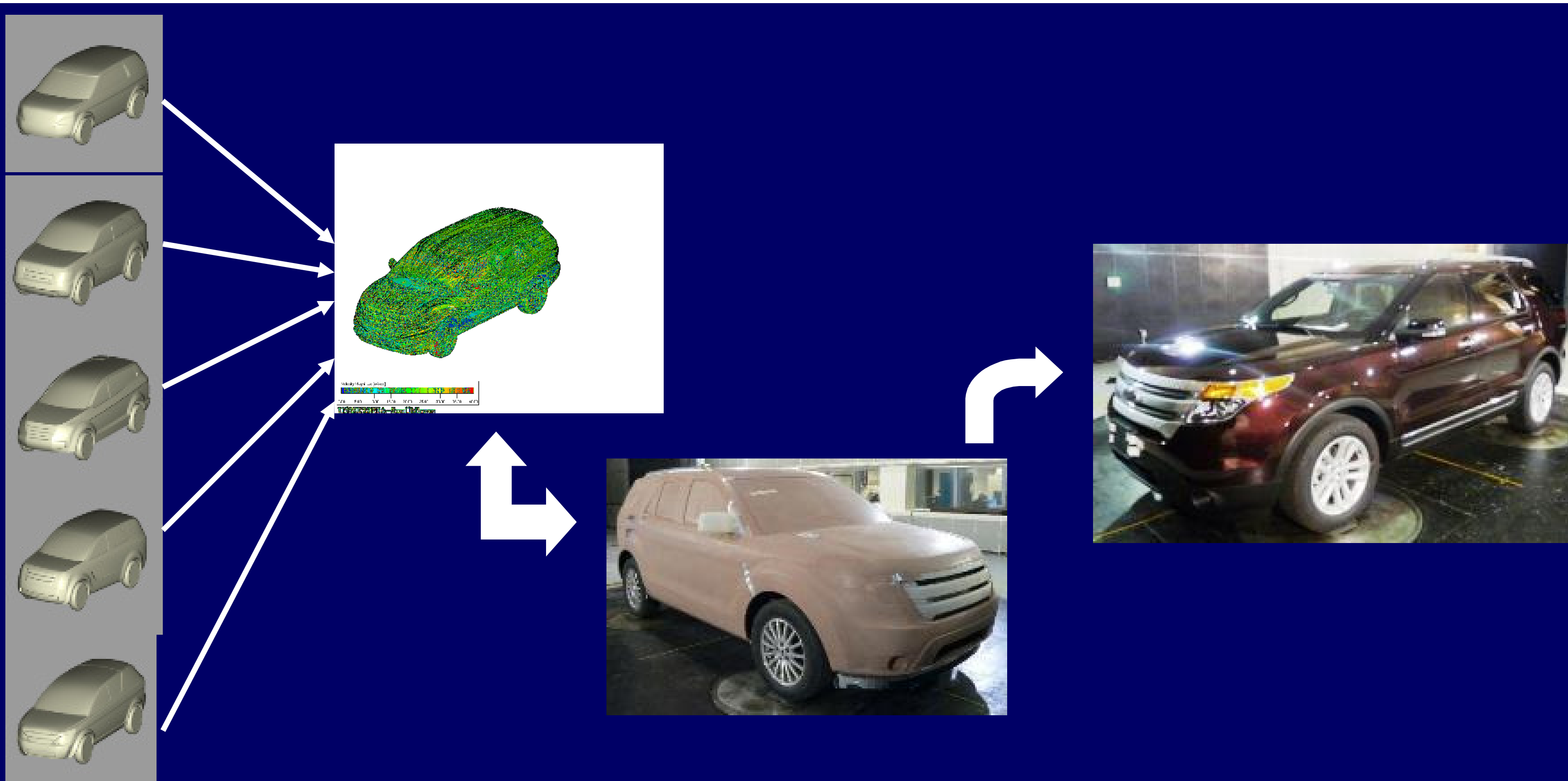
# *Aerodynamics Fundamentals for Automotive*

## *Ford Motor Company*

Neil Lewington



SAE-Australasia Aerodynamics Seminar

# Introduction

## Welcome

**The scope of this class is to provide a forum for all participants to freely exchange of knowledge and basic understanding and awareness of vehicle aerodynamics in the areas of:**

- **Impact of aerodynamic on fuel economy and related attributes**
- **Aerodynamic Fundamental.**
- **Aerodynamic and Vehicle Development Process**
- **Design Verification methods.**
- **Beware of public domain aero data**

The presenter would like to recognise the primary authors and contributors to this document from the global aerodynamics team. Bill Pien, Robert Leitz and Lothar Krueger

# Outline

- **Why Aerodynamic?**
- **Aerodynamic gives and gets, system interface**
- **Aerodynamic fundamentals**
  - Drag
  - Critical Xs
- **Aerodynamic process**
  - Vehicle development timeline
  - DV methods
    - Physical
    - Analytical
- **Media claims and gimmicks**
- **Q and A**

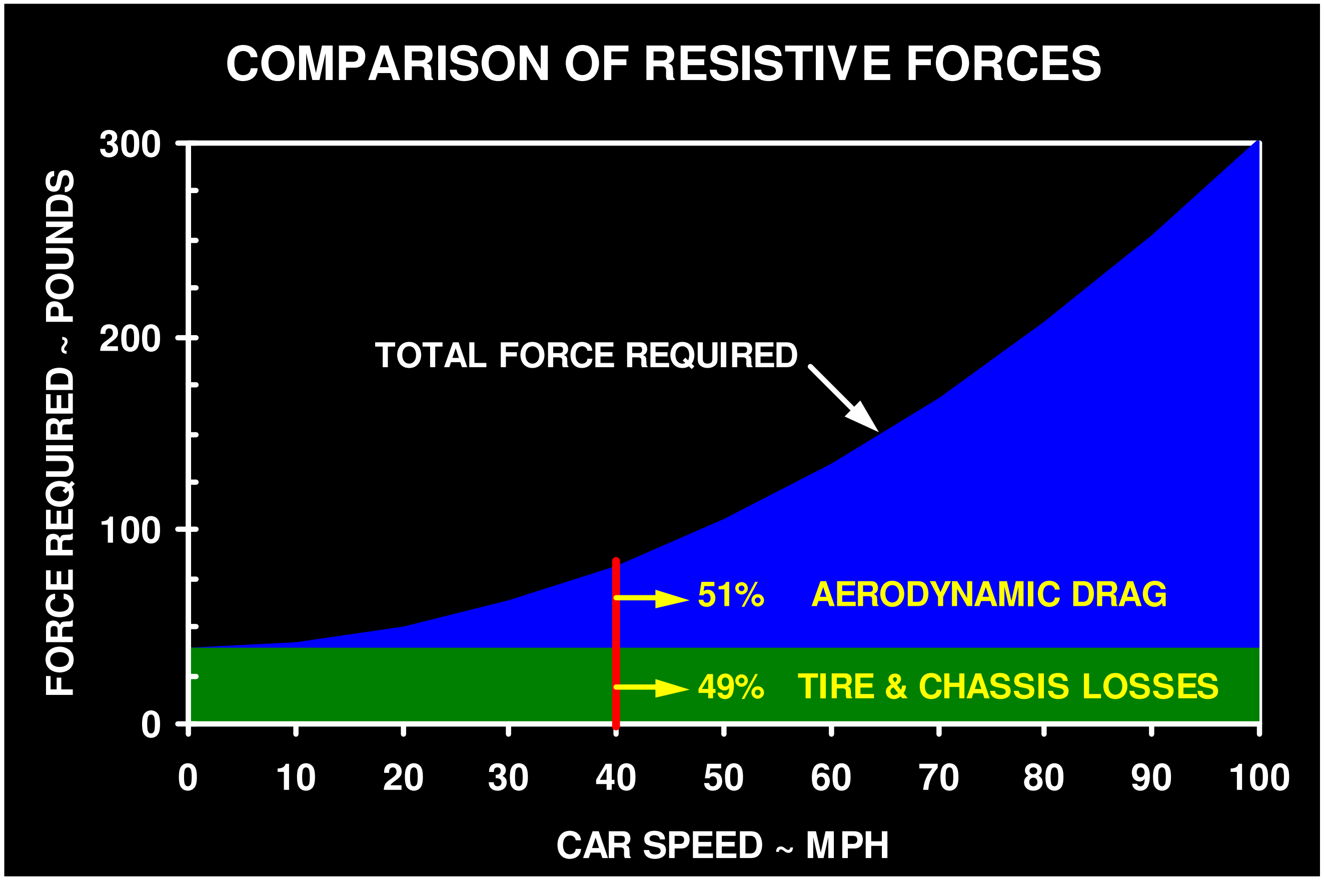
# Business Case

Fuel economy is a major contributor to the Ford sustainability strategy.

Fuel economy is a top “reason to buy”.

Aerodynamics is a major factor in total vehicle energy consumption.

# Why is Aerodynamics important?



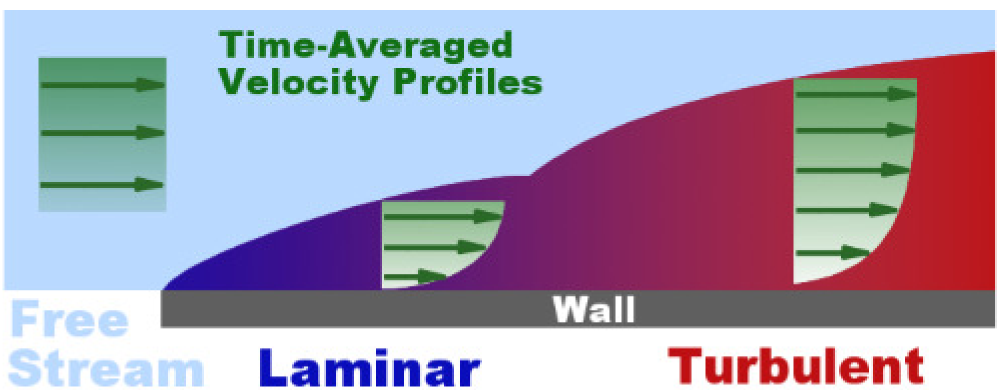

Drag = $k_1 V^2$

Energy = $k_2 V^3$

**Aerodynamic Drag contributes more than 50% of the resistive force starting from 40 mph (64kph)!**

# Fluid mechanics Primer

- **Reynolds number (Re), ratio between inertia and viscous force.**
  - $Re = \rho V d / \mu$, where d = characteristic length = Overall length of the car
- **Mach number (M), ratio between vehicle speed and speed of sound at sea level (760mph)**
  - Aero work with 80 mph, M ~ 0.1 ➔ <u>We are dealing with incompressible flow!</u>
- **Boundary layer.**
  - Due to viscosity, friction force retards the motion on the surface of the vehicle. The influence of friction force lessens with distance away in the direction vertical to the surface and eventually disappears. Friction force increases moving forward in the direction of the flow. This fluid – solid interaction forms a thin layer near the surface and it is referred to as the boundary layer (thanks to Prof. L. Prandtl).



# Laminar vs. Turbulent flow

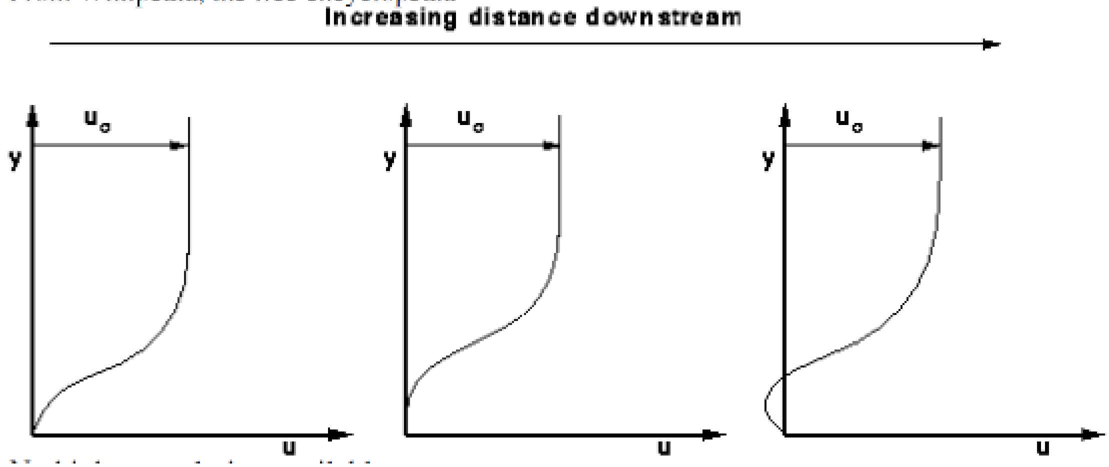
- Laminar flow: when the streamlines are parallel and the flow particles are travelling in the same direction.
  - $U = U_0$ = mean velocity
- Turbulent flow: when the streamlines seem to be parallel but the flow particles are fluctuating across the streamlines. It is time dependent.
  - $U = U_0 + u'$, $u'$ = fluctuation.

- Reynolds number is the key parameter to determine the type of flow.
- In aero development,
  - V = 80 mph (128 kph) = 117 ft/sec = 35.8 m/s
  - L = 16 ft (typical sedan)
  - $\mu = 0.375 \times 10^{-6}$ lbf sec / ft $^2$
  - $\rho = 0.00234$ lbf sec $^2$ / ft $^4$
  - $Re = \rho V L / \mu = 11.5 \times 10^6$
  - We are operating in region of turbulent flow.

# Flow separation / attachment

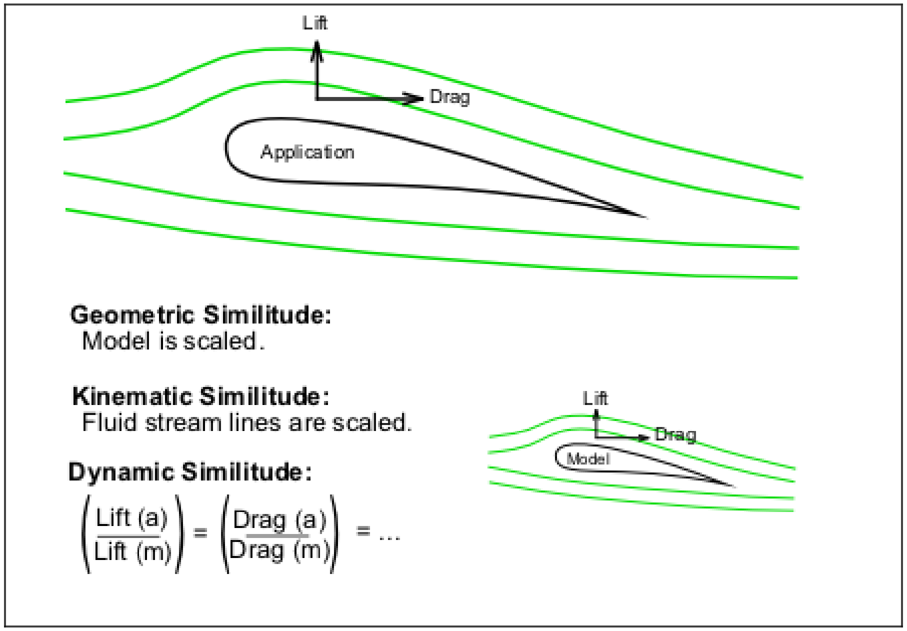
- The point on the surface where the inertia force of the near wall fluid particle equals the frictional force. The flow starts to reverse the direction, we refer to this as the separation point. Flow starts to separate or peel away from the surface.

From Wikipedia, the free encyclopedia




In general, this is BAD news for aero in the front but can be leveraged in the rear to reduce drag!

- **Law of similarity (similitude)**




Two identical models with different geometry scales and identical kinematics result in similar lift, drag forces and flow patterns.

This is the concept behind scale model wind tunnel testing.

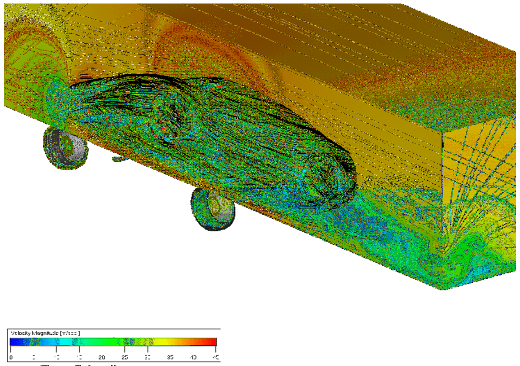
Scale model tests can be misleading due to:

- Difficult to replicate the fidelity of the full scale model.
- Local Reynolds number sensitivity.
- Test facility constraints.

# Vehicle Aerodynamics: A system approach to manage the air flow:

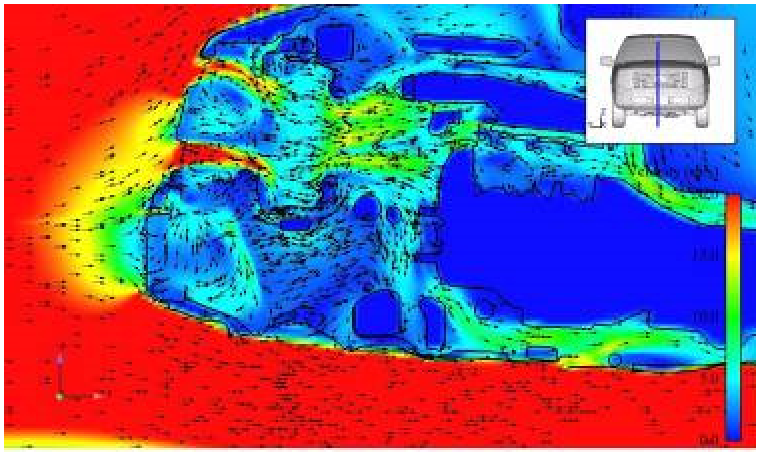
Over

, under



around

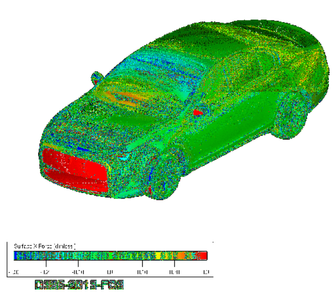
, and through



The vehicle to ---

# Minimize the

# Drag Force: Using analytical prediction or physical measurement



# With given constraints to maximize fuel economy.

- Design leadership
- Functional requirements
  - shields, wheels, etc
- Attribute requirements
  - weight, noise, water, etc
- Manufacturing requirements
  - assembly, sequence, etc

# Aero System look, interfaces (example)

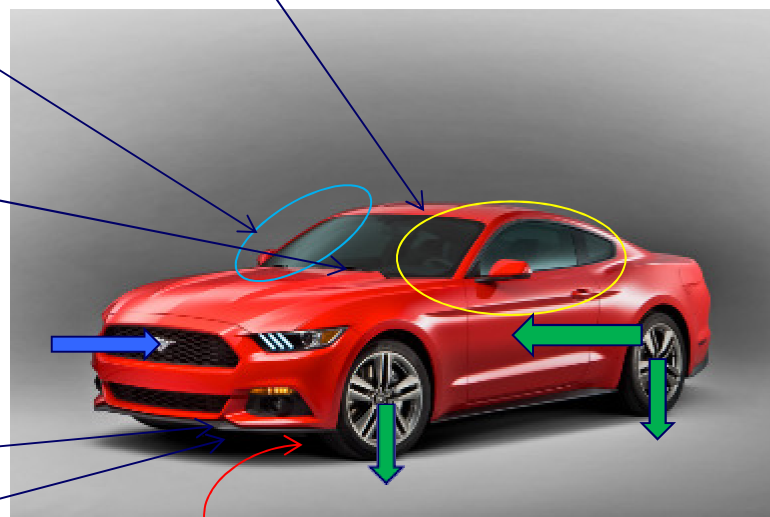
Vehicle MUST look great to get the customers into show room!

Wind noise : A-pillar, side glass, mirror shape and location, door deflection under wind load (TGW)

Water management: smoker window , A-pillar water channel

A&U: Sit x persons, meet all vision requirements with 5.0L engine. Meet ground clearance, approach angle. Off road capability (truck/SUV/CUV), ride height

Climate control: airflow for condenser, pressure a cowl, air extractor position



Thermal system: airflow for powertrain cooling with and without trailer

Vehicle Dynamics: lift/down force at front / rear axle and response to cross wind for driving dynamics (VER).

EESE: sensors for radar in the front open area

Thermal system: airflow for underbody heat management , e.g. carpet temperature (MDT)

Chassis: brake cooling, muffler shape, spare tire package, wheel design, tire selection

Body: panel vibration under wind load, underbody component (spoiler, tire spoiler, shields ) durability. Front bumper air dam deflection under wind load.

Deliver Cd and fuel economy targets within the cost target.

# Aero P-diagram

## Noise Factors

- Wind speed
- Wind direction
- Air density
- Vehicle speed
- Degradation with age
- Weather – rain, snow
- Vehicle attitude -loading
- Windows open/closed
- Customer modifications
- Vehicle build variation
  - Body panel margins/gaps
  - Ride heights
- Tire profiles

**Input Signal**
Vehicle Motion

**System:**
**Total Vehicle**

**Output Response**
Aero Drag Resistance

## Control Factors

### Program Control

- Frontal area
- Vehicle attitude – height & pitch
- Bumper Spoiler - Approach angle
- Body margins / gaps
- Mirror frontal area
- Underbody package
- Side glass offset

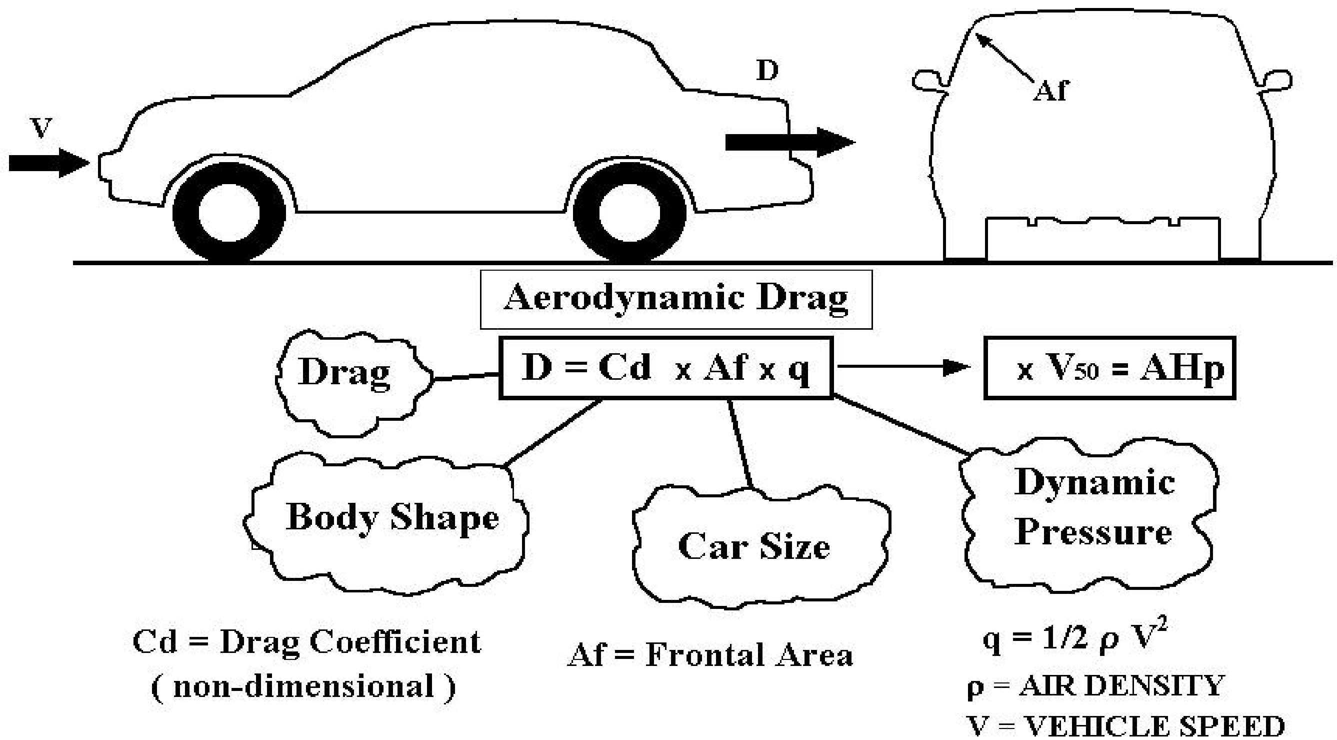
### TASE input

- Vehicle proportions
- Vehicle shape:
  - Hood & fender edge radius, SV & PV
  - Roof crown & taper
  - Backlite header radius
  - Tailgate top trailing edge radius
  - Box plan view taper
  - A Pillar shape
  - Mirror shape
  - Cooling drag

## Failure State

- Does not achieve Fuel Economy
- Bad appearance
- Customer dissatisfaction

**Aerodynamic Drag: Shape and size matter. Aero measures and calculates "Drag force" and reduces it to "drag coefficient".**




**Aerodynamic drag of a vehicle is determined by its shape, characterized by drag coefficient and its size, which is defined by the frontal area.**

# $C_d$: Drag Coefficient.

- It is a dimensionless parameter used to determine the shape efficiency
- In the wind tunnel, "Drag Force, D" is measured on the balance or calculated from CFD.
- Drag coefficient is calculated from the equation:

$$Cd = D \ / \ (q \times A_f),$$

where: $q$ = dynamic pressure = $0.5\rho \ V^2$, (aero test is set to q not V)

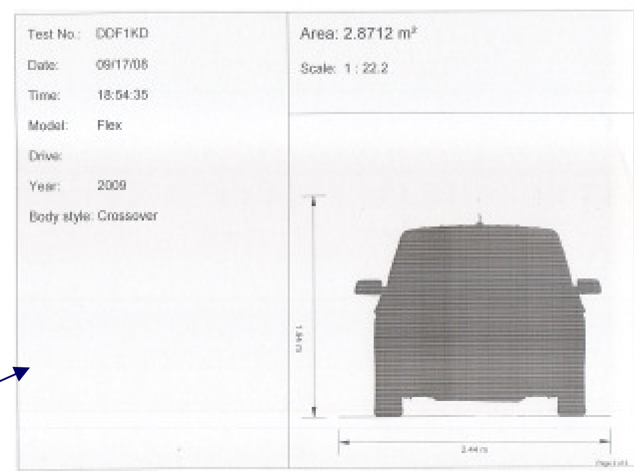
$\rho$ = density of the air, $V$ = straight head on air speed

$A_f$ = projected front silhouette

- For example,
  - A parachute has Cd = 1.35 while a typical wing as Cd ~ .05

# Af: Frontal Area (Attribute ownership/lead: A&U)

- It is a front silhouette of the "total vehicle".
- It can be measured with physical model or calculated from CAD or CFD models
- Not to be confused with "projected grille opening area".
- It has a unit of $Length^2$




Actual FAMS data

**The vehicle propulsion system needs to produce the equivalent amount of energy to overcome the aerodynamic drag.**

**At 50 mph:**

$$AHP = 0.5\ \rho\ V^3 C_d A_f$$

**At t = $68^0$ F, sea level (Hg = 29")**

$$\rho = .0022633 \text{ lbf sec}^2/\text{ft}^4$$

$$V = 50 \text{ mph} = 73.3 \text{ ft /sec}$$

$$AHP = 446.295\ C_d A_f \text{ (ft-lbf/sec)} \quad \text{.... Eqn (1)}$$

$$1 \text{ HP} = 550 \text{ (ft-lbf/sec)}$$

**Divide Equation (1) by the conversion factor;**

$$\boxed{AHP = .8114\ C_d A_f}$$

**AHP (Aerodynamic Horse Power) is the metric that influences fuel economy.**

$$AHP = .8114 * Cd * Af\ (ft^2)$$

**General rule of thumb:**

**1% reduction in AHP equates to:**

- 0.1 % increase in vehicle fuel

**Cd is a non-dimensional parameter that assesses shape efficiency.**

**Af is a dimensional parameter ($m^2$ or $ft^2$) which influences the AHP.**

# Drag Decomposition by major system (BMW)

A study conducted by BMW (2010):

| System | BMW |
|---|---|
| Upper body / proportion | 40% |
| Cooling drag | 10% |
| Under body / component | 20% |
| Tire / wheel / wheel arch | 30% |

- Based on typical BMW products.
- Percentage of opportunities for improvements.

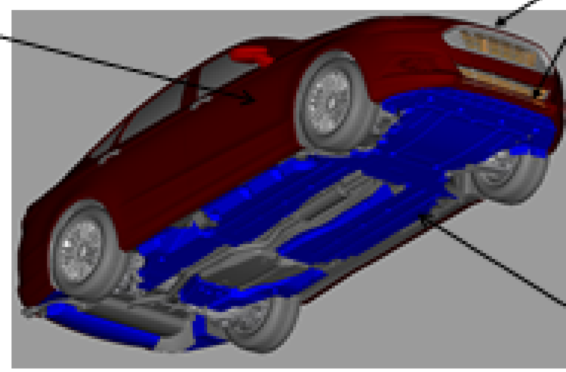
# Drag decomposition by major system (2013):

## 2013 Fusion Design for Aerodynamics

Go Further

**Designed for Styling/Aero (Red): 36%**
Integral approach with design studio: Assures smooth flow over leadership styling

**Addition of Full Active Grill Shutters With Optimized Sealing Pack (Orange): 23%**
Reroutes wasteful cooling flow when not required



**Shield Package (Blue) Increased and Optimized for Aerodynamics: 41%**
Smooths flow under vehicle, minimizing drag

Every facet of the Fusion has been improved for aerodynamics to provide maximum customer value and fuel economy:

- Top – Styling
- Underbody – Shielding
- Engine Compartment – Grille Shutters

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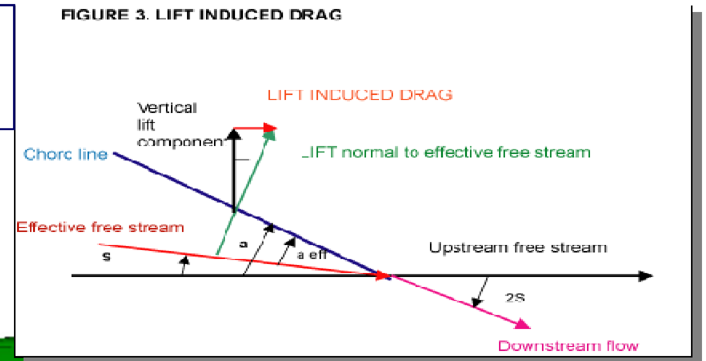
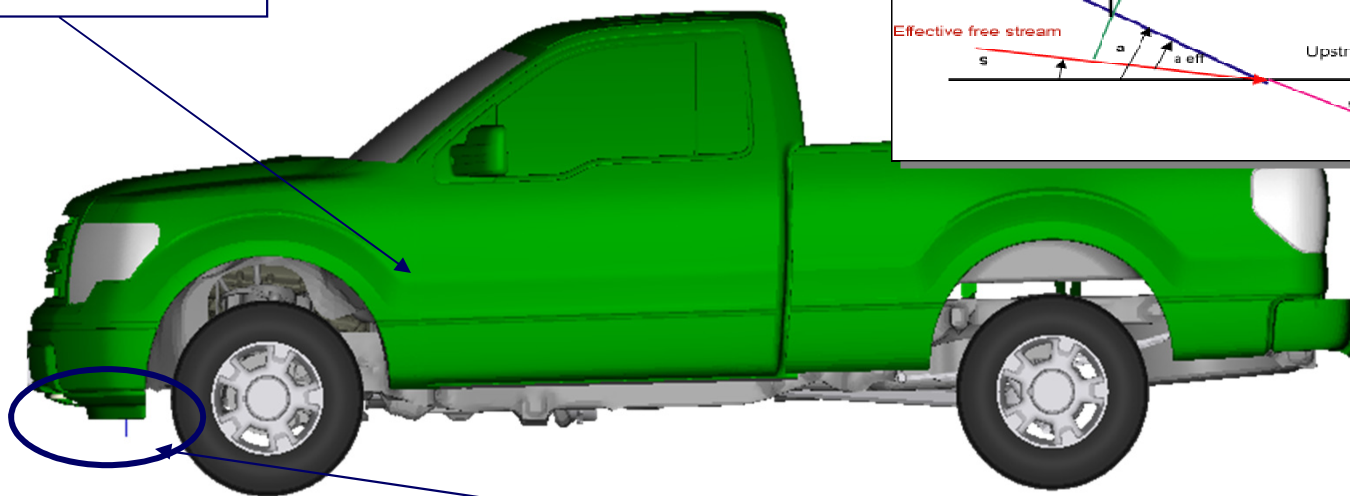
# Aerodynamic Drag Decomposition by Physics

Drag = Pressure (Form) drag + Skin Friction + Induced Drag + Interference Drag

Pressure (form) drag: drag generated from main body

Induced drag: drag induced by lift



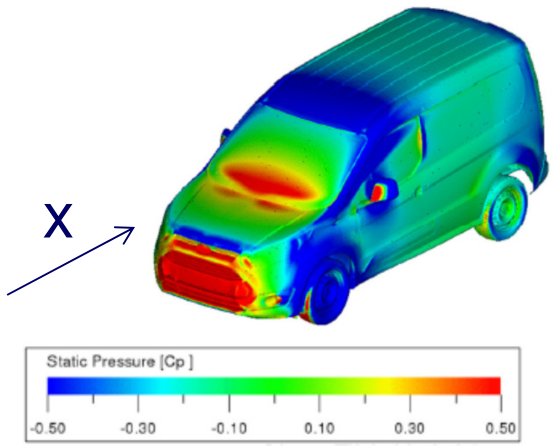



For automotive aerodynamic application, skin friction is much smaller than the other three sources and often not addressed in the aero development process

Interference drag: drag generated or reduced by components joined to the main body, depending on attachment.

# Drag: Form drag (Largest contributor)

Drag from surface pressure:

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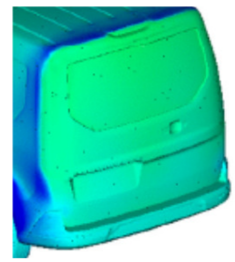

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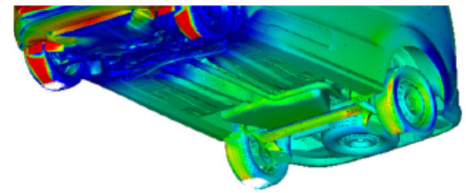


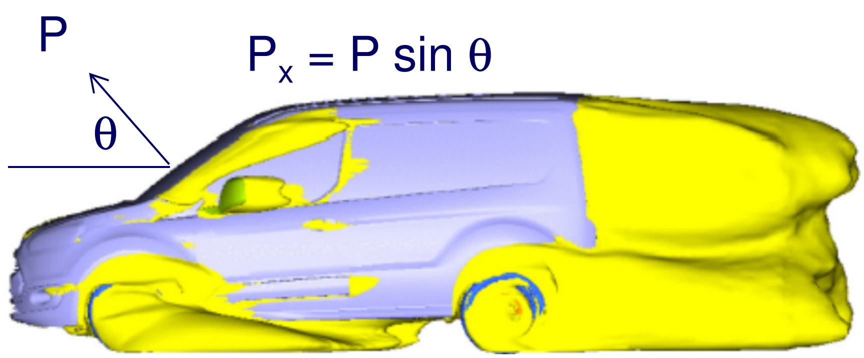
Drag due to pressure = $\int P_x \, d\,S$

S =surface area, upper, lower, front, back

+

Drag from pressure deficits/loses:

$P_x = P \sin \theta$



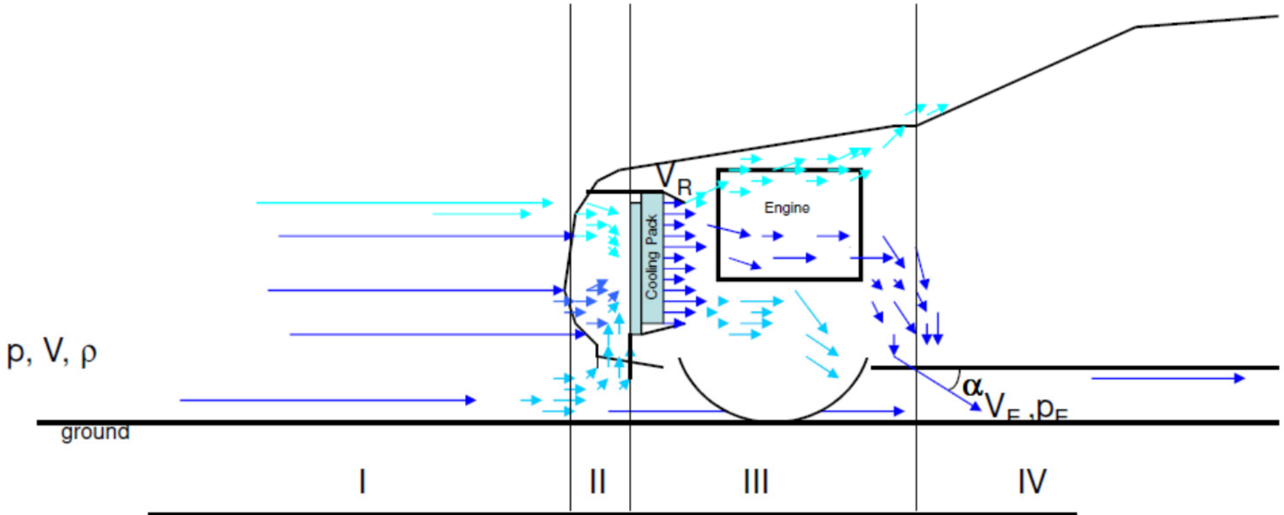

= Form Drag

# Cooling Drag: Second major contributor

\-

Cooling Drag ($\Delta C_{d,\,EC}$) = $C_{d,\,\text{open front end}} - C_{d,\,\text{closed front end}}$,

It measures the drag due to ram air (no rotating fan). It could contribute up to 14% of the total vehicle drag.

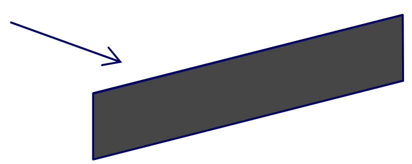



| Stage | I | II | III | IV |
|---|---|---|---|---|
| Kinetic energy and momentum losses through stages | Stagnation Point/Region and flow split | HEX inlet airflow and pressure | Engine bay Outlet airflow and pressure | Under body airflow and pressure |

# Interference Drag / Interactions:

Each body is a drag generating device but as a system it can:

- Reduce the drag of the system (favorable interaction)
- Increase the drag of the system (unfavorable interaction).
- Depends on how and where this piece is installed!



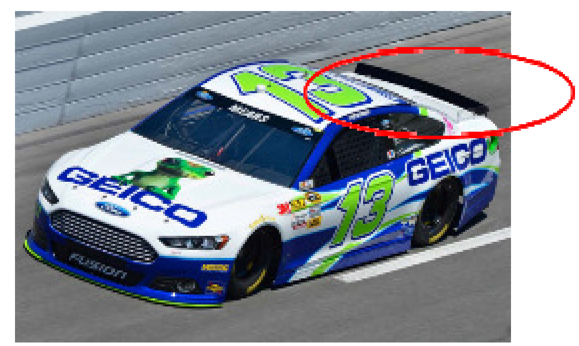
A vertical piece of blade is a high drag device.

## Favorable

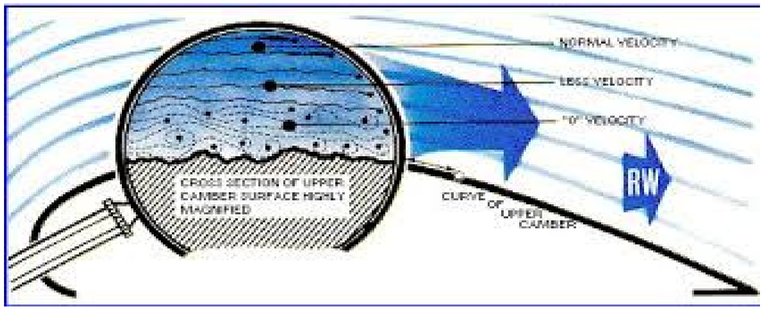
Example:
7% drag reduction from airdam on pick-up truck

## Unfavorable:

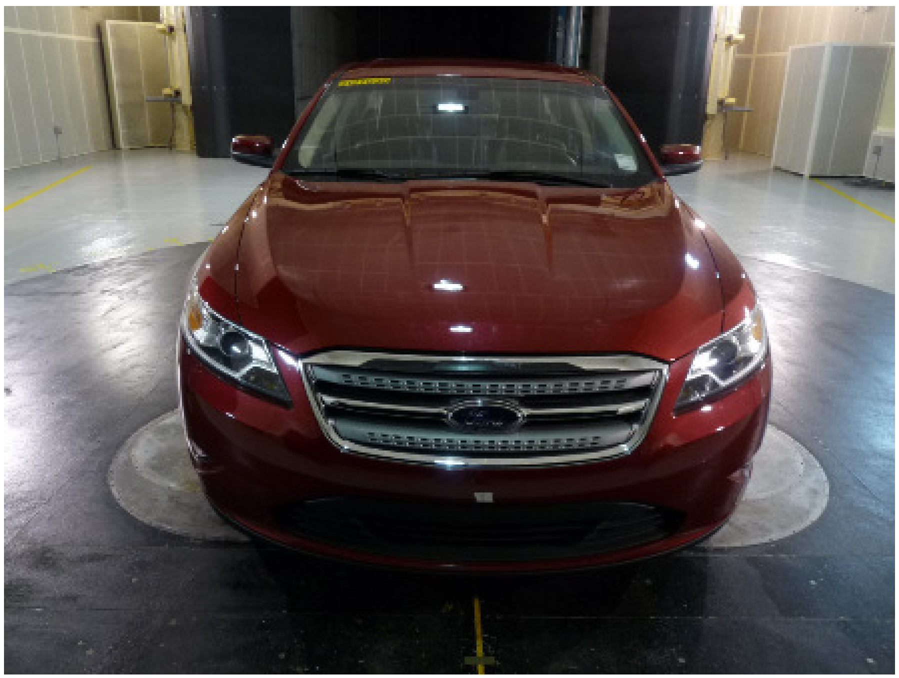
NASCAR deck spoiler, added to increase downforce. Drag increased.



# Skin Friction:




Very small impact on overall drag for automotive aerodynamics.



Aero did a test by applying a coating (claimed to have significant reduction in fuel consumption on airplane), Could not obtain any measurable drag reduction on a 2010 Taurus.

# "Critical Xs" in vehicle aerodynamics

- **Vehicle proportion (reference to Muto and Hucho)**
  - Ratio of OAL/OAH
  - Ratio of OAH/OAW
  - Other vehicle dimensions
    - Ground line /ground clearance, break ramp angle, wheelbase
    - Approach angle
    - Hood / bonnet height and length
    - Cowl height
    - Front overhang
    - Windshield / wind screen angle
    - Roof contour (taper, crown)
    - Back light angle
    - Deck / boot height and length
    - Departure angle
    - Rear overhang
    - Tumblehome angle
    - Pick up box (height, length, interaction with cab length)

# Critical Xs in vehicle aerodynamics

- **Design execution (after proportion being set)**
  - Front bumper and valance (plane view and side view, tire coverage)
  - Hood/grille intersection
  - Fender and wheel house molding
  - A-pillar section, wind shield header section
  - Mirror head and mount (sail or body mount), arm
  - Side glass / door offset
  - C / D pillar sections
  - Rocker section
  - Roof section and backlight header section
  - Quarter panel and tail light
  - Rear bumper / lower fascia
  - Lift gate / pick up box

(Details can be found in Aero Design Guide)

# Critical Xs in vehicle aerodynamics

- **Design execution to deliver favorable interaction and mitigate unfavorable interaction:**
  - Front chin spoiler (height, fore and aft position, cross section shape, fluid and structure interaction, body and assembly)
  - Air curtain
  - Underbody shield package
  - Tire spoiler (front and rear)
  - Roof rack
  - Wheel /rim shape, contour, opening
  - Active grille shutter
  - Wind throb feature
  - Seals
  - Tires

# Aero Process Applied to Typical Vehicle Programme

**Summary of the Aero process:**

- Customer Needs
- Vehicle Usage
- Design Concepts

→

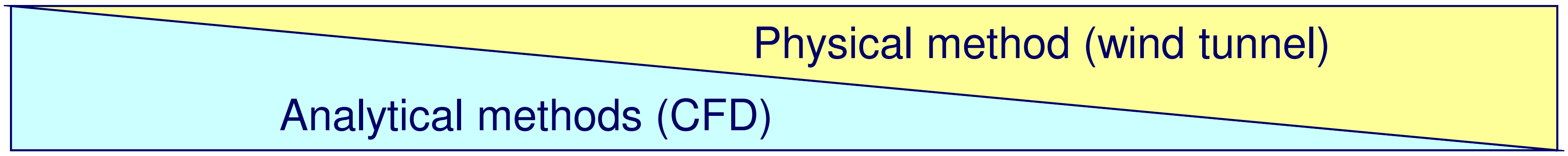
- Programme checkpoints
- Clay Model

→

- Vehicle Prototype

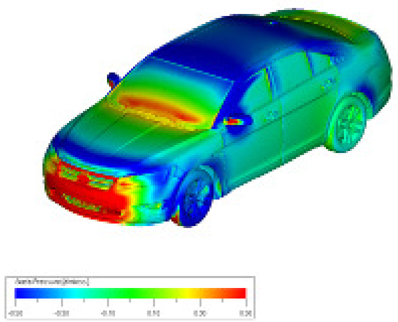
| Target setting | Negotiating | Compatibility | Objective | Confirm target with clay buck | Verify target |
|---|---|---|---|---|---|
| Proportion | Concept | Compatible with Design Leadership | | | |
| Theme evaluation | Multiple themes developed with customer and attribute focus | Single theme defined, engineering refinement for target compaibility | | | Vehicle test |

**DV methods:**



# Design Verification methods

## Analytical



Computational Methodology:

• Steady-State and Transient flow solutions to predict Aerodynamics drag coefficient

Model Complexity:

• Full vehicle:

  •Heat Exchangers, Fully Detailed Engine Bay, Underbody Components, Moving Ground & Rotating Wheels

Design Alternatives:

• Fully automated rapid morphing techniques

• Enables rapid evaluation of Design Studio changes

Data Analysis Capabilities:

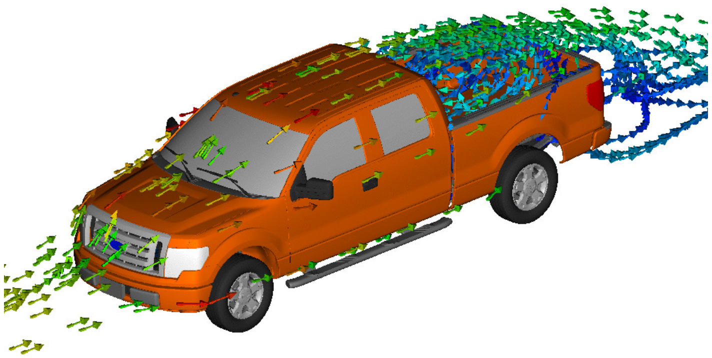
• Designed Experiments

• Statistical Analysis

• Optimization Algorithms

• Response Surface Methodologies

• Virtual Optimization Algorithms



Program Team Interface:

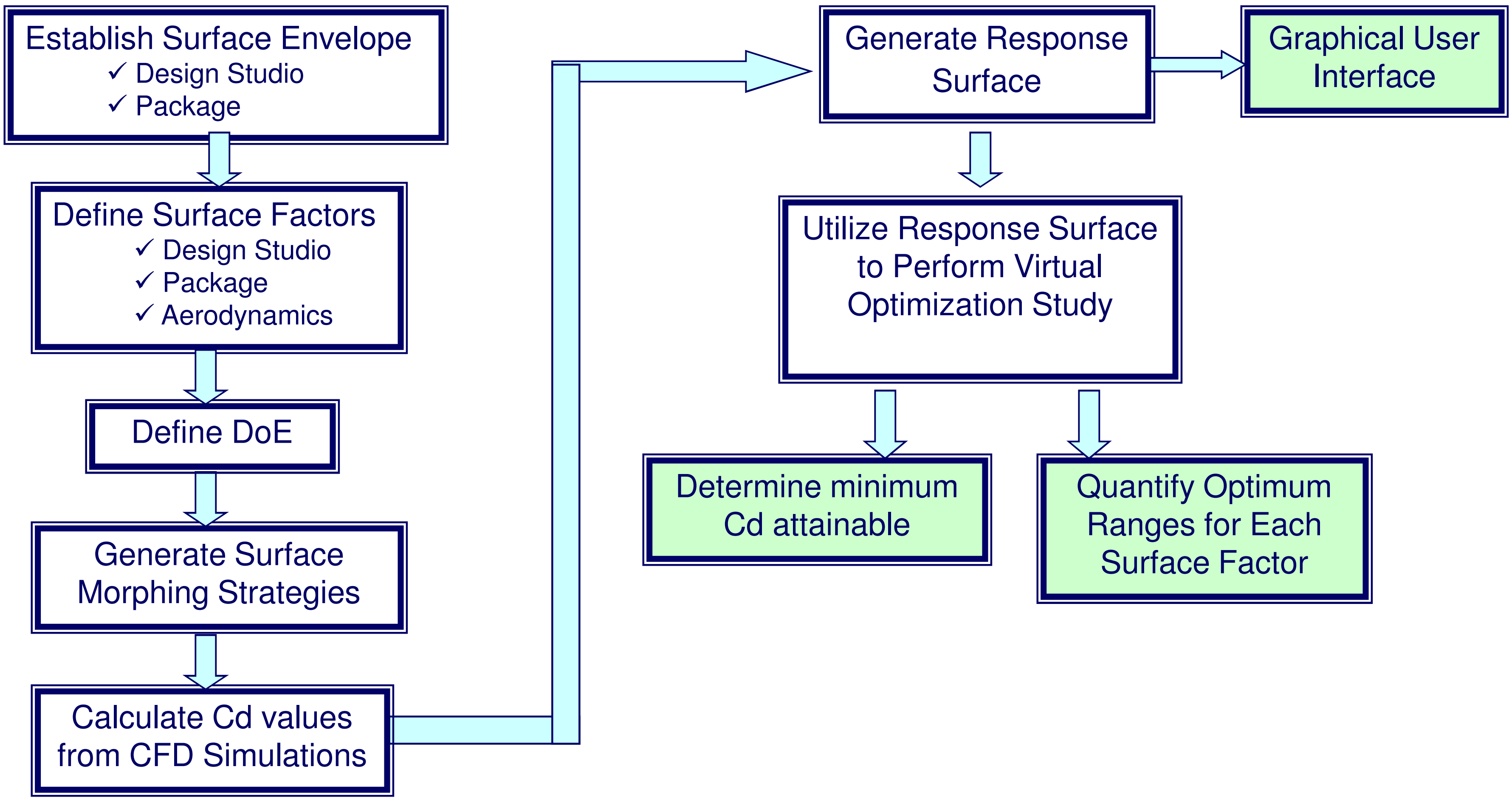
• Automatically generated graphics to enhance program communica

Compute Resources:

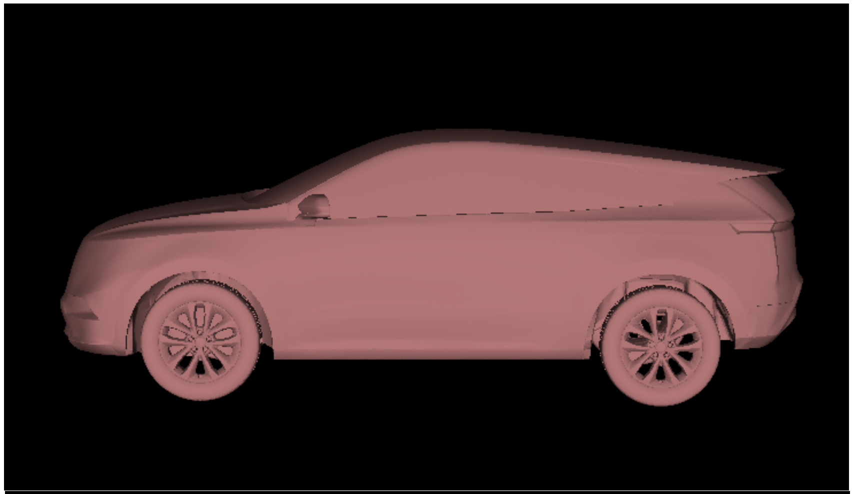
• In excess of 8 million cpu-hrs per year

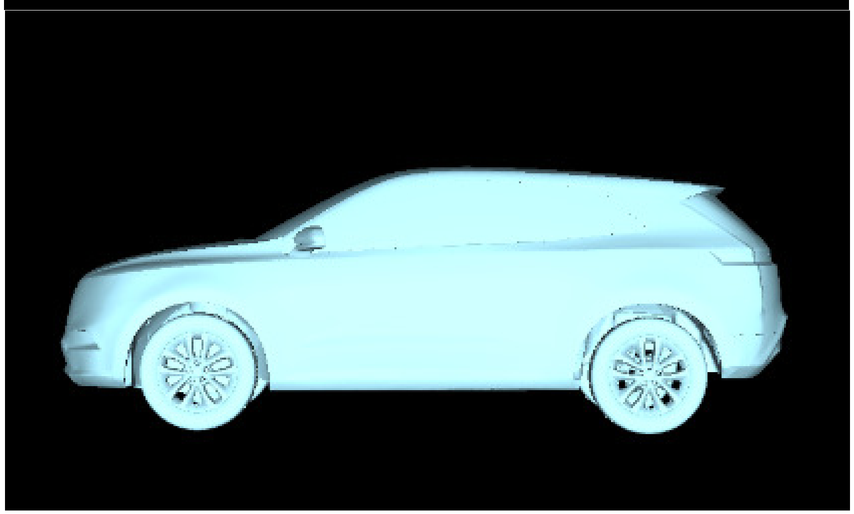
# Aerodynamics Analytical Development Process Flow Chart

(Integrates automated surface morphing and CFD analysis to support designed experiments, response surface generation, and optimization studies.)



# Rapid Morphing Steps



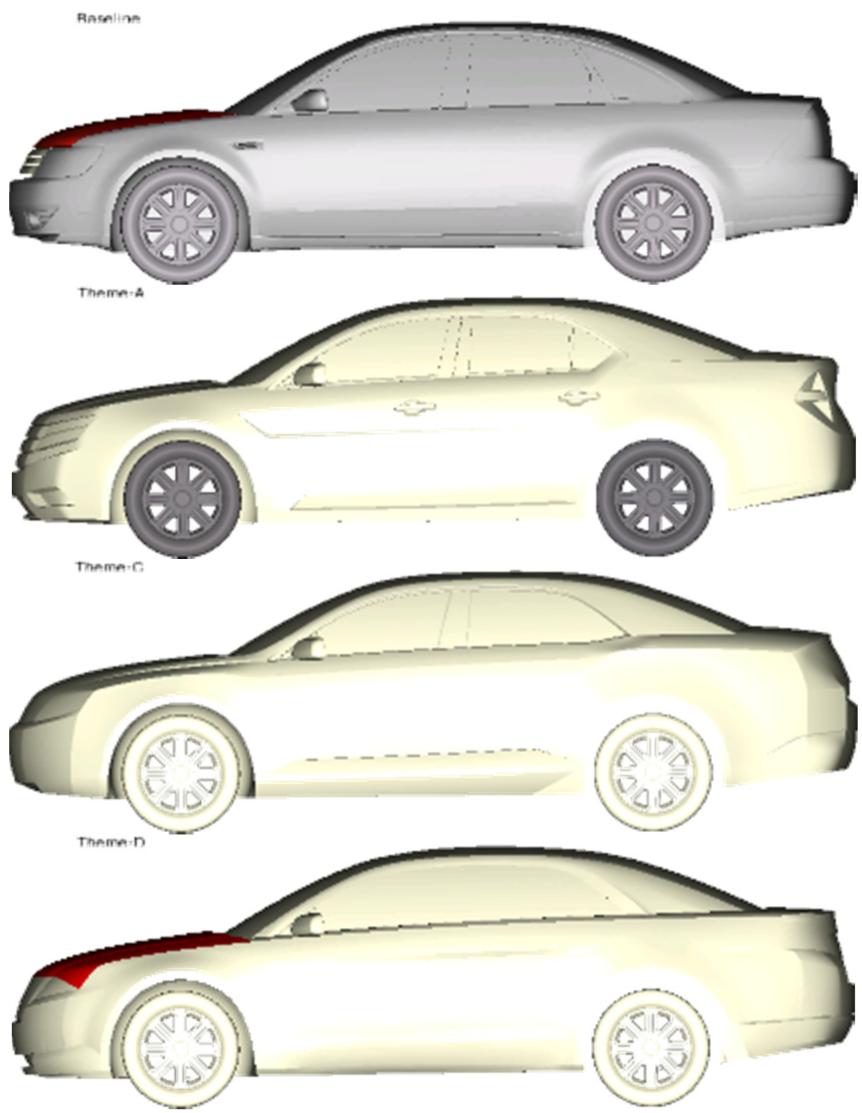


**Modifies DV file according to settings on screen**

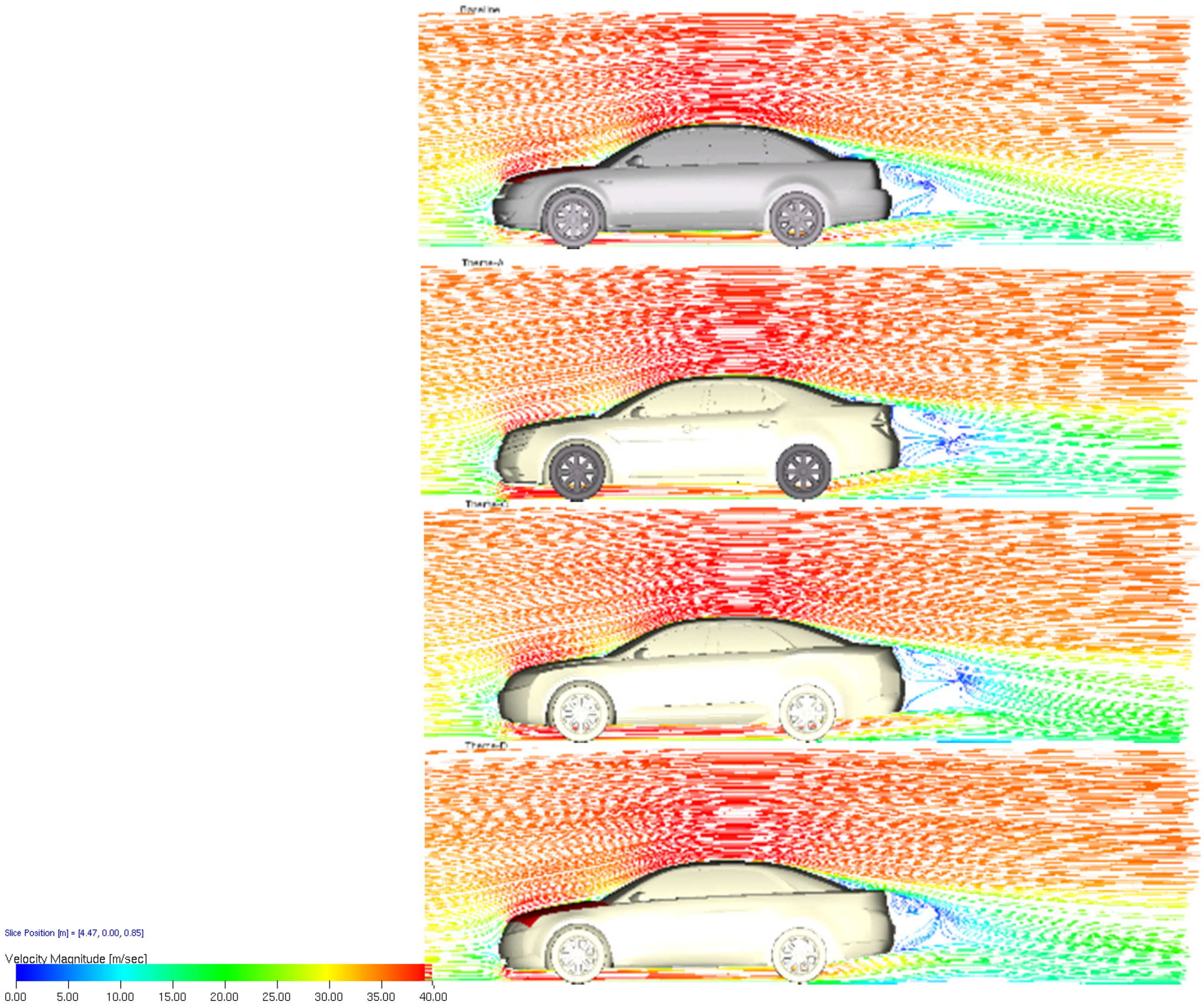
**Executes automated morphing command**

# 2010 Taurus Theme Assessment -

Theme A was the higher than Theme B and C. Theme B ~ Theme C:



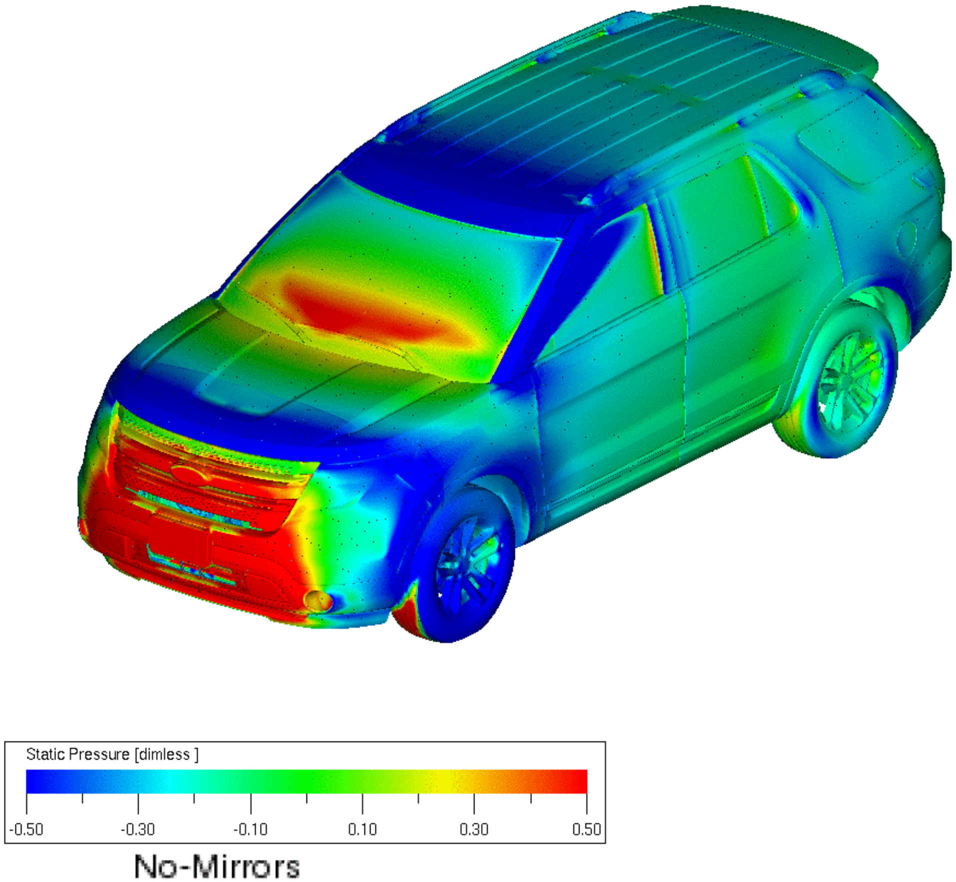
# Streamlines in Central Plane



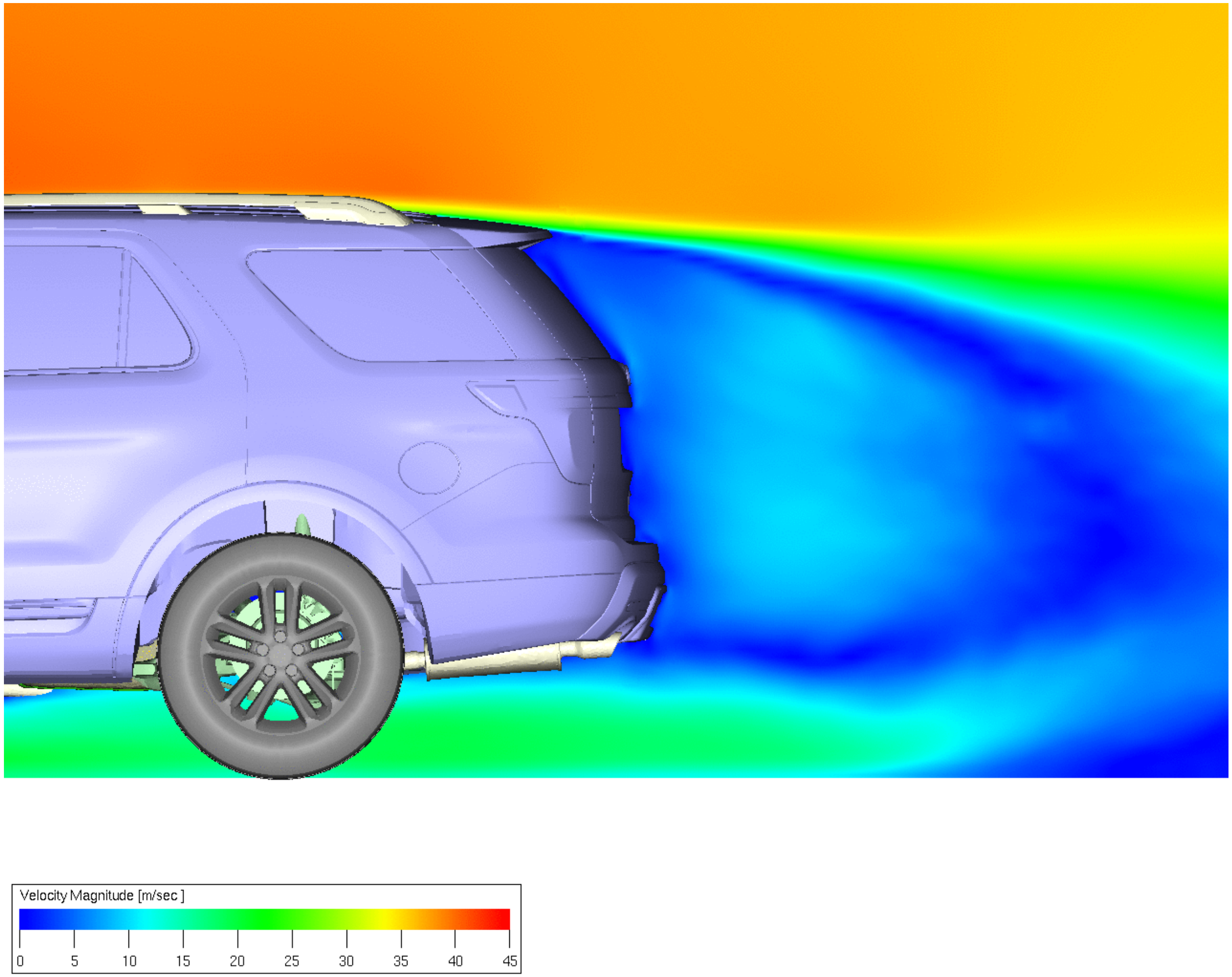
# What do we look for ?

- **Review:**
  - Drag development
  - Surface pressure
  - Velocity – flow field , especially the wake region
  - Surface drag
  - Vorticity
  - Iso surface
  - Etc
- **Develop aero actions**
- **Confirm the aero actions**
- **Guide wind tunnel test  development**

# CFD Visualization of Results – Pressure Contours

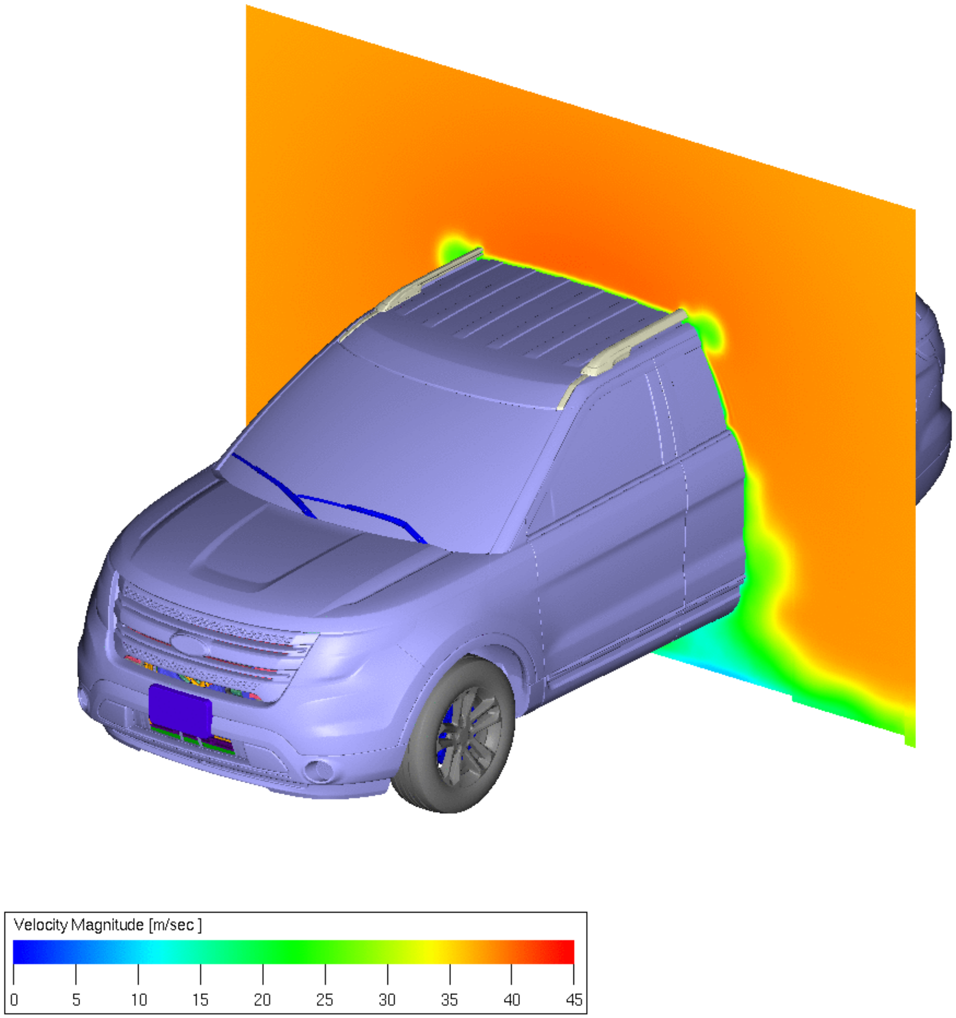


# CFD Visualization of Results – Velocity Field Slices



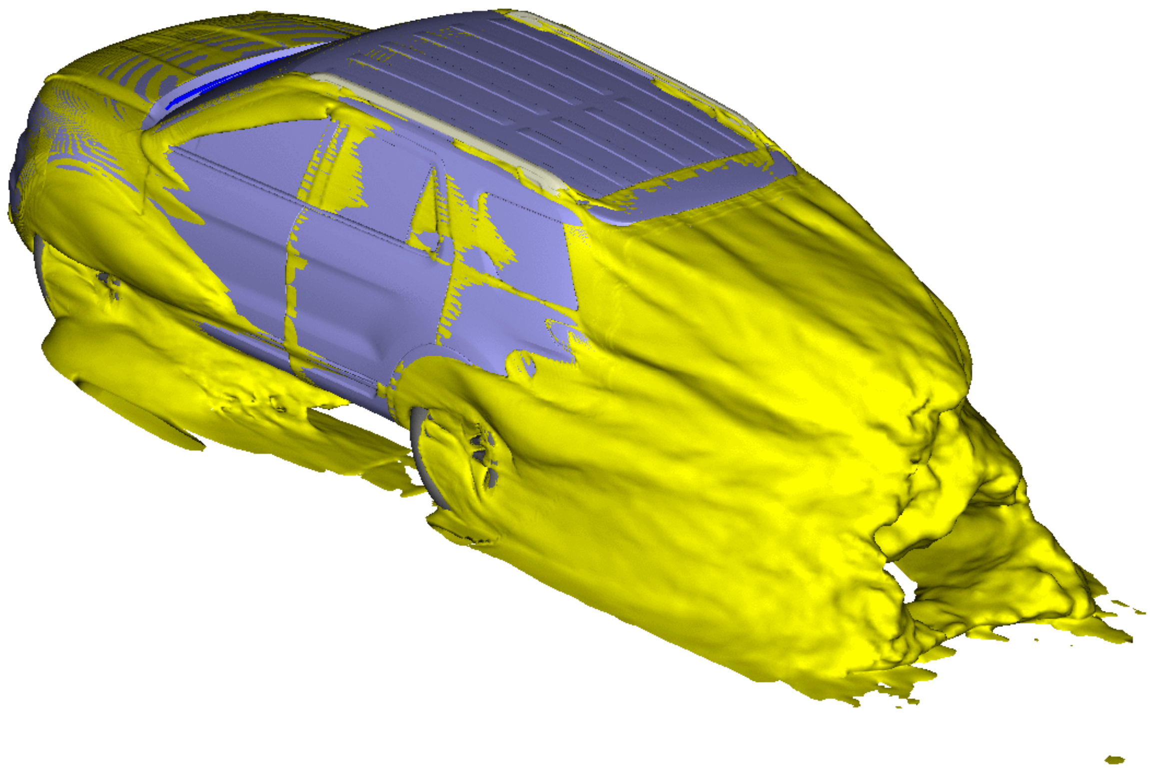

No-Mirrors [redacted]

# CFD Visualization of Results – Velocity Field Slices



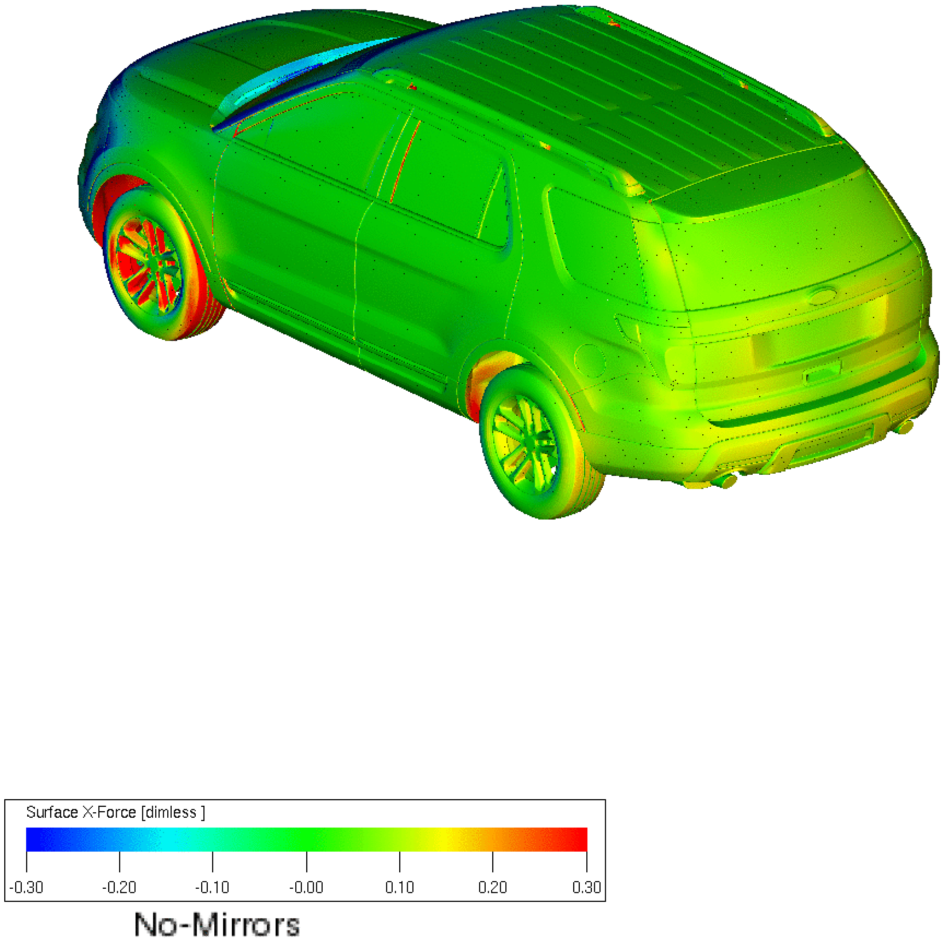

No-Mirrors

# CFD Visualization of Results – Turbulence Wakes



No-Mirrors

# CFD Visualization of Results – Drag Contours



# Single Theme Refinement

## Full Size Wind Tunnel Testing

- Complementary to CFD analyses
- Used early in the development process with clay models
- Engineers work closely with Designers to optimize shape
- Used through production to refine the details with program team
- Visualization tools include smoke, ink, tufts
- Pressure survey (surface taps and rakes)

# Test Facilities

- **Primary test facility:**
  - FNA: DTF in Allen Park, MI
  - FoE:  AWT in Merkenich, Germany
  - FAPA: Monash University

- **Moving ground wind tunnel also used:**
  - FNA: WindShear Inc., Concord, N.C.
  - FoE: Volvo wind tunnel, Gothenburg, Sweden
  - FoE: FKFS, University of Stuttgart, Stuttgart, Germany
  - FAPA: Tongji University

## What do we do in the wind tunnel?

- Competitive Benchmarking
- Aerodynamics Clay Buck Test
    - a. surface development
    - b. add-on device development
- VP and PV tests

# 1. Set up vehicle in the wind tunnel:

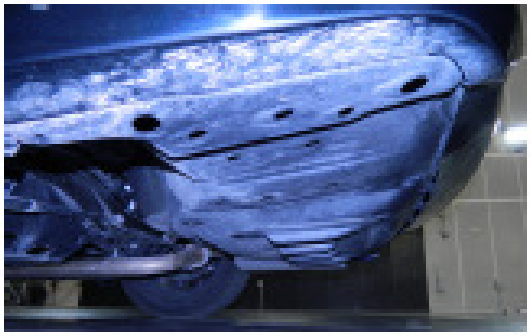
- Align the center of WB and center of the front/rear bumper to the center of the balance.
- Set the vehicle ride heights to  to the specified ride heights (EPA or VDA), measured from center of the wheel lip to ground:
  - EPA: 2 passenger in the front (75 kg x 2)
  - VDA: Per VDA seating chart

Center of WB aligns with
center of the balance

Ride heights measured from center  (x,y) of
the wheel lip to ground (z).

# Overall Vehicle - [2012 Camry Hybrid]



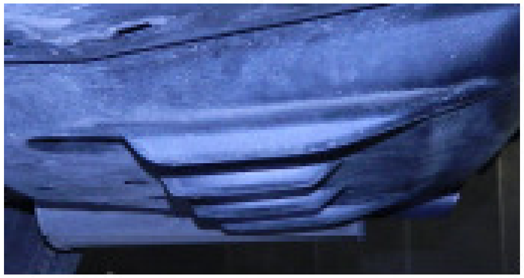

# Unique Details - [2012 Camry Hybrid]


Front Tire Spoiler


Rear Tire Spoiler

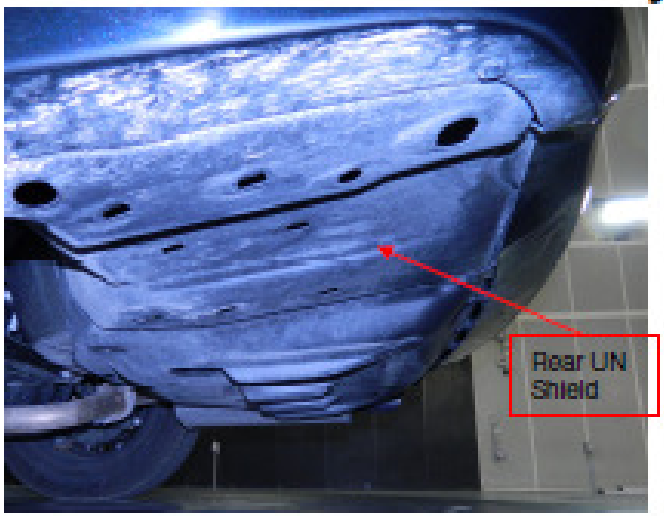

Mirror Dart

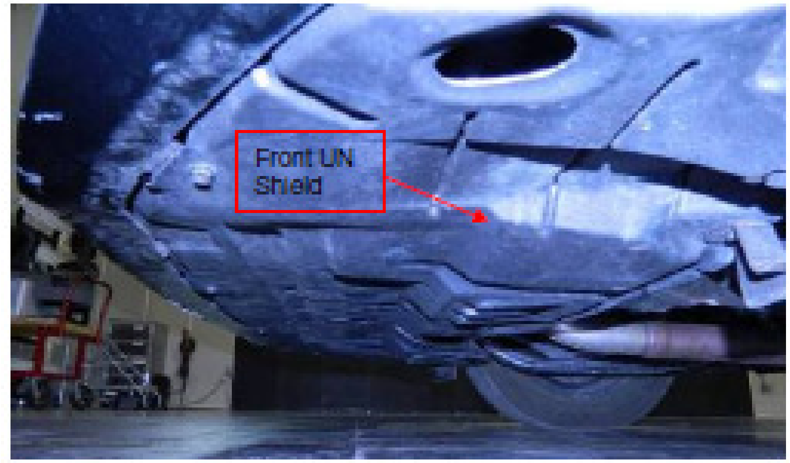

Tail Lamp Dart


Rear UN Shield Fins

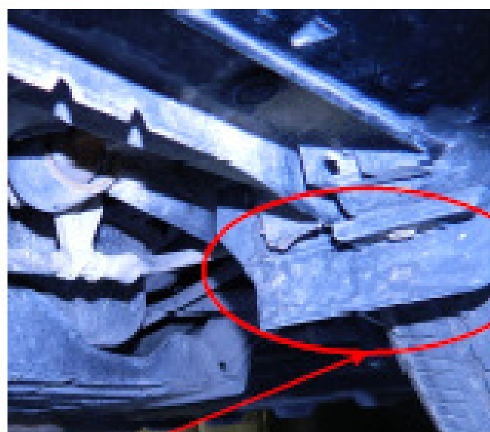

Fog Lamp Blank

# Vehicle Underbody - [2012 Camry Hybrid]




Front Tire Spoiler

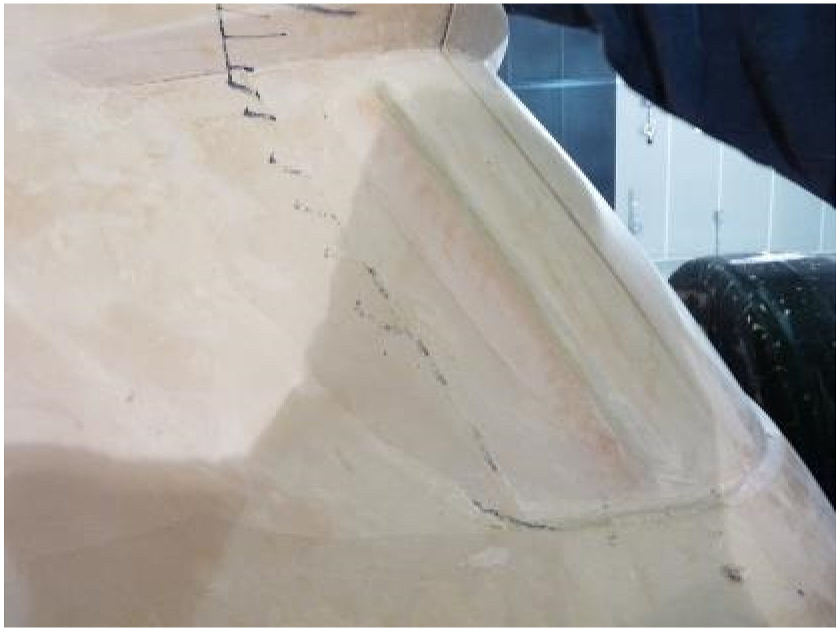


Rear Tire Spoiler

Fins on Rear UN Shield

# Clay Model Surface Tuning:

Square rocker section



Add vertical strake on D-pillar

## Add-on Device Study: Done Either on Clay Buck or VP

Front bumper spoiler development

Rear tire spoiler development

# Survey Cooling Drag

Open Front End

Closed Front End

Cooling Drag ($\Delta C_{d, EC}$) = $C_{d, \text{open front end}} - C_{d, \text{closed front end},,}$

It measures the drag due to ram air (no rotating fan). It could contribute up to 14% of the total vehicle drag.

Includes impact of cooling (outlet) flow on remainder of vehicle

Optimized layout

Streamlined components

## Prototype vehicle assessments:

Aero shape: no mirrors, taped all cutlines and front end opening, full wheel cover

Baseline test of VP

# MOVING GROUND WIND TUNNEL TESTS

# Types of moving ground wind tunnel

5-belt system (FKFS, Volvo, Audi, Mercedes Benz Toyota)

Single belt system (ARC, WindShear, Honda)

# Ford perspective: Moving Ground wind tunnel

- **Industry (global aerodynamic community – all OEMs) believes that moving ground wind tunnel test environment provides closer simulation of real world driving condition.**
- **Regulatory changes require vehicle sign-off in moving ground wind tunnels (WLTP)**
- **Continue to use analytical tool to simulate moving ground environment.**
  - Correlation study on going.

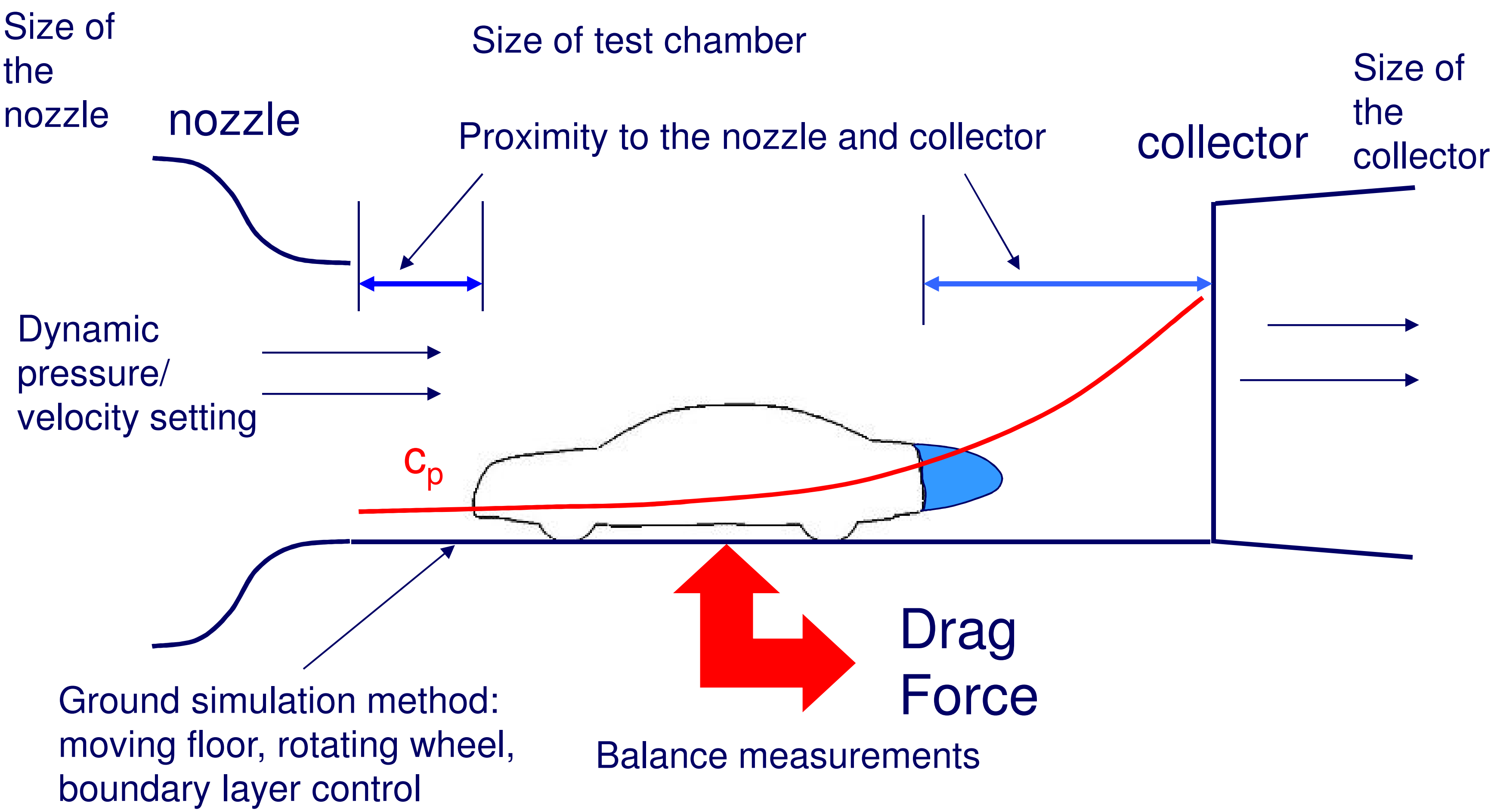
- **Media claims**
- **Public domain data**

**CAN WE TRUST THESE INFORMATION?**

# Competitive Wind tunnels

- **Every wind tunnel has own unique construction and constraints.**
- **Cd (wind tunnel A) ≠ Cd (wind tunnel B) due to the construction and data reduction methodology**
- **Some of the Cds from competition quoted in media were:**
  - Measured in moving ground wind tunnel with rotating wheels
  - Have unique configurations (small tires, wheels, special aero features) that are not disclosed in the published Cd.
- **Critical mindset required when considering media published data**
- **Global consortiums exist where data is shared with high confidence in data accuracy**

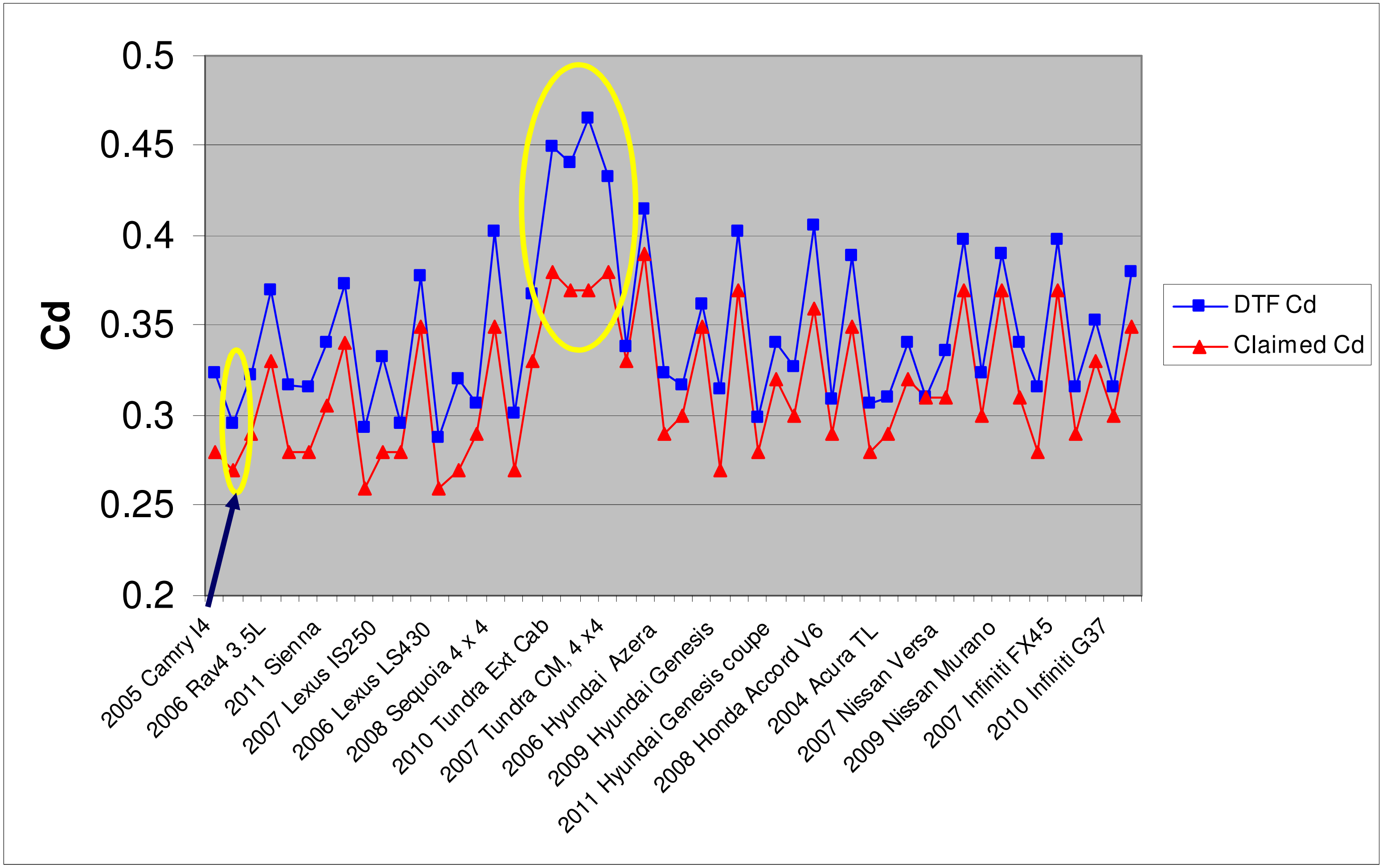
# Many Factors Influence the Cd!



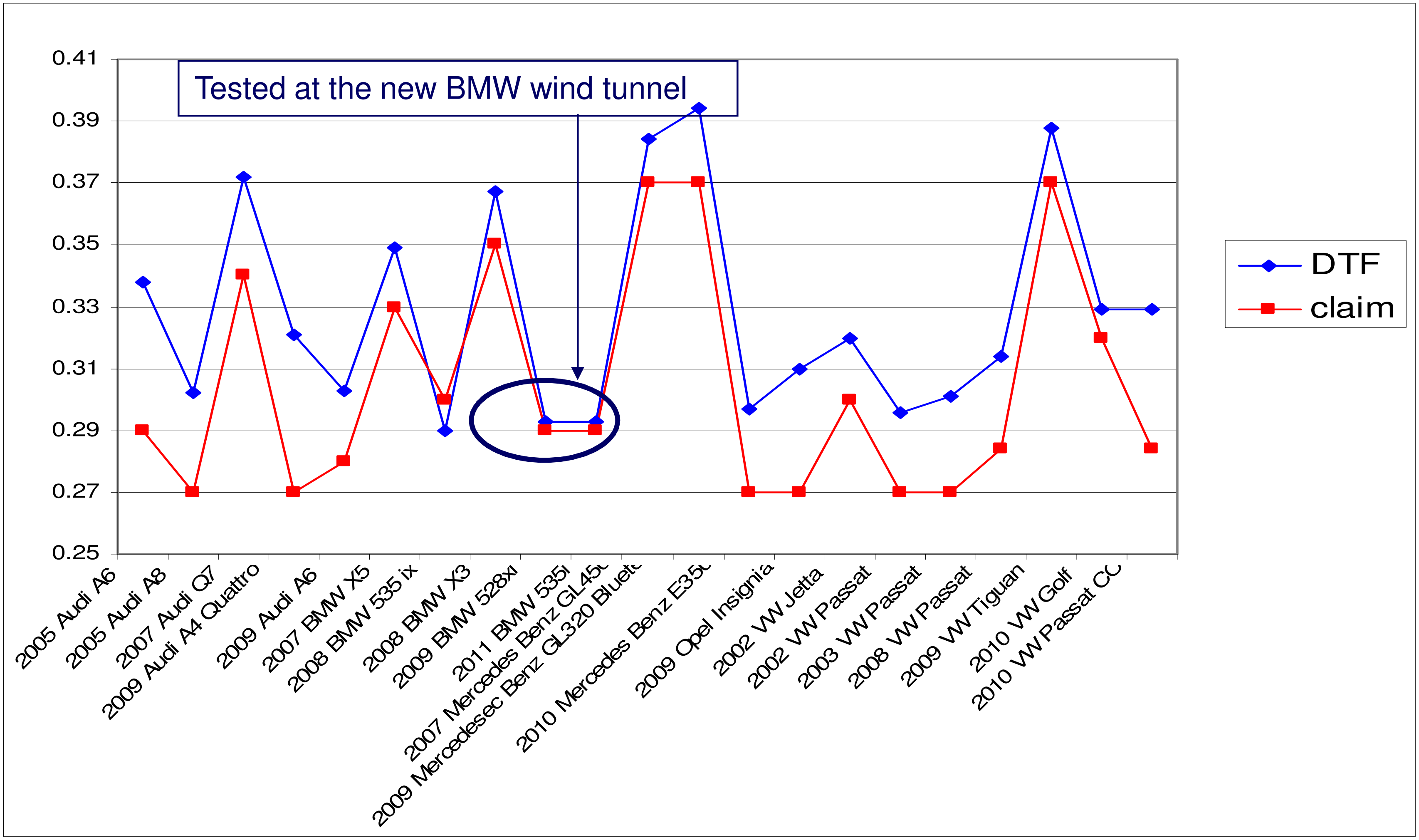

Typical vehicle set up in an open jet wind tunnel

# Cd Comparison:

## Ford Tunnel vs Asian OEMs



# Trend: European OEM vs Ford measured Cd



# Normalize Cd in industry

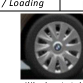
- **Attempt to eliminate ambiguity.**
- **Engineering vs. marketing claims.**
- **Target setting based on realistic data.**
  - Identify impact due to test facilities and test set up.
  - Identify impact due to vehicle configurations.
  - Identify the method used in data reduction.

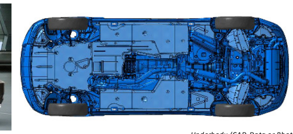
- **European Aero Data Exchange (EADE) and SAE Road Vehicle Aerodynamic Committee to adopt a standardize report and disclose the test.**
- **Standardize test procedure.**
  - SAE standard J2881
  - Ford Aero process is consistent with J2881

**EUROPEAN AERODYNAMIC DATA EXCHANGE** — EADE

| | | | | | |
|---|---|---|---|---|---|
| COMPANY | BMW AG | DATE | 10/11/2012 | CHART NO. | 318 |
| VEHICLE | 1 Series 114i | BODY TYPE | 5-Door Hatch | INTRODUCTION | July 2012 |

| Tyres and Wheels | | Geometrical Data | | | |
|---|---|---|---|---|---|
| TYRES FRONT | 195/55 R16 | TRACK FRONT (mm) | 1535 | LENGTH (mm) | 4324 |
| TYRES REAR | 195/55 R16 | TRACK REAR (mm) | 1569 | WIDTH (mm) | 1765 |
| WHEEL TRIM | Steel with Caps | WHEELBASE (mm) | 2690 | HEIGHT (mm) | 1421 |
| BRAND | Pirelli Cinturato P7 | | | | |

| Engine and Suspension | | Cooling Intakes / With Active Shutters<br>yes, no / no, active (act.), behind heat exchanger (bhe) | | | Trim Heights<br>from Ground to Wheel-Arch | |
|---|---|---|---|---|---|---|
| G/BOX | 5-Man | UPPER COOLING INTAKE | yes | no | FRONT (mm) | 653 |
| ENGINE (COMB.) | 1598cc, 75 KW, R4 | MIDDLE COOLING INTAKE | yes | no | REAR (mm) | 638 |
| | | LOWER COOLING INTAKE | yes | no | ECI / Loading | ECI |
| ENGINE (ELECTR.) | | LEFT SIDE BELOW FRONT LAMP | no | |  Wheels as tested | |
| AIR COND. | yes | RIGHT SIDE BELOW FRONT LAMP | no | | | |
| 4-WHEEL DRIVE | no | BRAKING DUCTS | no | no | | |
| SUSPENSION: Standard/Sport/Active | Standard | ACT. DEVICES / SPOILERS | no | | | |



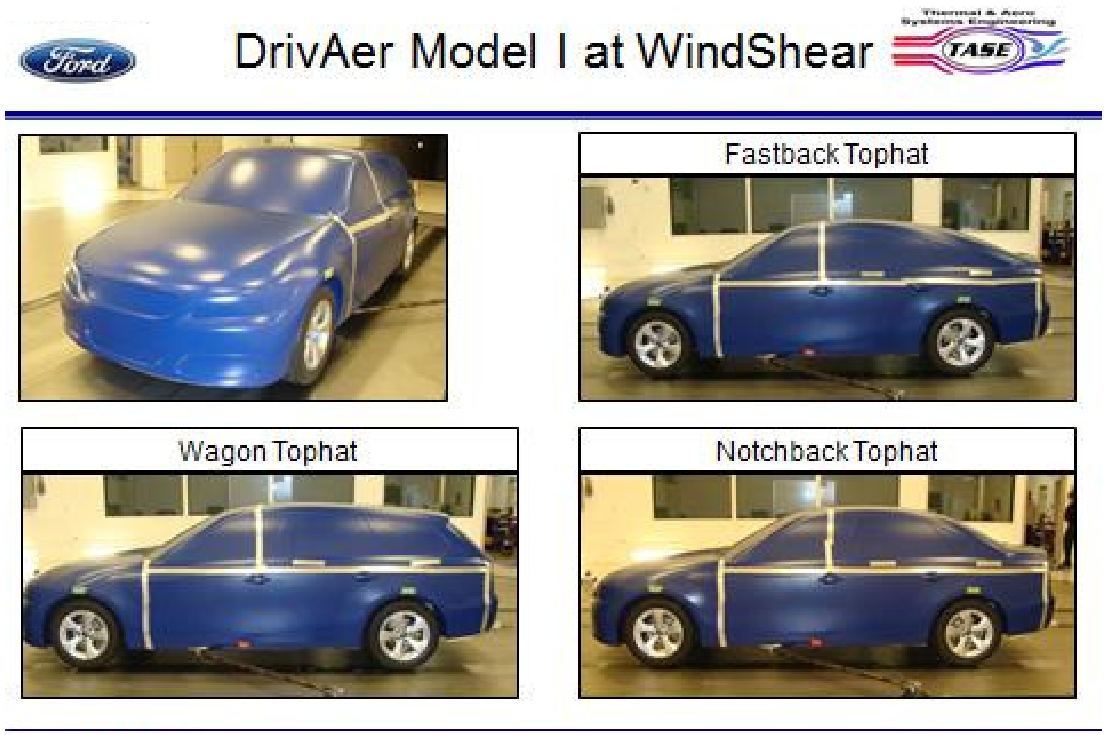
Underbody (CAD-Data or Photo)

| | | | | |
|---|---|---|---|---|
| WIND TUNNEL | BMW AWK | WINDSPEED km/h | 140 |  Front View |
| DATA CORRECT. | no | ROAD SIMULATION | yes | |
| REMARKS | | | | |

| | Standard | Mock-Up Cooling Intakes | eg. Mock-Up Break Cooling Intakes | eg. Cab Down Windows closed | Additional Data |
|---|---|---|---|---|---|
| Cx | 0.310 | -0.019 | | | |
| A ($m^2$) | 2.14 | | | | |
| Cx x A ($m^2$) | 0.663 | | | | |
| Czf | 0.06 | -0.06 | | | |
| Czr | 0.04 | -0.01 | | | |
| Cmz (15°) | 0.11 | | | | |

# Attempt to normalize the Cd in industry: 2

Use of common model (DrivAer) to establish global wind tunnel correlation.



# SPECIAL FEATURES AND GIMMICKS

# Vortex Generators

This vortex generator on the Mitsubishi Lancer Evolution MR is like those used on airplane wings; it reduces drag and increases the downforce generated by the rear spoiler.
*(Photo courtesy of Mitsubishi Motors North America, Inc.)*

Partially true: vortex generator works if the backlight angle is not optimized. This "fixes" bad aero. In many cases, a poorly applied vortex generator could increase drag.

# Discovery Channel: Dimpled Taurus

2 mpg better in previous episode vs “dirty car” ?

26.0 mpg

?

29.6 mpg

Lexus “dimples” underbody heat shields. Claims aero benefit. Discovery channel creates a clay “Taurus”, and then dimples the surface like a golf ball. The fuel economy is measured through semi controlled on road testing. The staff finds an improvement with the dimpling!

Some of the noticeable/possible design changes:

Ride height change: Dimple “divots” all moved to back seat….

Clay added on the surface and provide more front tire coverage – good for aero

Dimples used in golf balls to increase impact of spin, and therefore distance.

Test Variability? Dirty car: 24 mpg; Base car: 26 mpg; Dimpled Car: 29.6 mpg

USCAR AERODYNAMICS WORKING GROUP

**Mythbusters TV program claimed road test results of +3 mpg improvement from dimples applied to a car**

USCAR
AERODYNAMICS WORKING GROUP

**Test results from GMAL showed drag increases for dimples applied to vehicle forebody, body sides and roof**

| | $\Delta C_D$ | $\Delta C_L$ | $\Delta C_{PM}$ |
|---|---|---|---|
| Fore-body Dimples | +0.011 | -0.003 | +0.004 |
| Body-side Dimples | +0.003 | -0.008 | +0.010 |
| Roof Dimples | +0.006 | -0.012 | +0.009 |

AIRTAB Investigation:

Motivation:

Airtabs are being sold world wide with increasing popularity.

This test verified and quantified the claimed benefit of these devices and sketched the potential impact to our products future design.

# Airtabs


Ford of Europe test: drag increase!

# Summary

- Aerodynamics is one of the key enablers to deliver fuel economy targets.
- Aerodynamics design process starts from earliest concept and continues up to and beyond production.
- Competitive benchmarks, Aero Design Guide, CFD analyses, and peer reviews are used to deliver aerodynamic improvements.
- Both analytical (CFD) and physical testing Design Verification methods are used. They are complementary to one other.

# 2013 Fusion Aerodynamics

# Ford Fusion Aerodynamics

Low CD

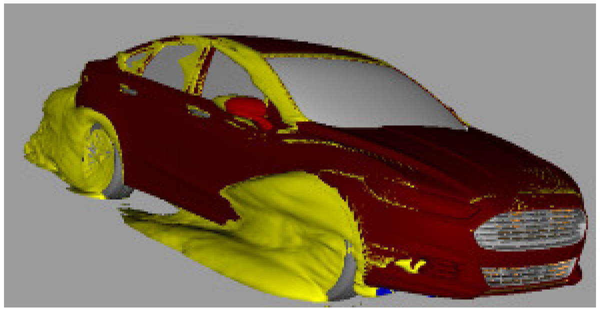
achieved by

- extensive **C**omputer **F**luid **D**ynamics

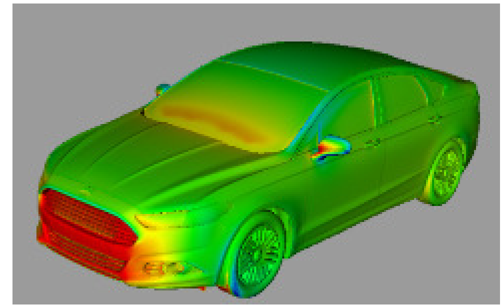
  (more than 2 MILLION CPU-hrs )

- 450 hrs Wind Tunnel Time

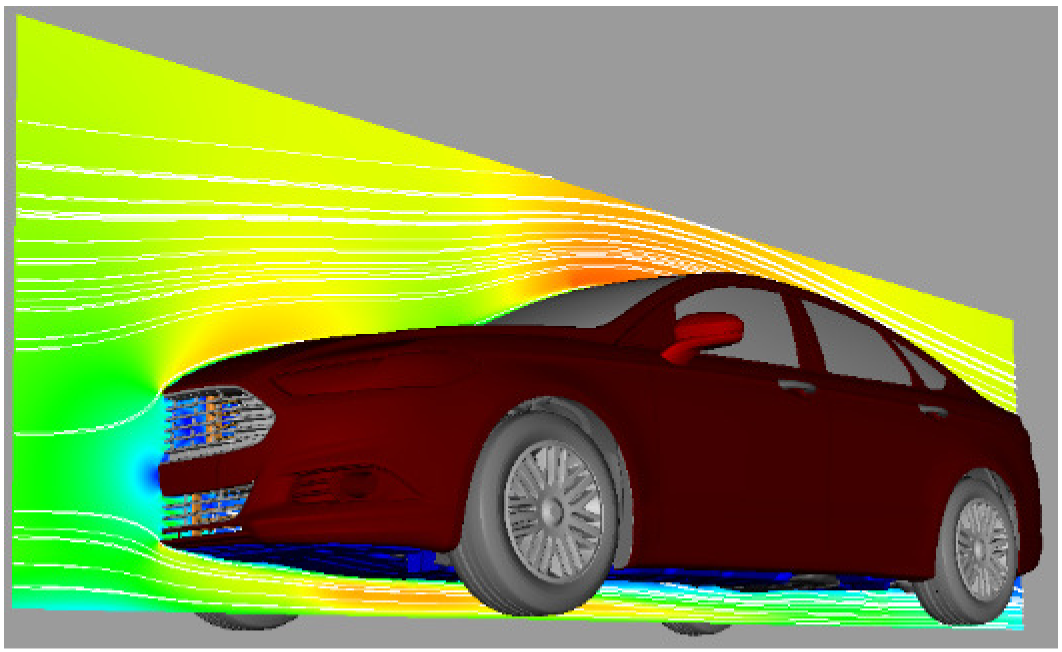
# CFD Optimization



Wake Structure



Pressure On Surface

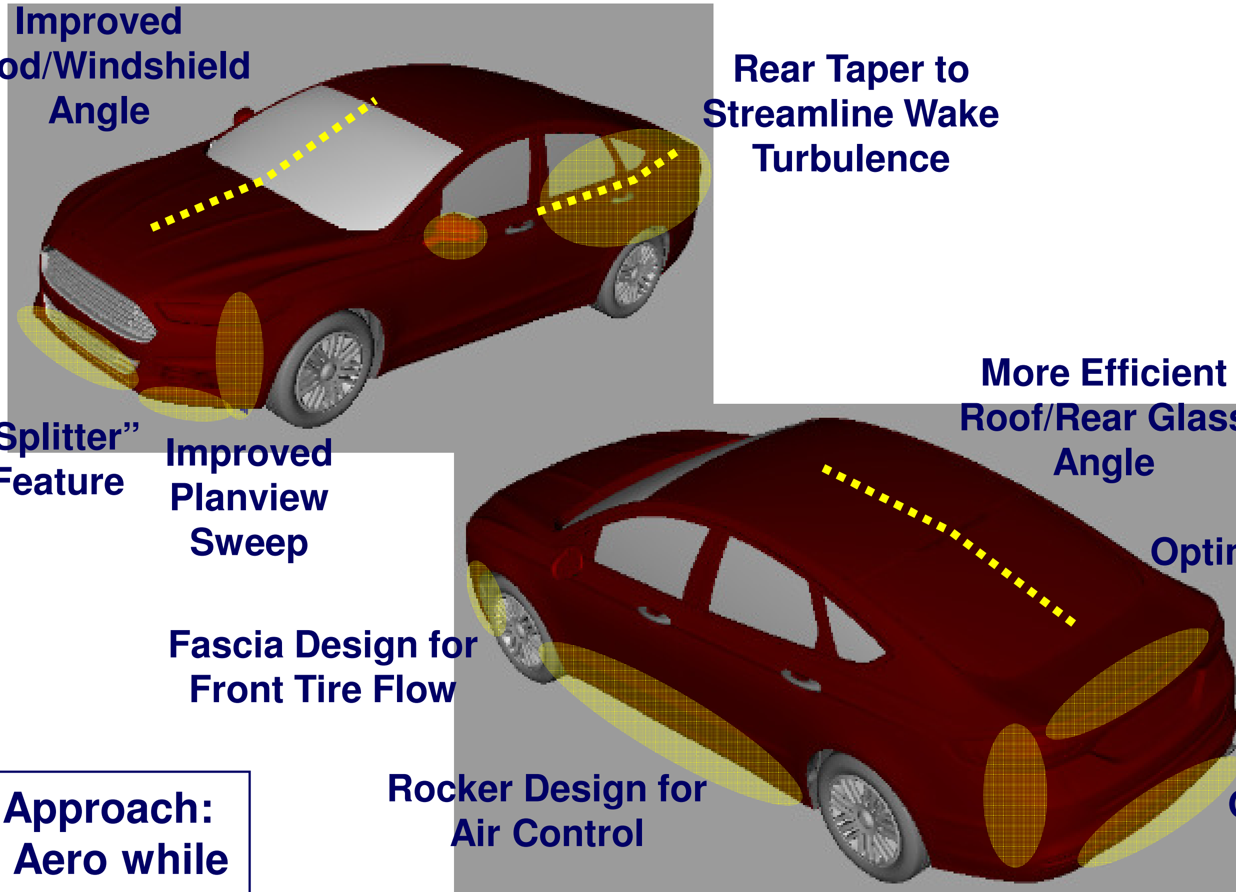


Velocity Over/Under Vehicle

## Fusion Clay Theme Study/Optimizations

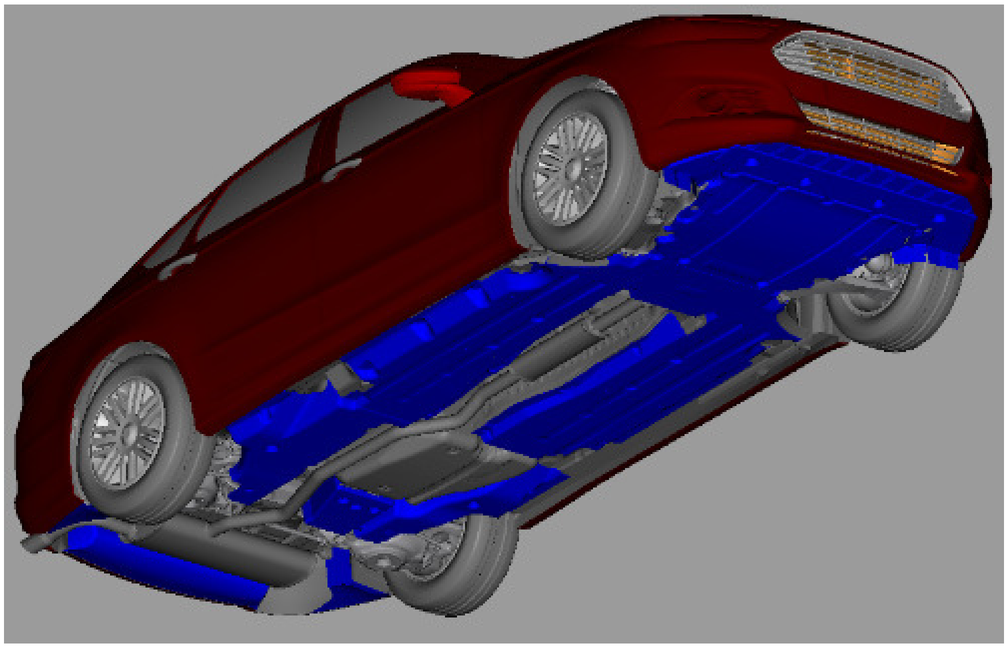
## DTF Wind Tunnel 8,

# Areas of special attention to improve Aero Drag on
# - Upper Body -

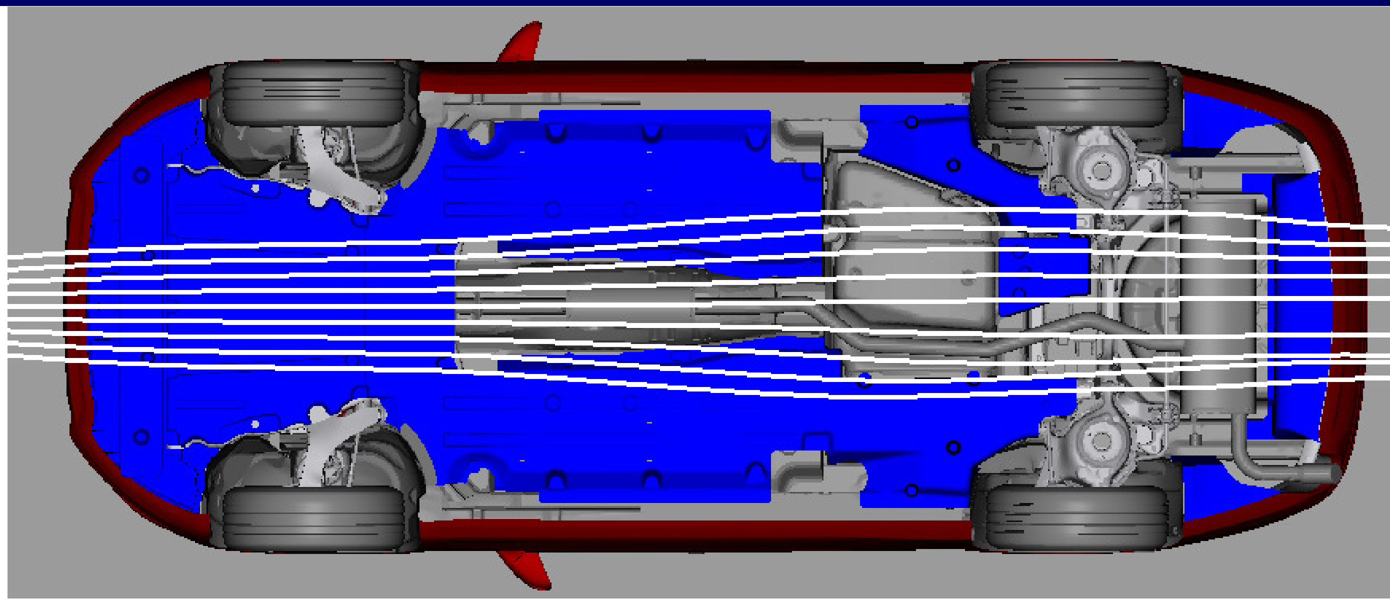



**Integral Approach: Optimize Aero while Maintaining Leadership Styling!**

# Areas of special attention to improve Aero Drag on - Under Body -

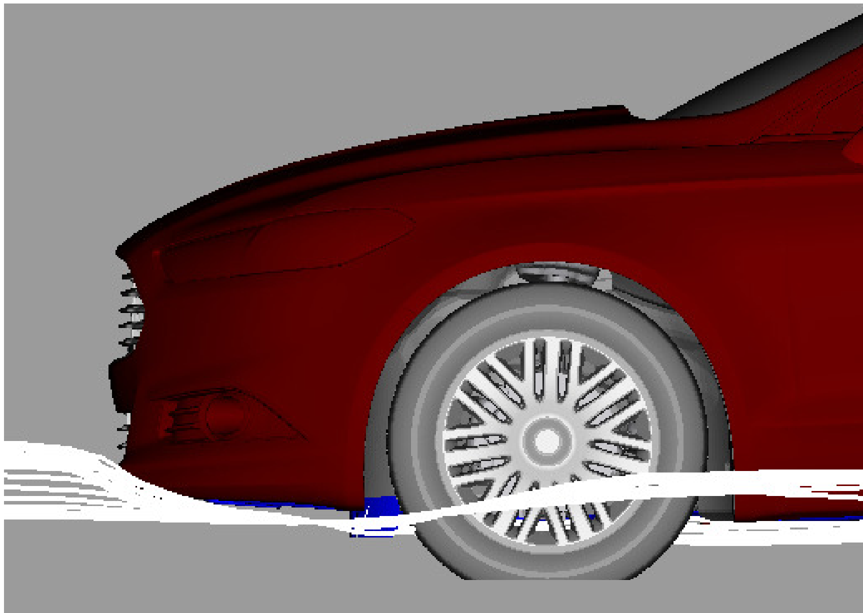


**Special Underbody Shield Package (Blue) for Optimized for Underbody Aerodynamics**



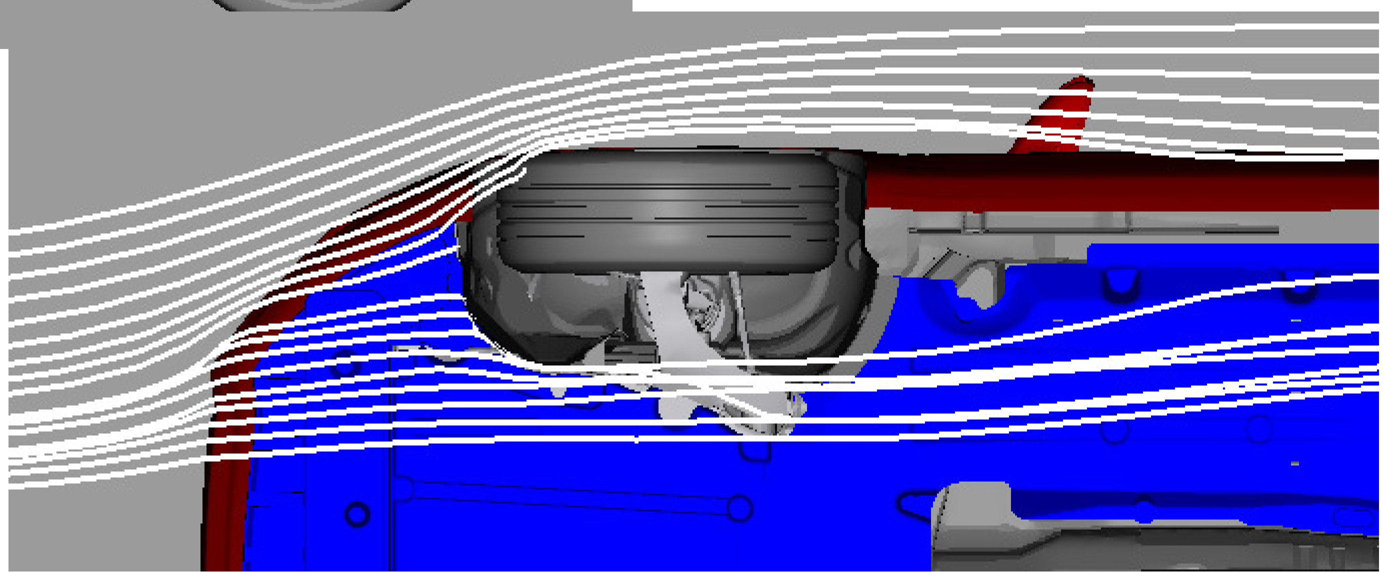
Smooth Underbody with Optimized Rear Lower Fascia Ensures Flow Remains Attached

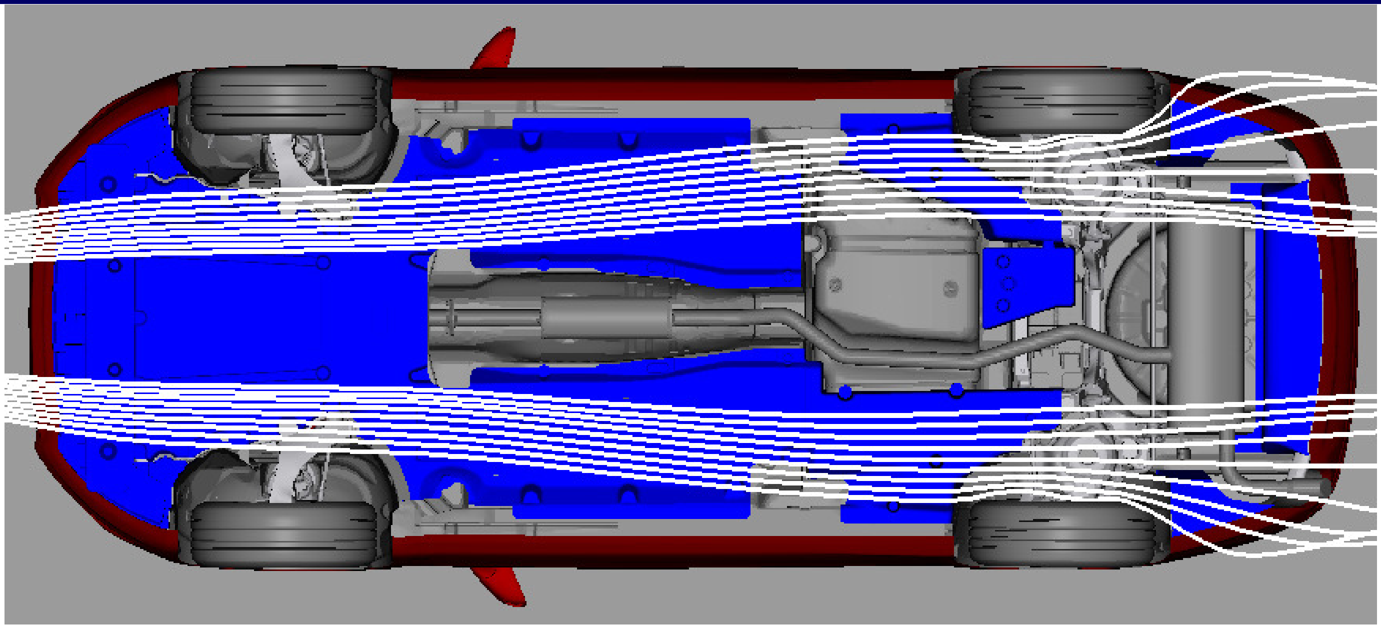
Flow Kicks Up at Rear Fascia so Wake is Minimized



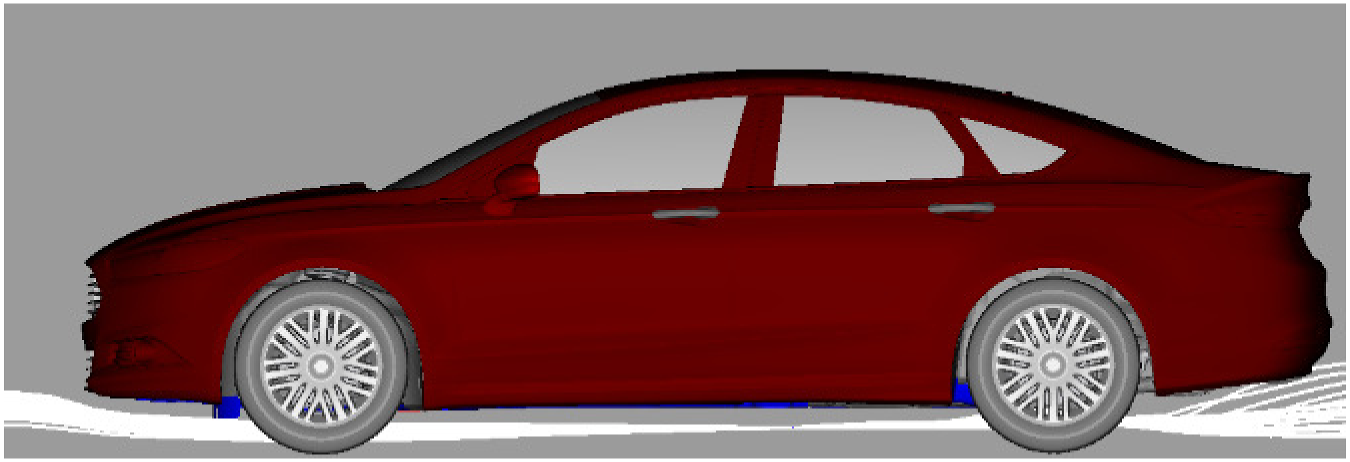
# Front Tire Spoiler Performance

Flow is Cleanly Redirected Around the Wheel, Which Reduces Front Tire Induced Turbulence.  Flow Along Side of Vehicle is Subsequently Smoother, Creating Less Drag

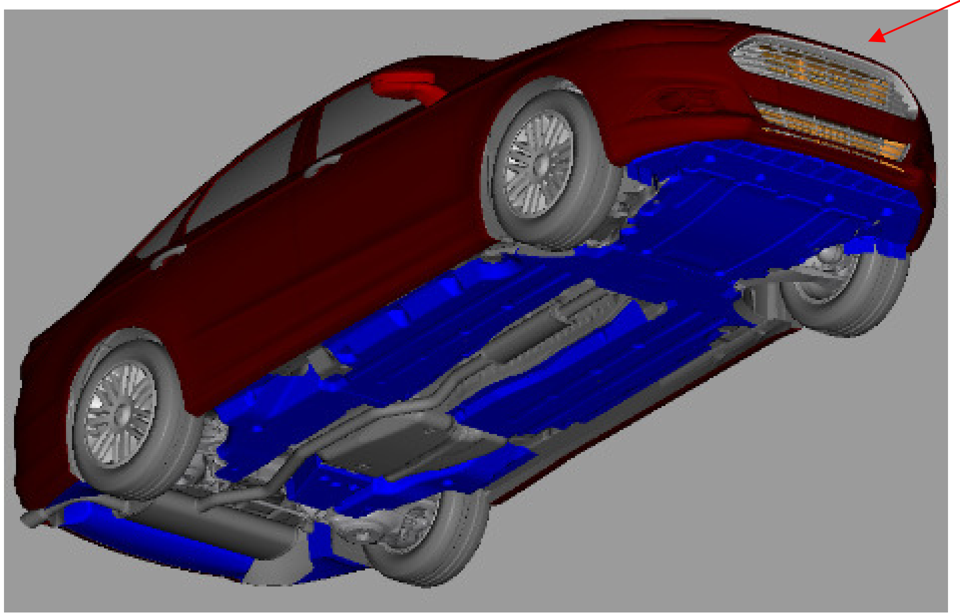


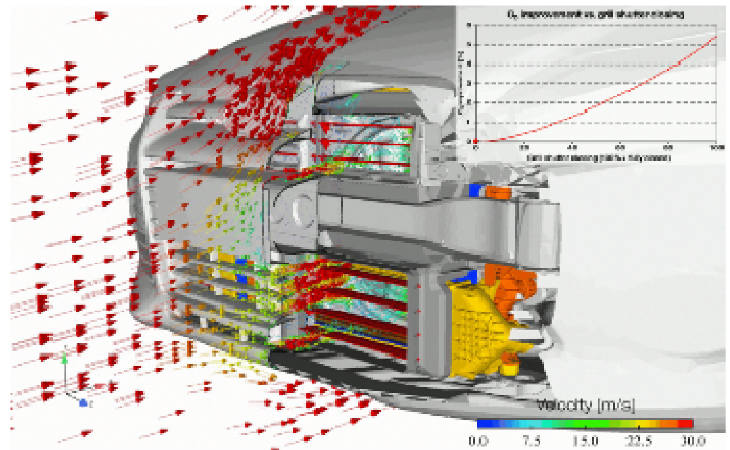


Shield Package Ensures that Passes Smoothly Under Vehicle
Drag Reduction is Obtained: Additional Shots



## Areas of special attention to improve Aero Drag on
## - Active Grill Shutter -






7.5% aero drag improvement by closing grill shutter

## Over 30% of the Aero Drag will be created on the under body of a vehicle.

Optimizing the under body airflow by smoothing the under body and special tuning of the airflow around / through the tires can significantly reduce the aerodynamic drag. This can only be done with a correct simulation of the under body airflow by using a wind tunnel with moving ground of by CFD simulation simulating rotating wheels and a moving ground.

The moving ground simulates the real road situation by eliminating the boundary layer a conventional wind tunnel will have. Through the rotation of the tires the wake around the wheels will be reduced, resulting in less drag. There is also a change of the flow direction approaching the under body influencing the under body shield optimization. The rotation of the rear tires creates a 'pumping of airflow' to the rear of the vehicles also reducing the drag by reducing the back pressure of the vehicle.