Drag Reduction Achieved through Heavy Vehicle Platooning

Thesis Defense

Andrew Watts

04/15/2015
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
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]
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
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
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
    \[
    \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
    \]
  - Conversation of Momentum
    \[
    \frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot (\mathbf{\tau}) + \rho \mathbf{g} + \mathbf{F}
    \]
- 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

- 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
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>
<thead>
<tr>
<th>Skewness</th>
<th>Element Quality</th>
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<tbody>
<tr>
<td>0</td>
<td>Ideal</td>
</tr>
<tr>
<td>0.01 – 0.25</td>
<td>Excellent</td>
</tr>
<tr>
<td>0.26 – 0.50</td>
<td>Good</td>
</tr>
<tr>
<td>0.51 – 0.75</td>
<td>Fair</td>
</tr>
<tr>
<td>0.76 – 0.90</td>
<td>Poor</td>
</tr>
<tr>
<td>0.91 – 0.99</td>
<td>Bad (Sliver)</td>
</tr>
<tr>
<td>1</td>
<td>Degenerate</td>
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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-corrector 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-\(\varepsilon\)
  - Detached Eddy Simulation

Figure 11. Wingtip vortex turbulence [8]

Figure 12. Solar wind turbulence [9]
Realizable $k-\varepsilon$ (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
  \[ k \equiv \frac{1}{2}(u'u' + v'v' + w'w') \]
- Turbulent Dissipation
  \[ \varepsilon \equiv \nu \frac{\partial v_i' \partial v_i'}{\partial x_k \partial x_k} \]
- Realizable
  - Satisfies physical constraints not applied in the standard k-epsilon to model turbulent viscosity $\mu_t$
  - 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

- 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

Figure 14. Error vs. mesh size variation
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>
<thead>
<tr>
<th>Model</th>
<th>Drag</th>
<th>Error</th>
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</thead>
<tbody>
<tr>
<td>RKE</td>
<td>0.26150</td>
<td>4.6%</td>
</tr>
<tr>
<td>DES-RKE</td>
<td>0.23899</td>
<td>4.4%</td>
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</table>

Figure 15. DES drag prediction over time

Figure 16. RKE (top) and DES velocity profiles
Two Ahmed Simulation

- 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
Two Ahmed Results

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

Figure 18. Two Ahmed drag coefficient
Simulation 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

Figure 19. Two Ahmed CFD vs. Wind Tunnel
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

Figure 20. Two Ahmed surface drag
Pressure Distribution

- 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

Figure 21. Two Ahmed surface drag
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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
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

Figure 25. MBA CAD (b) Simplified

(a) Original

Figure 26. P379 (a) Original  (b) Simplified
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
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

Figure 29. Workaround feature example
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>
<thead>
<tr>
<th>Model</th>
<th>Drag</th>
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</thead>
<tbody>
<tr>
<td>P579</td>
<td>0.5271</td>
</tr>
<tr>
<td>P379</td>
<td>0.8766</td>
</tr>
<tr>
<td>MBA</td>
<td>0.5078</td>
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</table>

Figure 30. Single vehicle drag composition
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• Conclusions & Future Work
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

- 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

Figure 32. Two vehicle drag vs spacing
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)
• 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
Drag Composition by Surface

- **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
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:
  \[
  \vec{v} \times \omega = \nabla p + \frac{\nabla v^2}{\rho} + \frac{\nabla v^2}{2}
  \]

Figure 37. Tractor-trailer gap streamline

Figure 38. Rear vehicle trailer front pressure distribution
Trailer Front Surface Pressure

- 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
• **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**
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
Three Equidistant Vehicle Results

- 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
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

<table>
<thead>
<tr>
<th>Surface</th>
<th>Vehicle 1 to 2</th>
<th>Vehicle 2 to 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractor</td>
<td>37.6%</td>
<td>35.2%</td>
</tr>
<tr>
<td>Trailer Rear</td>
<td>43.6%</td>
<td>36.1%</td>
</tr>
</tbody>
</table>

Table 5. Inter Vehicle Surface Drag – 20 ft

Table 6. Inter Vehicle Surface Drag – 80 ft
Three Vehicle Non-equidistant Comparison

- Can directly compare homogeneous and heterogeneous 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 44. Homogeneous and heterogeneous drag comparison](image)

![Figure 45. Vehicle 2 case comparison](image)
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)
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

Figure 47. Multiple geometry lead vehicle drag reduction
### Rear 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

![Figure 48. Multiple geometry lead vehicle drag reduction](image)
MBA Pressure Distribution

- 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

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