduction

- All geometries offer little reduction at far distances
  - Result of limited upstream influence via wake interference
- P579 and P379 offer similar percent reductions
- MBA offers noticeably more drag reduction to the leading vehicle at close distances

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Rear Vehicle Drag Reduction

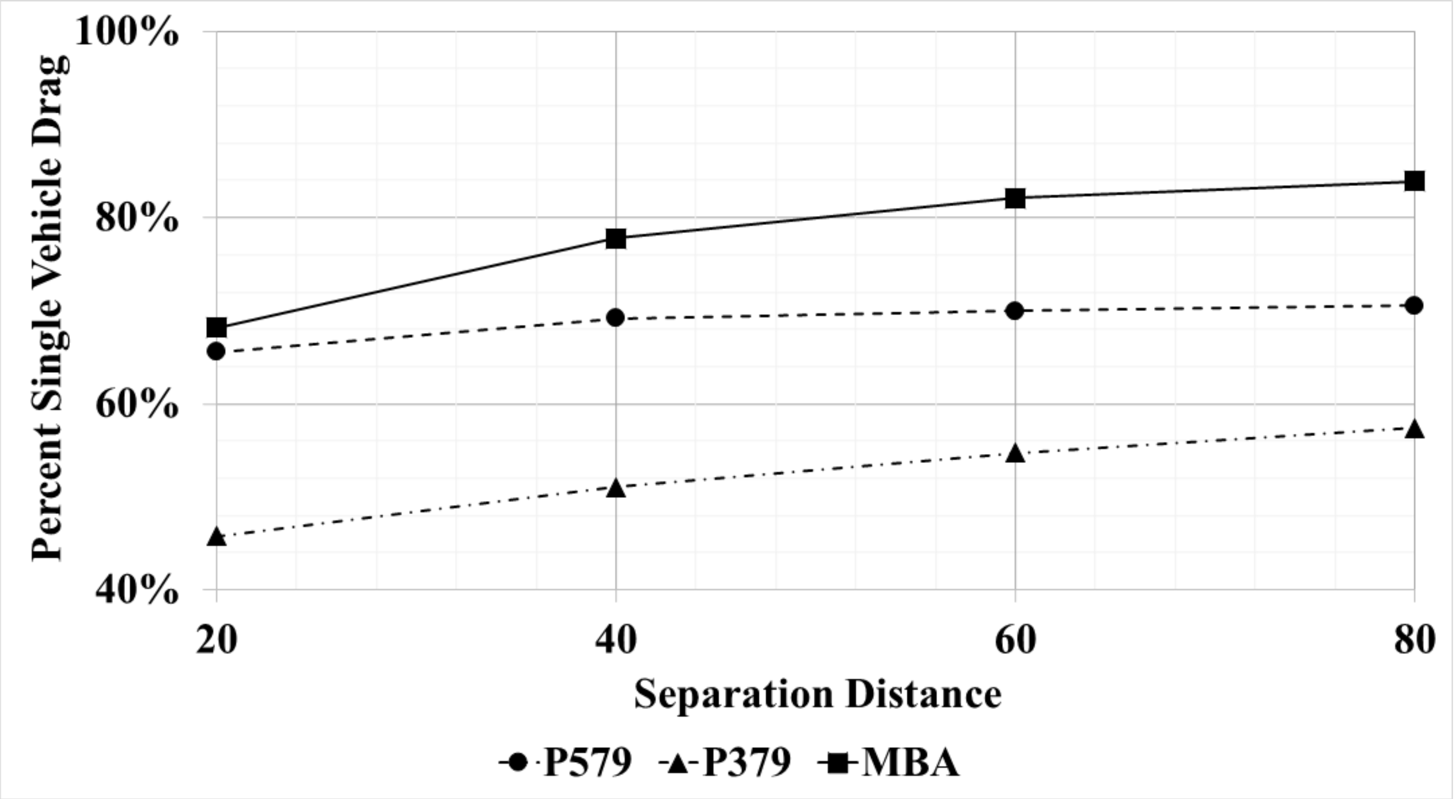

Figure 48. Multiple geometry lead vehicle drag reduction

- Mercedes-Benz ACTROS – Least benefit
  - Only at very close distance does it begin to overtake P579, due to a steeper slope
- Peterbilt 579 – Medium benefit
  - Decreases much more slowly than MBA as spacing decreases
- Peterbilt 379 – Most benefit
  - Lack of aerodynamic hood fairing still causes the main contributor to be the trailer front surface
  - Greatly reduced drag magnitude causes resulting drag force comparable to P579
- Desirable to have least aerodynamic vehicle in the follow position, platoon sees most overall benefit

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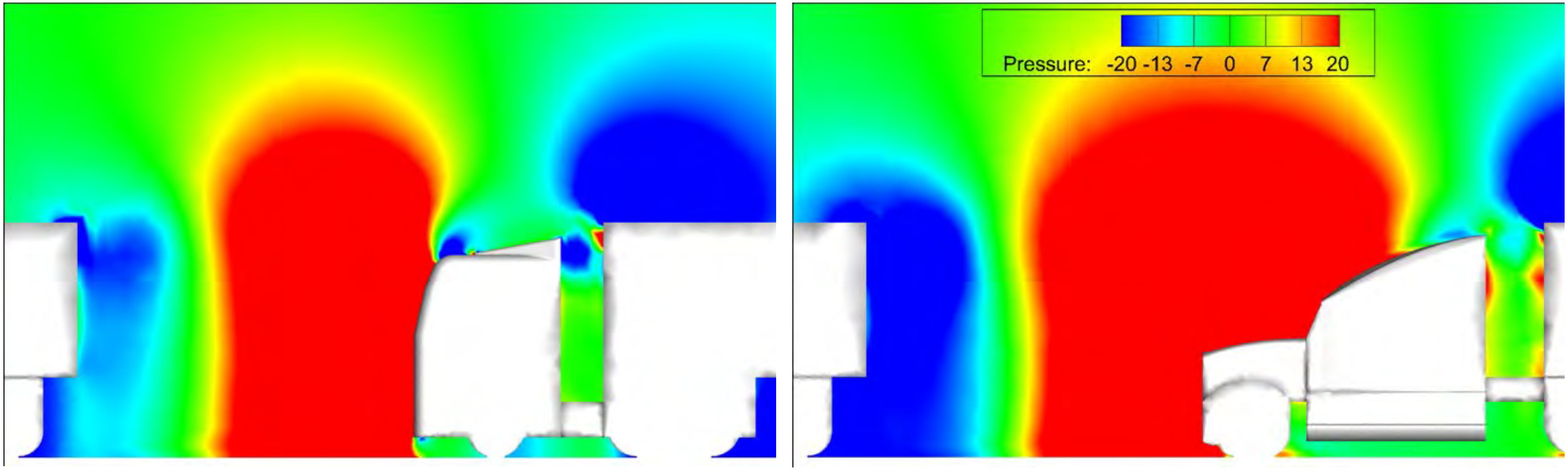
MBA Pressure Distribution



(a) MBA (b) P579

Figure 49. Inter-vehicle pressure distribution, 20 ft separation

- Flat-nose results in larger flow “footprint”
  - Larger upstream disturbance
  - Increased wake interference
  - Reduces rear drag on leading vehicle
- Pressure concentrated into single large region
  - More reduction at close distances
  - Less reduction at far distances

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Topics Covered

- Introduction & Motivation
- Meshing and Simulation Methodology
- Simplified Car Body
  - One body
  - Two body
- Single Heavy Vehicle
  - Baseline model
  - Three vehicle geometry
- Multiple Heavy Vehicle
  - Two vehicle
  - Three vehicle
  - Multiple geometry two vehicle
- Conclusions & Future Work

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Two Vehicle Conclusions

- Three well-defined regions for rear vehicle
  - Wake
  - Slipstream
  - Freestream
- Wake
  - Both vehicles see large savings
  - Vehicle 2 interferes with the formation of Vehicle 1 wake, reducing rear drag
- Slipstream
  - Vehicle 1 experiences no benefit
  - Vehicle 2 sees an approximately constant drag force, which is reduced from the single vehicle drag
- Freestream
  - Rapid transition from slipstream to freestream at termination of Vehicle 1 wake
- Most savings generated by small separation platoons
  - Still possible for following vehicles to experience significant savings at multiple body lengths

Three Vehicle Conclusions

- The influence of a vehicle is severely limited beyond adjacent vehicles
  - No upstream influence
  - Little downstream influence
- Interior vehicles see the largest benefit
  - Frontal drag reduction from preceding vehicle
  - Rear drag reduction from following vehicle
- Larger platoons generate more savings on a per vehicle basis than smaller platoons

Multiple Geometry Conclusions

- Lead vehicle benefit is dependent on follower tractor geometry
- Comparisons between MBA and Ahmed body can be drawn due to bluntness
  - MBA sees less benefit than P579
  - Rapidly decreases at extremely close following distances
- Least aerodynamic vehicle in the rear generates the most overall benefit for the platoon

Applications to Highway Environments

- Aerodynamic drag is the #1 contributor to force at highway speed
- Drag reduction offered by platooning is an immediate, low cost method to generate fuel and cost savings
- Implementation of the CACC system allows for safe platooning at distances that generate large savings
- Considerations beyond aerodynamics
  - Logistic concerns
    - Competing companies might not be willing to platoon if they are the leading vehicle, which sees less savings than the follower
  - Traffic patterns
    - Large platoons may congest roadways
  - Safety
    - Least aerodynamic vehicle may have the worst braking performance

Recommended Future Investigations

- Compare simulated results to experimental data
  - Requires accurate drag force-fuel consumption relational model
- Transition fully to DES model
  - Allows development of time-averaged flow profiles
  - Generate solutions at large separation distances
- Investigation of rear vehicle drag at large distances
  - Nearly constant in slipstream
  - Transition from slipstream to freestream

Questions

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