IEF Solar Car Conference 2021

Aerodynamic Development of the 2019 Durham University Solar Car

Prof. David Sims-Williams

Outline

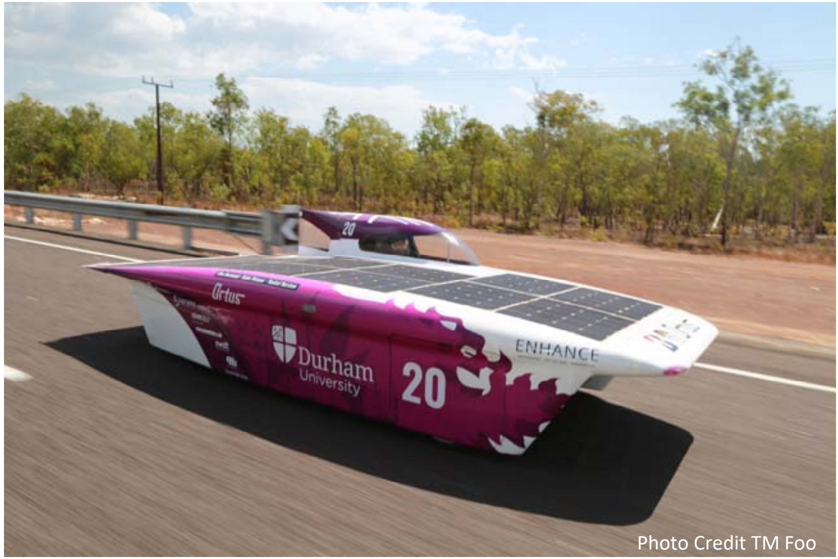
Solar Car Aerodynamics Fundamentals

Vehicle Conceptual Design

Aerodynamic Development of DUSC 2019

Build

Test & Compete



Durham
University

Where is *Durham?*

- Durham is a small city in the North East of England
- 3rd university in England
- First to teach Engineering – in 1838.
- Multi-Disciplinary Engineering programme
  - Good fit for Solar Car

Durham University


Durham

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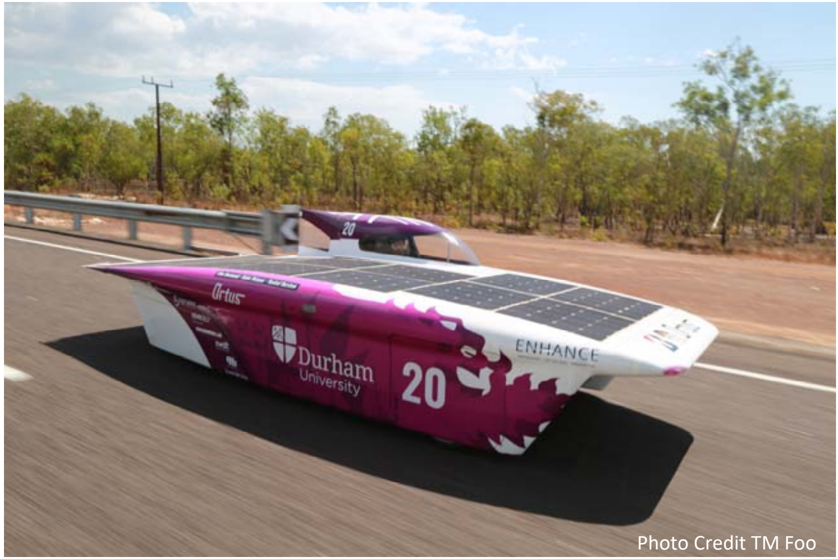

Photo Credit TM Foo

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Solar Car Aerodynamics - Fundamentals

- Requiring input power from a solar array on the vehicle means:
  - The size of the vehicle will be on the scale of a conventional road car.
  - Must design a car that needs much less power than a conventional road car.
- Main outgoings:
  - Aerodynamics
  - Rolling Resistance

Photo Credit S Wilson

Solar Car Aerodynamics - Fundamentals

- Aerodynamic drag increases with velocity squared.
  - $Drag = C_D A \frac{1}{2} \rho u^2$
  - Aerodynamic power increases with velocity cubed
    (Power = Force x Velocity)

- Rolling Resistance is approximately independent of speed.
  - Rolling power will be proportional to velocity
    (Power = Force x Velocity)

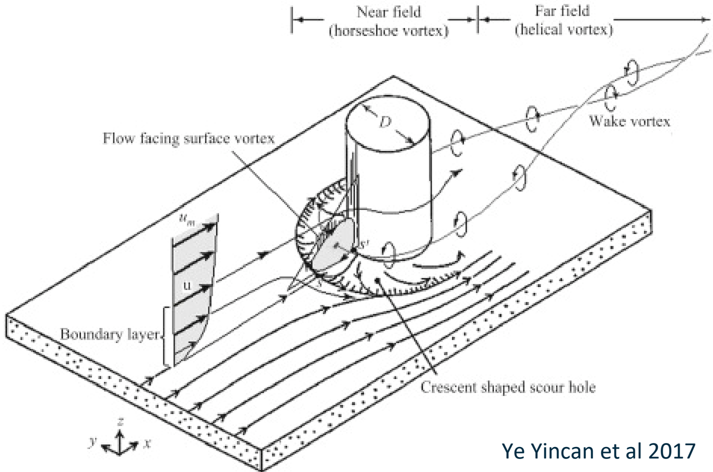
- For the fastest solar cars – aerodynamics becomes the dominant outgoing.

Solar Car Aerodynamics - Fundamentals

- The first priority is to avoid separated (reversed) flow.
- Then:
  - Avoid lift-induced drag (trailing vortices)
  - Minimise skin-friction (eg: by delaying transition from laminar to turbulent)

- For a low drag vehicle - small things become significant
  - Junction drag – horseshoe vortices
  - Ventilation drag (cooling drag – see [1])
  - Body gaps and steps – see [2], [3]

- Useful references: [4] – Solar Car Aero
  [2] – Drag of anything from canopies to bolt heads



Ye Yincan et al 2017

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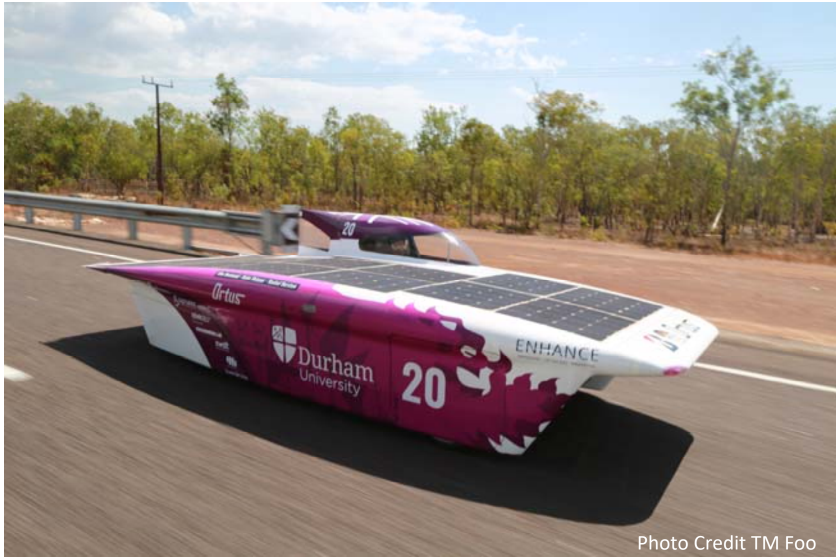
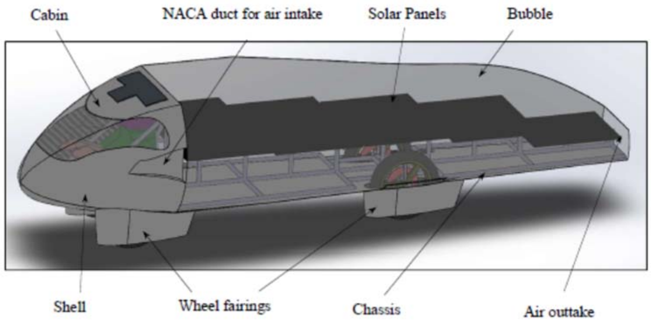


Photo Credit TM Foo

Vehicle Conceptual Design

- There is a strong interaction between the aerodynamic design and other systems on the car!



  - Previous undergraduate design projects had investigated:
    - vehicle concepts (eg: tilting arrays)
    - suspension space requirements etc.
  - Vehicle configuration was decided by the senior members of the extra-curricular team
    - before any specific aerodynamic development
  - Main aerodynamic development undertaken as a capstone project [5].

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Vehicle Conceptual Design

- Separate (/Tilting?) Solar Array Designs

North West University
(South Africa) “Naledi”

Halmstad
“Heart Three”

Chalmers
“Alfrödull”

Vehicle Conceptual Design

- Separate (/Tilting?) Solar Array Designs

TILTING ARRAY BRINGS MORE SOLAR POWER
AERO PENALTY FROM LARGE SURFACE AREA

North West University (South Africa) "Naledi"

Halmstad "Heart Three"

Chalmers "Alfrödull"

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DUEM
DURHAM UNIVERSITY ELECTRIC MOTORSPORT

Vehicle Conceptual Design

- “Monohull” Designs

Stanford University
“Black Mamba”

University of Michigan
“Novum”

Cambridge University
“Mirage”

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University

Vehicle Conceptual Design

- “Monohull” Designs

COMPETITIVE AERO STABILITY?

Stanford University
“Black Mamba”

University of Michigan
“Novum”

Cambridge University
“Mirage”

Vehicle Conceptual Design

- Asymmetric “Catamaran” Designs

TU Delft “Nuna”

University of Western Sydney “Unlimited 2.0”

Stanford “Sundae”

Vehicle Conceptual Design

- Asymmetric "Catamaran" Designs

LOW FRONTAL AREA
SELECTED

TU Delft "Nuna"

University of Western Sydney "Unlimited 2.0"

Stanford "Sundae"

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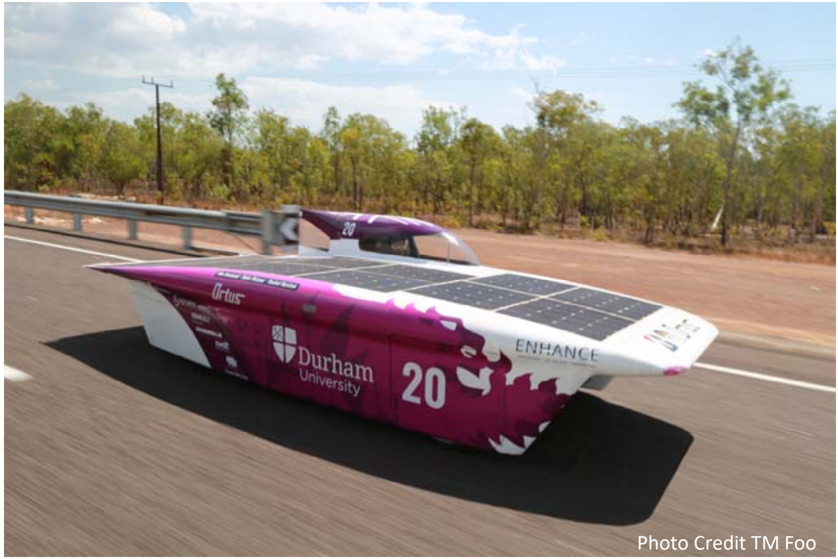

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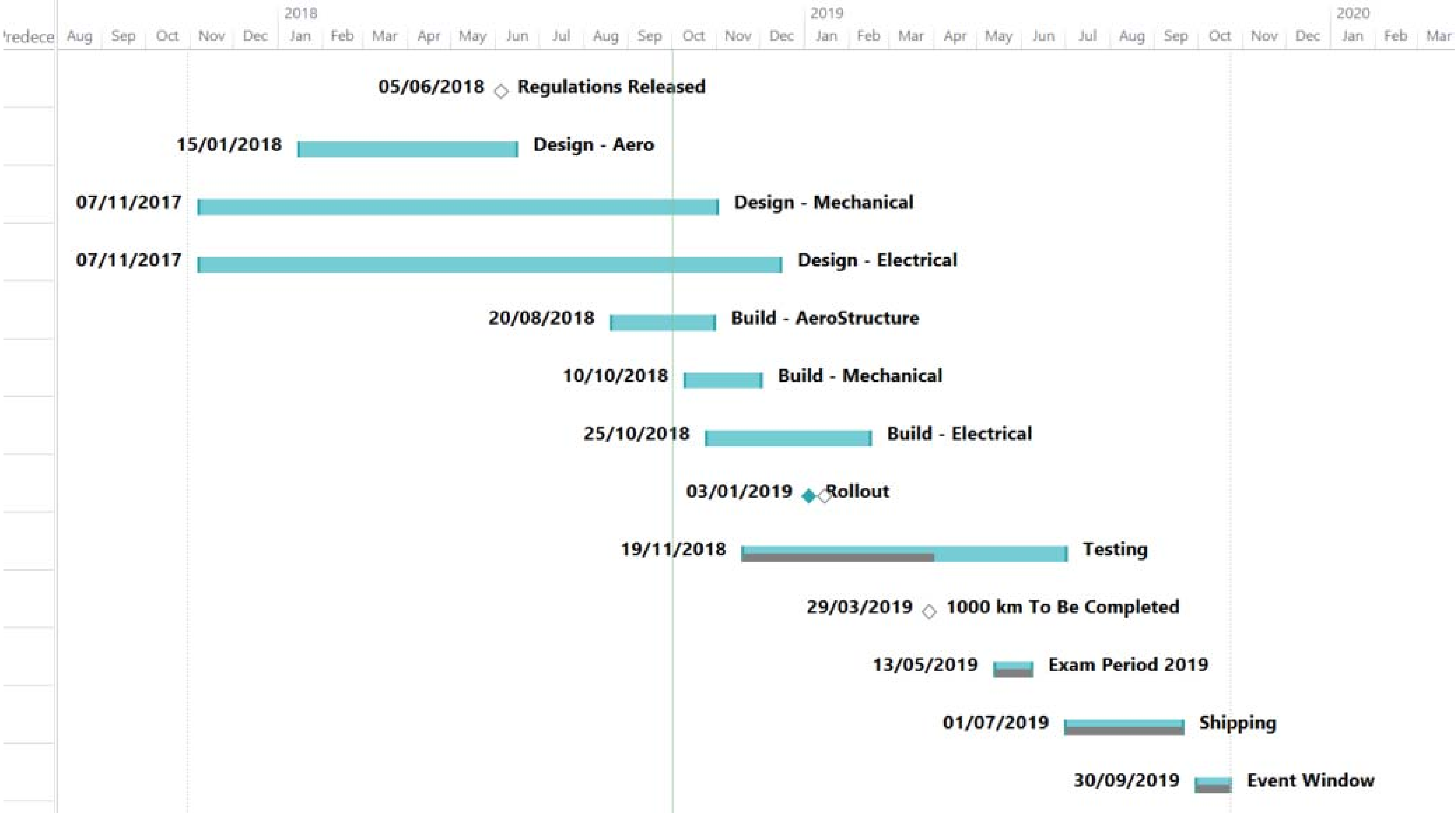
Aerodynamic Development of DUSC 2019



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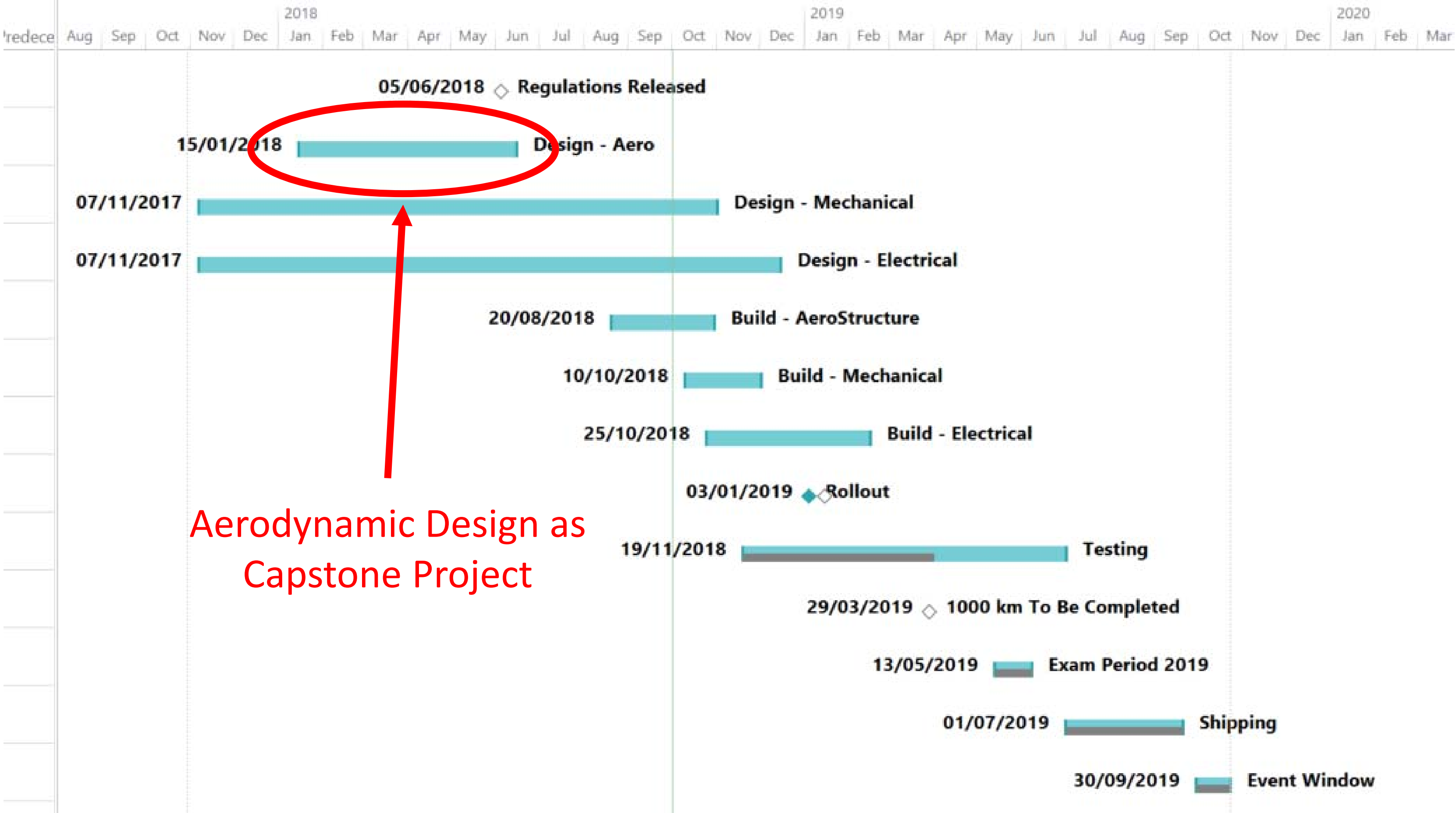
Aerodynamic Development of DUSC 2019



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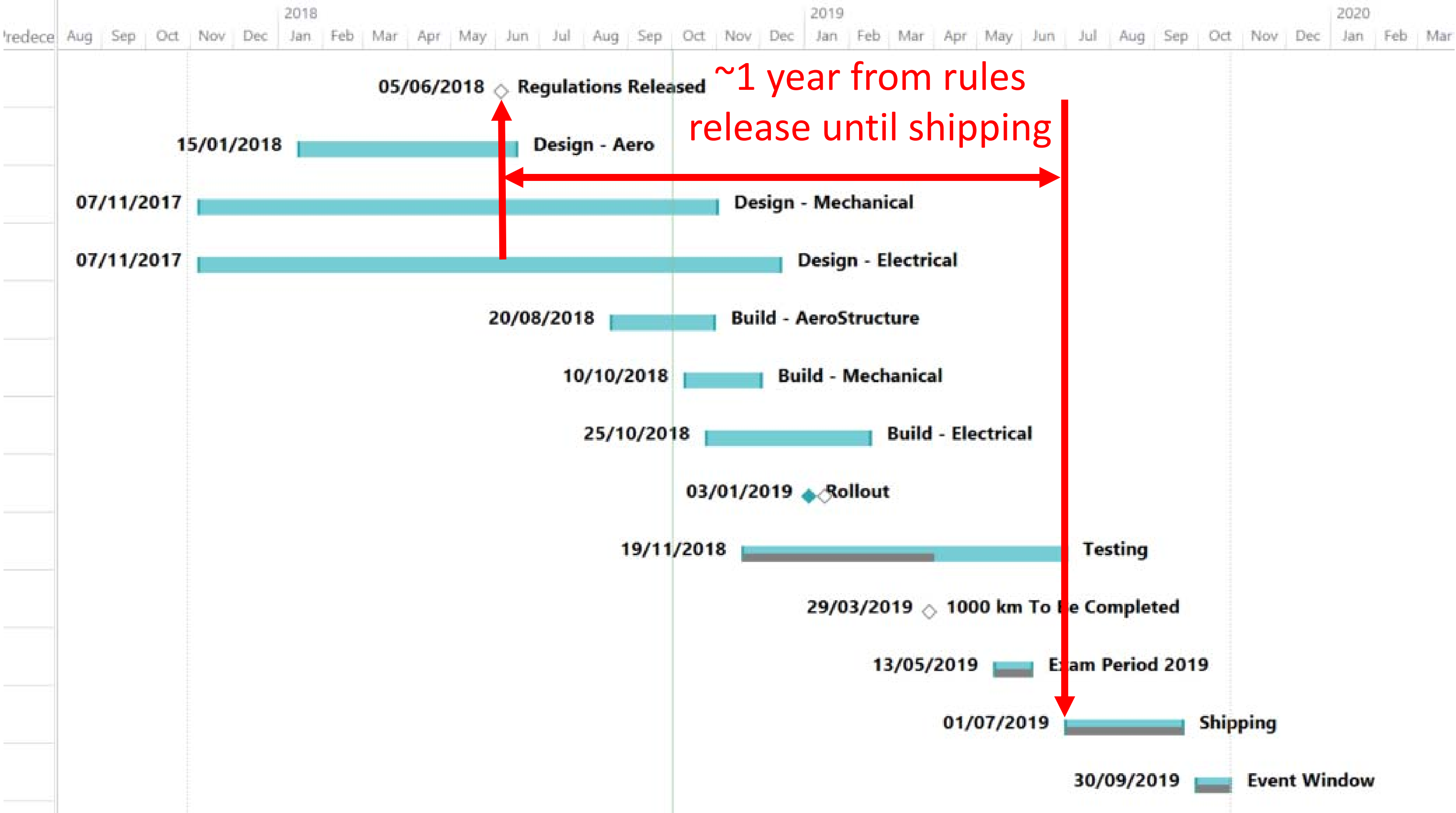

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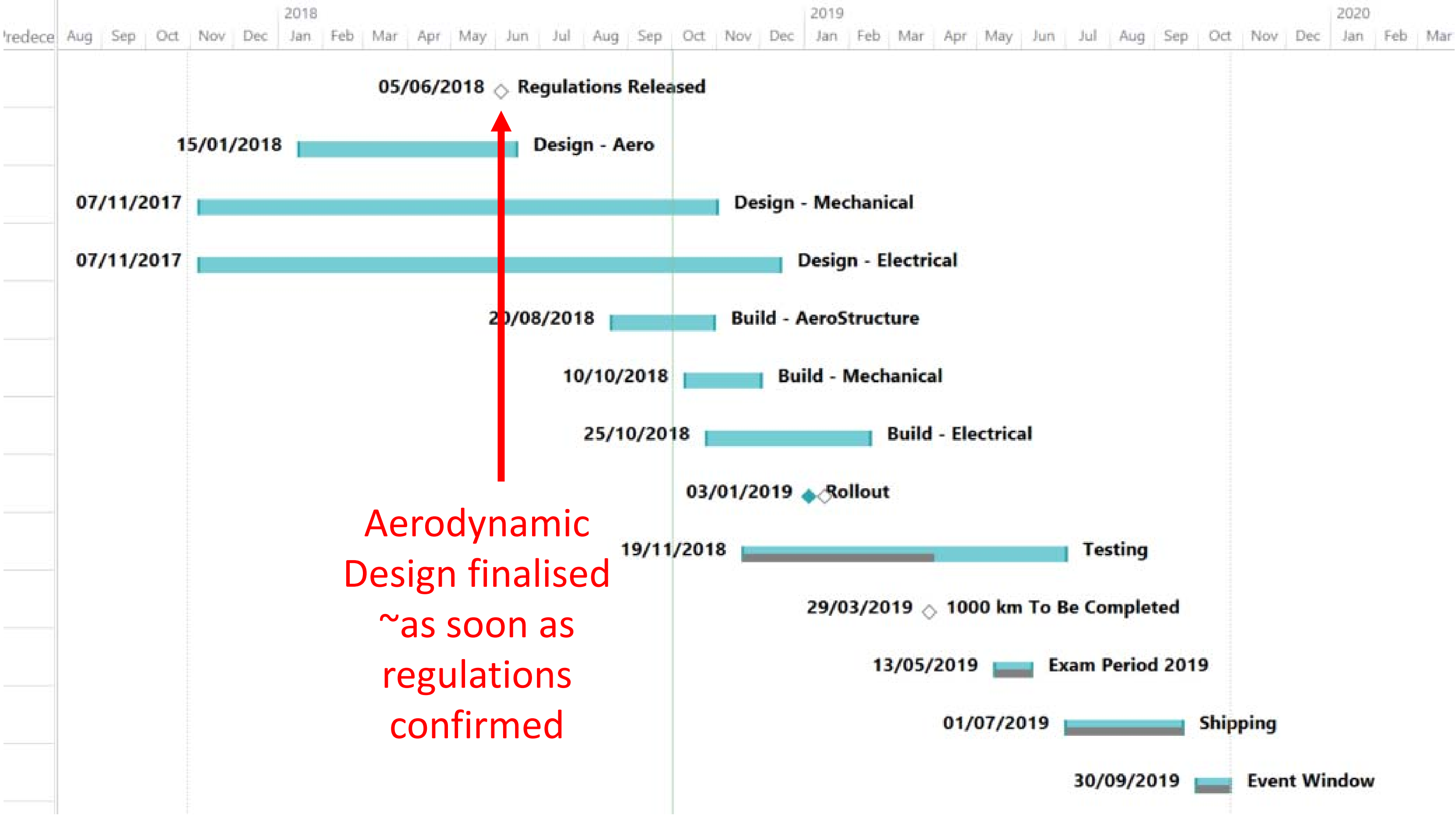
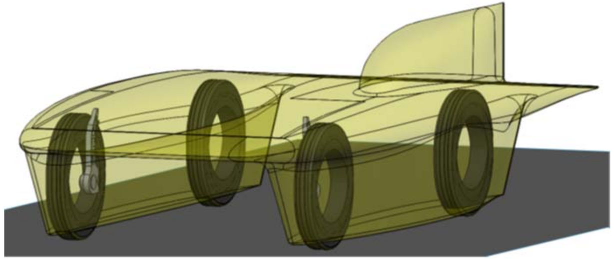
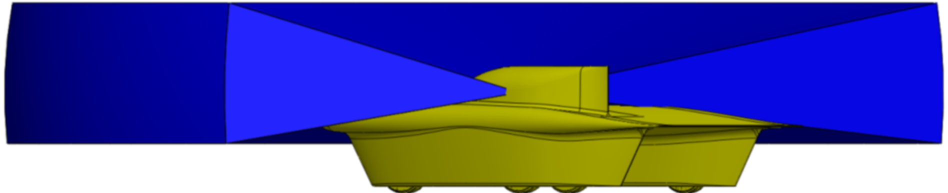
Aerodynamic Development of DUSC 2019



Aerodynamic Development of DUSC 2019

- Starting point:
  - Cell arithmetic, wheels/tyres, driver scan, driver headspace & rollhoop regulations, vision regulations and candidate suspension designs
  - Aerodynamic specification requirements on aerodynamic lift and sideforce resolved at front and rear axles (including yaw – up to 20º - 30º)
  - Aerodynamic drag target(s) (including yaw ~4º-5º is typical)



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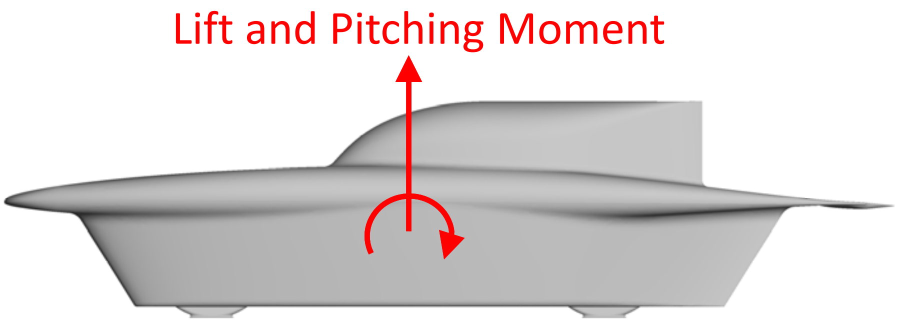
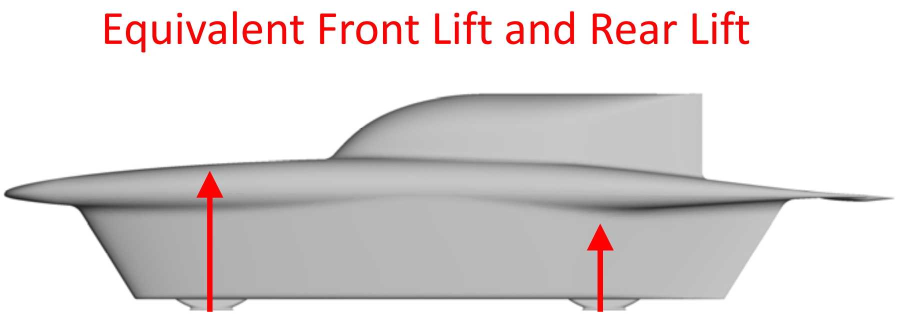
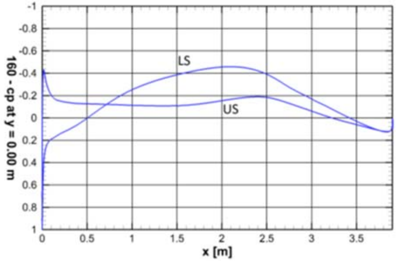
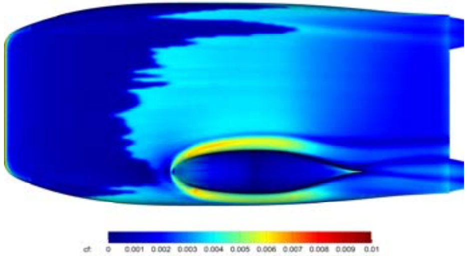


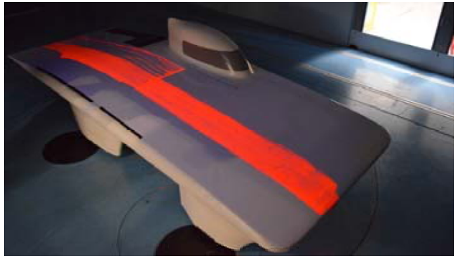


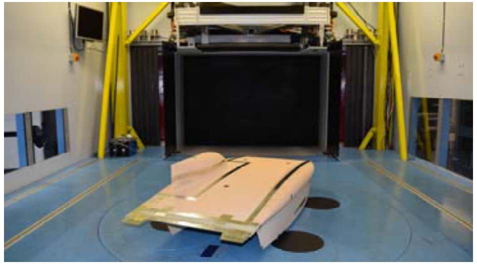
Aerodynamic Development of DUSC 2019

- Overall Process / Toolchain
  - Java Foil – Initial 2D design of main body.
  - Solidworks - Pointwise – Fluent – Tecplot
  - Scale Model Mule Test (Modified DUSC 2015/2017)
  - Scale Model Test of DUSC 2019





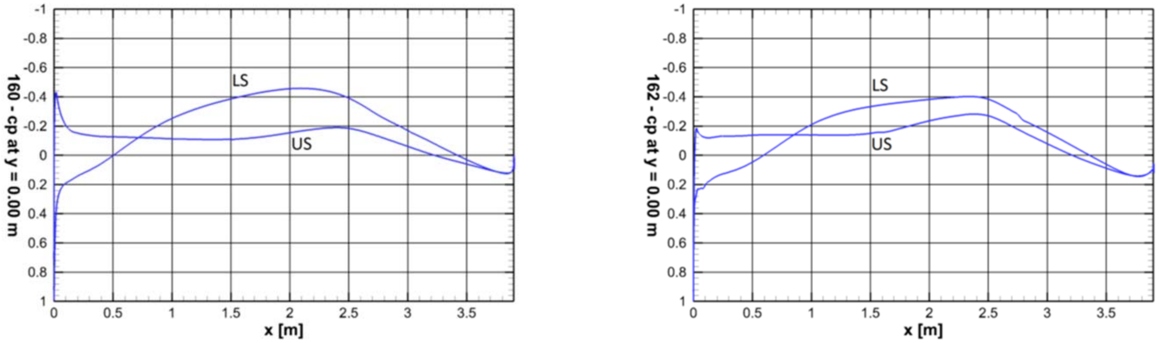




Figures from [5]

Aerodynamic Development of DUSC 2019

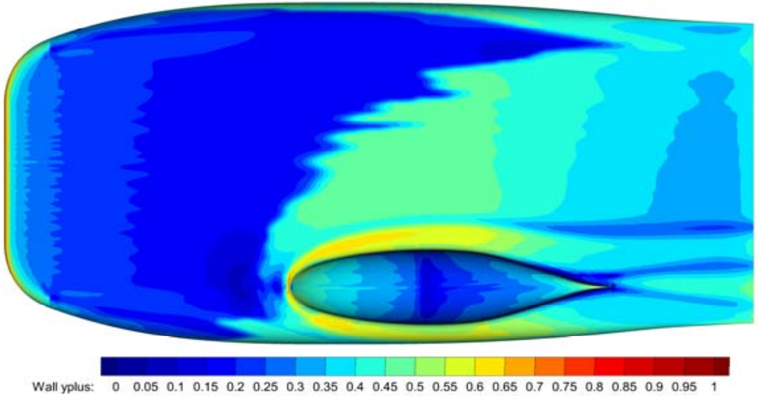
- Java Foil – Initial 2D design of main body.
  - Starting point: NACA 66009 laminar flow profile (see [6] for aerofoils)
  - Java Foil inverse design used to match baseline pressure distribution when in ground effect.

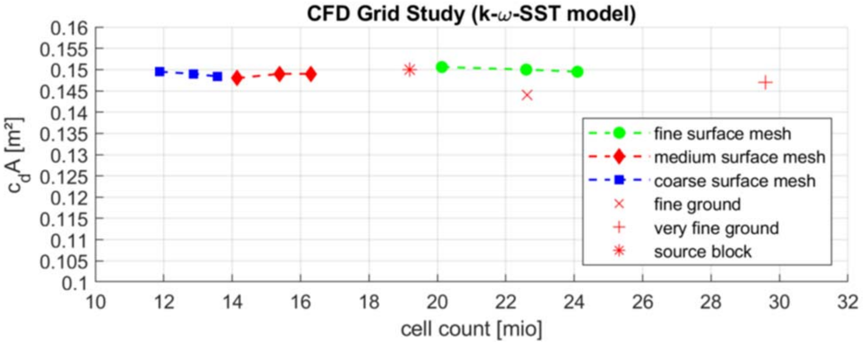


Figures from [5]

Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - Automated re-meshing when CAD geometry modified
  - Meshing in Pointwise
    - Quad-dominated surface mesh
    - Prism boundary layer mesh y+ < 1
    - Tetrahedral mesh in far field
    - 24-30M cells.





Figures from [5]

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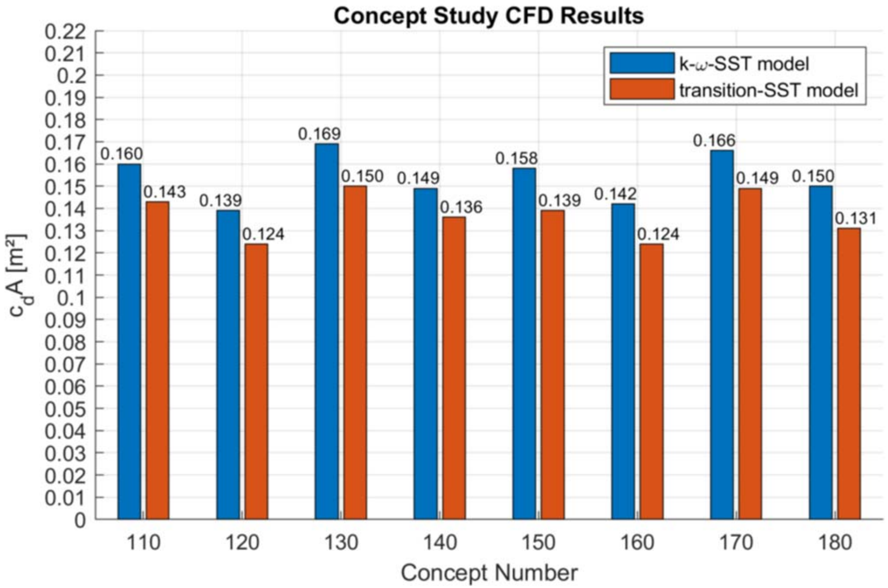
Aerodynamic Development of DUSC 2019

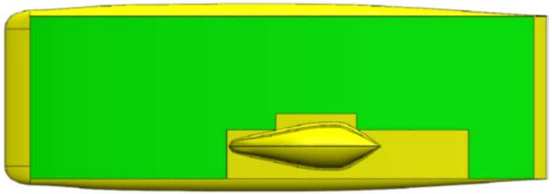
- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - Simulations ran overnight on 4 core Intel Xeon 3.7 GHz m/cs with 64Gb RAM
  - k-ω-SST and transition-SST models used.

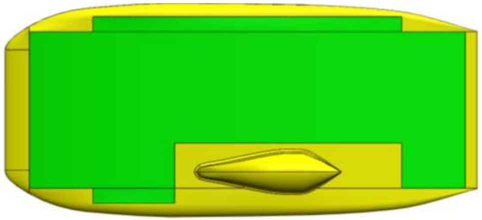


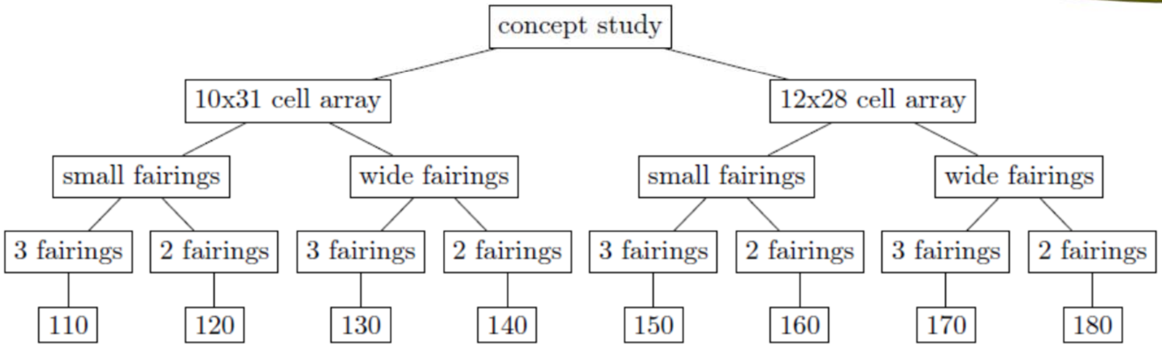
Figures from [5]

Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
    - 10x31 cell array vs 12x28 cell array
    - Small Fairings vs Wide Fairings
    - 3 Fairings vs 2 Fairings







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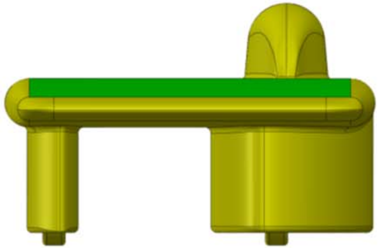

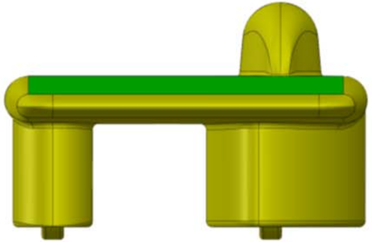

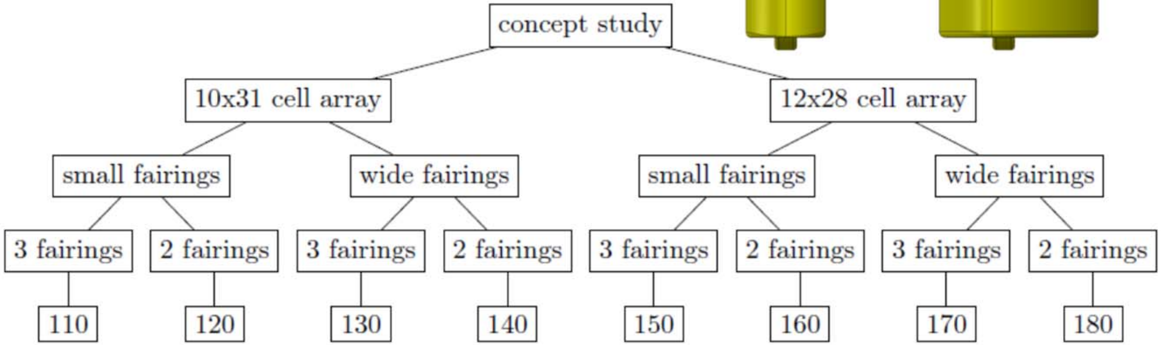

Figures from [5]

Aerodynamic Development of DUSC 2019

- Small fairings reduce vehicle aero drag
  ….. but are too narrow to allow the vehicle to steer
- Hence small fairings with opening doors when driver steers
- Need to be well-Engineered to work in practice!

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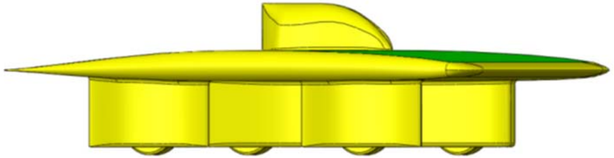
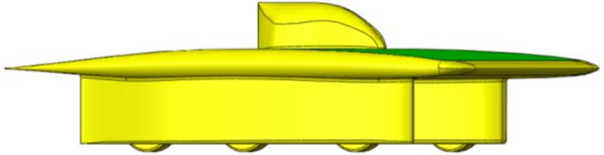
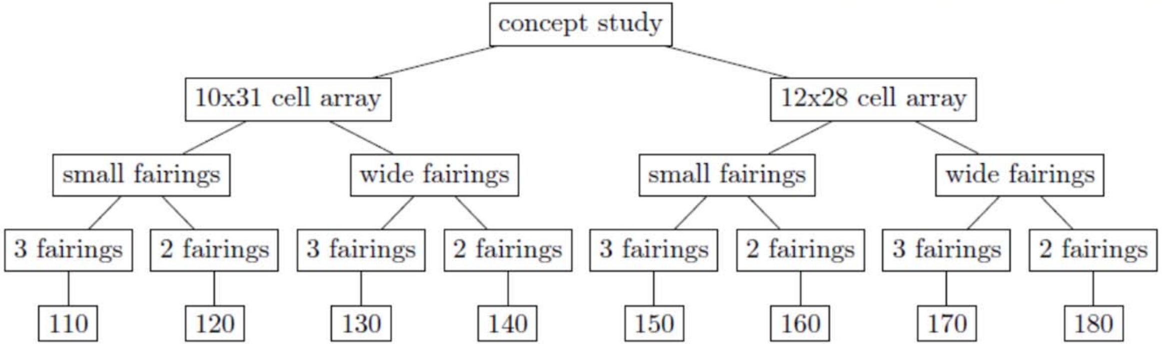
Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - 10x31 cell array vs 12x28 cell array
  - Small Fairings vs Wide Fairings
  - 3 Fairings vs 2 Fairings







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Figures from [5]

Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - 10x31 cell array vs 12x28 cell array
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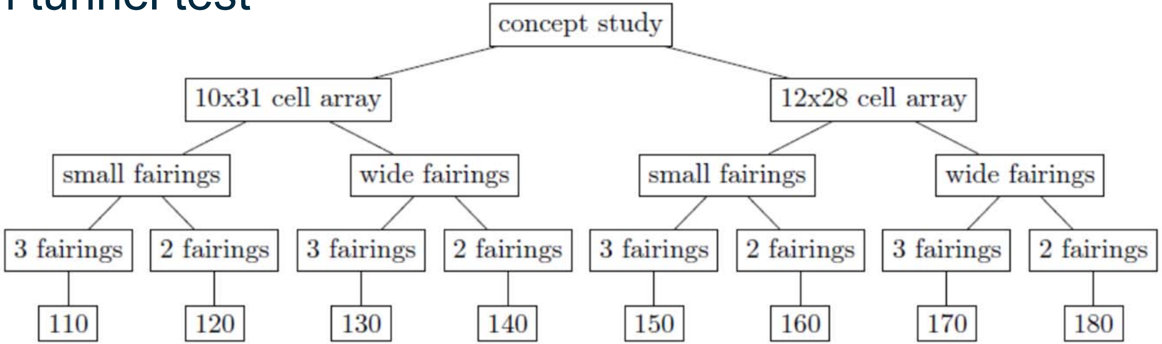
  - 3 Fairings vs 2 Fairings
    - Conflicting CFD results
    - Ran tunnel test



Figures from [5]
Model by [7]

Aerodynamic Development of DUSC 2019

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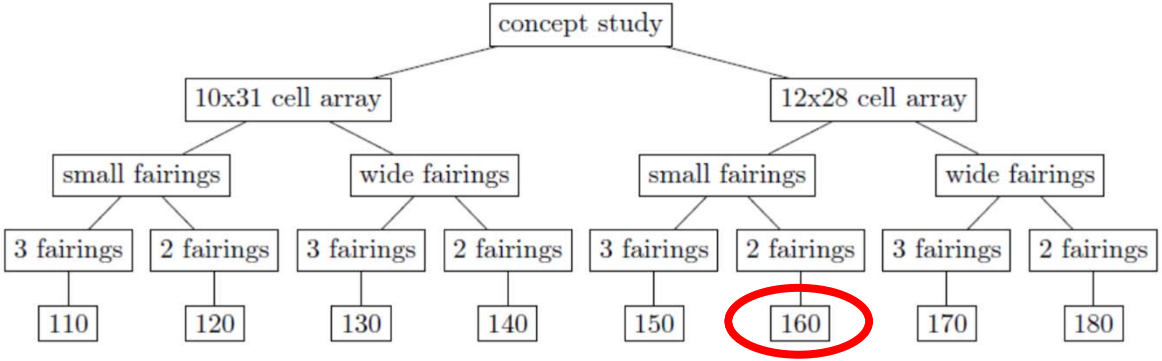

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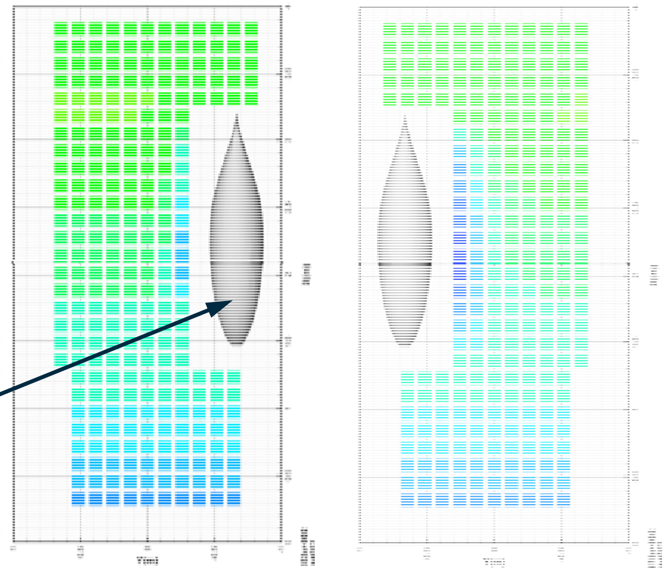
Aerodynamic Development of DUSC 2019

- Left Hand Drive? (The United Kingdom and Australia are both Right Hand Drive countries)
  - Drive: North to South, 8am-5pm
    - 4 hours before noon = sun in the East
    - 5 hours after noon = sun in the West

Aerodynamic Development of DUSC 2019

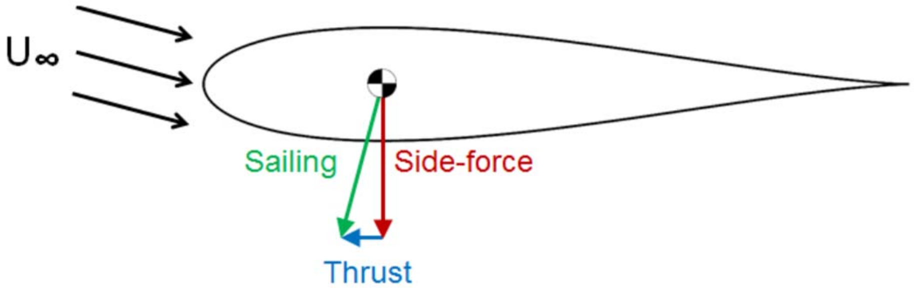
- Left Hand Drive? (The United Kingdom and Australia are both Right Hand Drive countries)
  - Drive: North to South, 8am-5pm
    - 4 hours before noon = sun in the East
    - 5 hours after noon = sun in the West

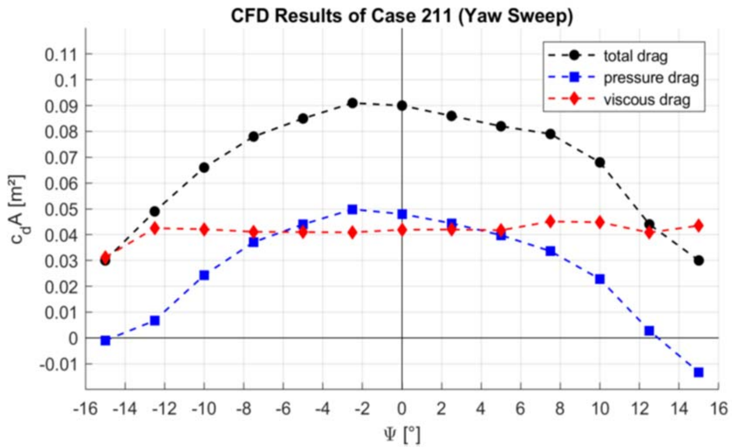
Simulated solar output cell by cell over event:



Aerodynamic Development of DUSC 2019

- Left Hand Drive?
  - Crosswinds on wheel fairings provide sailing thrust
  - Reduces drag at yaw





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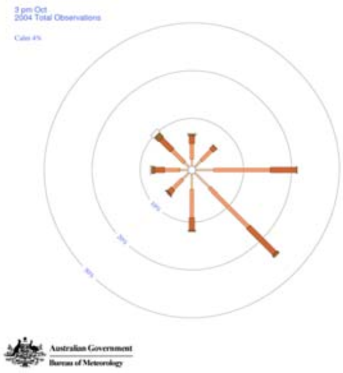
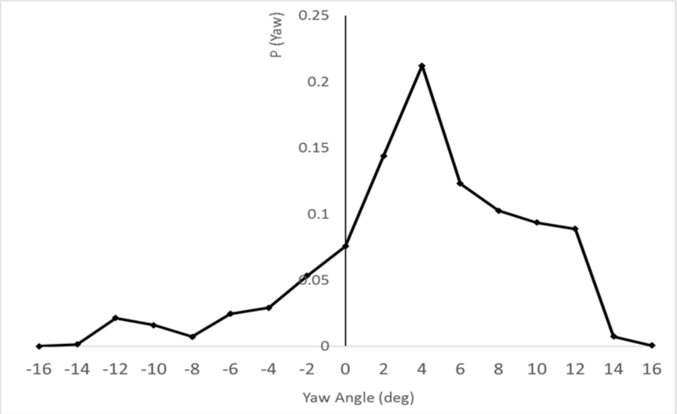
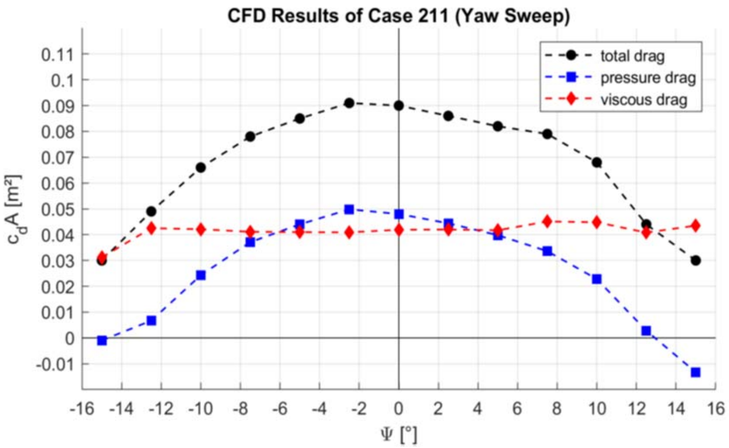
Aerodynamic Development of DUSC 2019

- Left Hand Drive?
  - Drive: North to South, 8am-5pm
    - Prevailing wind is from the East

Alice Springs
3pm in October
1942-2016







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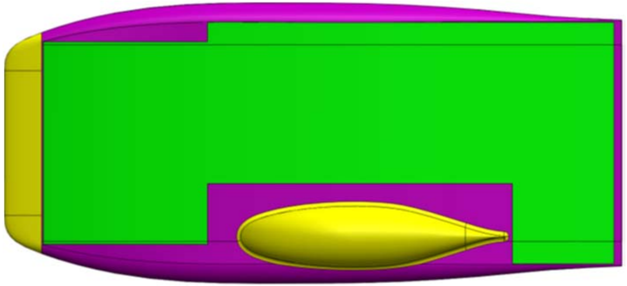
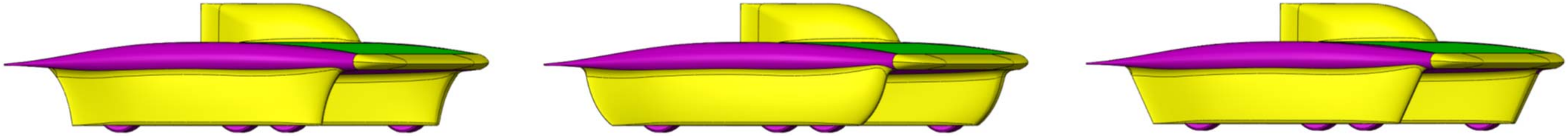
Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - Progressive refinement:
    - Cell arrangement
    - Leading edge
    - Canopy
    - Wheel Fairing Leading and Trailing Edges



Case 207



Figures from [5]

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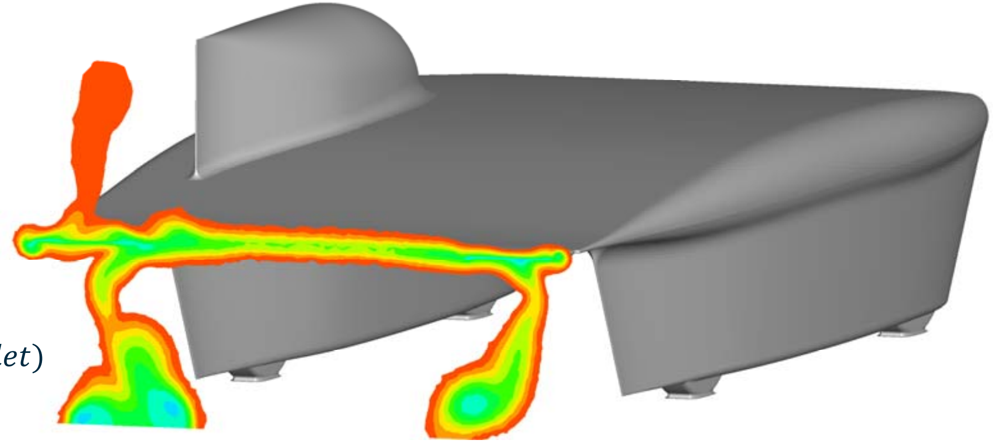
Aerodynamic Development of DUSC 2019

- Solidworks - Pointwise – Fluent – Tecplot – Main Design Development
  - Progressive refinement:
    - Forces (C_{DA}, C_{LAF}, C_{LAR}) are the bottom line.
    - Flowfield provides guidance on how to improve.
      - Automated standard plots for every case.
      - Wake Total Pressure

Contours of total pressure coefficient

$$C_{PTot} = \frac{\left(P + \frac{1}{2}\rho u^2\right) - P_\infty}{\frac{1}{2}\rho u_\infty^2}$$

where ∞ denotes freestream (inlet)



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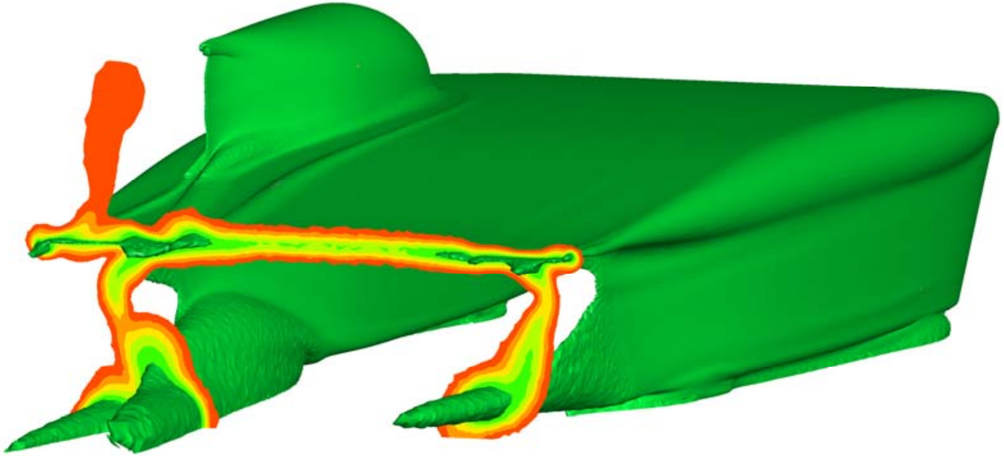
Contours of total pressure coefficient + Isosurface at C_{PTot}=0.5



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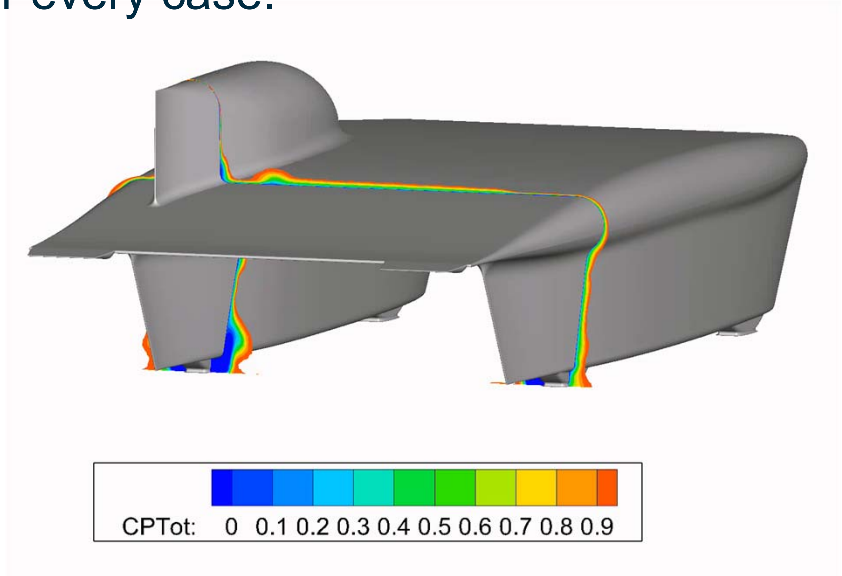
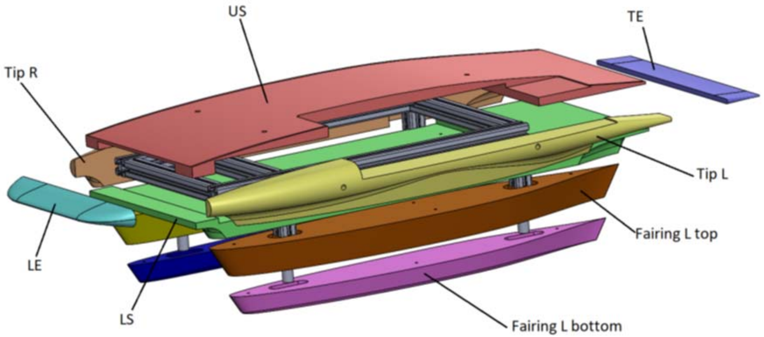
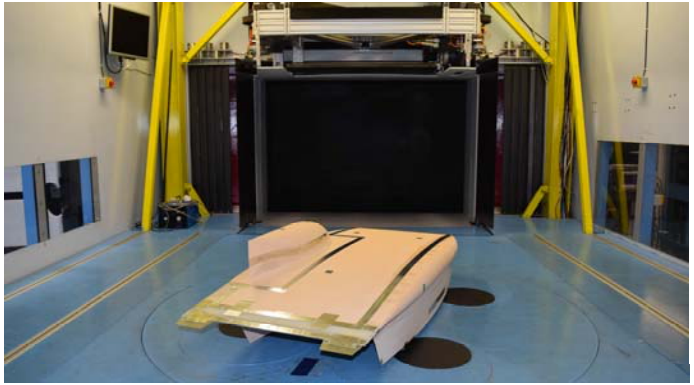


Aerodynamic Development of DUSC 2019

- Scale Model Test of DUSC 2019
  - 35% Scale Model
  - Necuron 480 Model Board on Aluminium Frame
  - Detail parts rapid prototyped on Objet Eden 500V
  - Durham 2m^2 Wind Tunnel in Fixed Ground Configuration
  - Blockage < 5%
  - Re = 2.3 x 10^6 (30 m/s)





Figures from [5]

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Aerodynamic Development of DUSC 2019

- Scale Model Test of DUSC 2019
  - Wind tunnel results >10% higher on C_DA vs CFD at same Re.
  - ~30 repeats of baseline config. over the test programme all within 1% ($0.001m^2$ C_DA Full Scale)

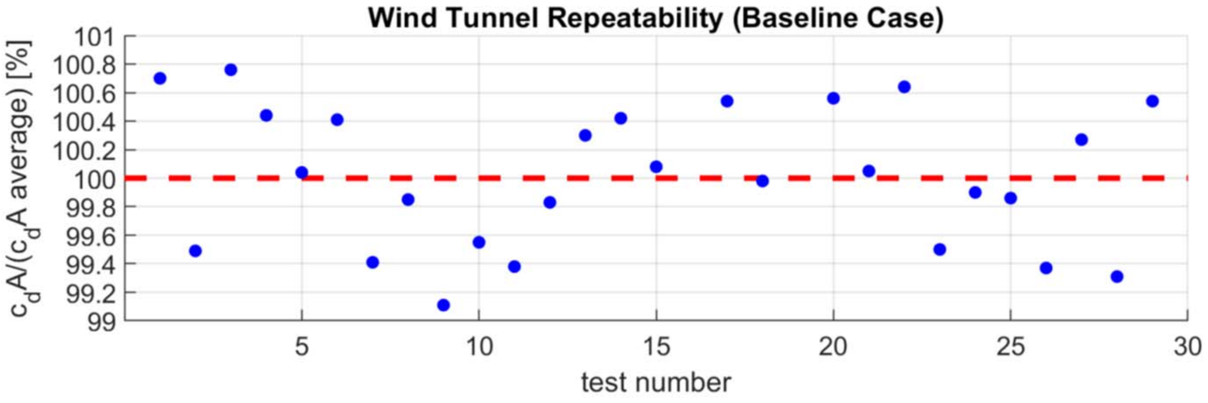
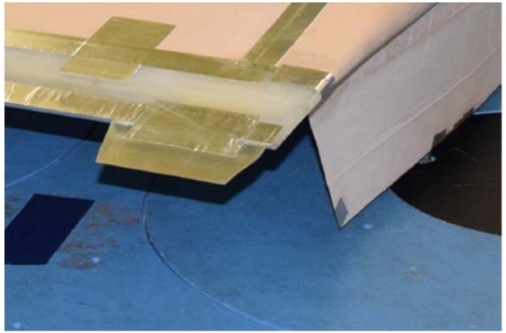
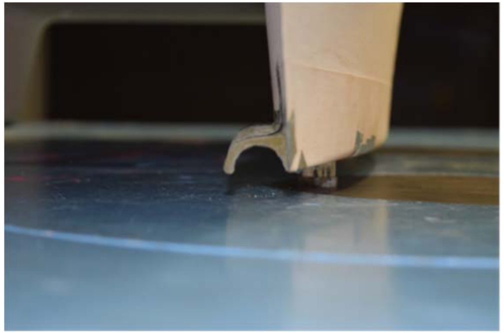


Figure from [5]

Aerodynamic Development of DUSC 2019

- Scale Model Test of DUSC 2019
  - Refinement of rear lights
  - Investigation of impacts of small devices (winglets, footplates etc).
  - Detailed Yaw Sweep
  - Effects of Pitch and Rideheight





Figures from [5]

Aerodynamic Development of DUSC 2019

- Zero Yaw:
  - C_DA = 0.105m^2 (wind tunnel, model Re), 0.092m^2 (CFD, full scale Re)
  - and yaw makes things better…

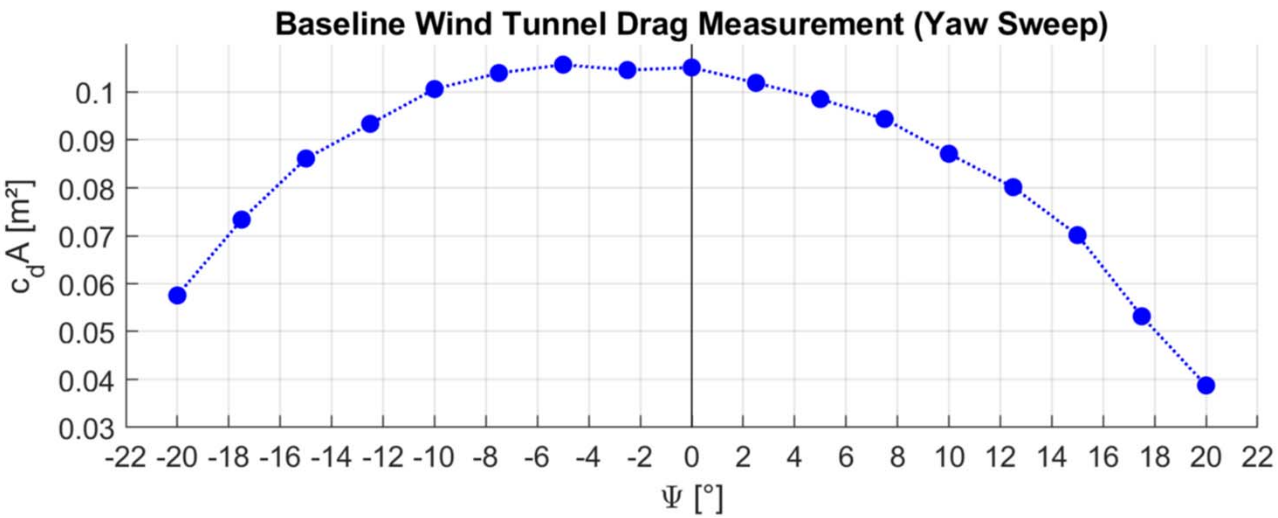


Figure from [5]

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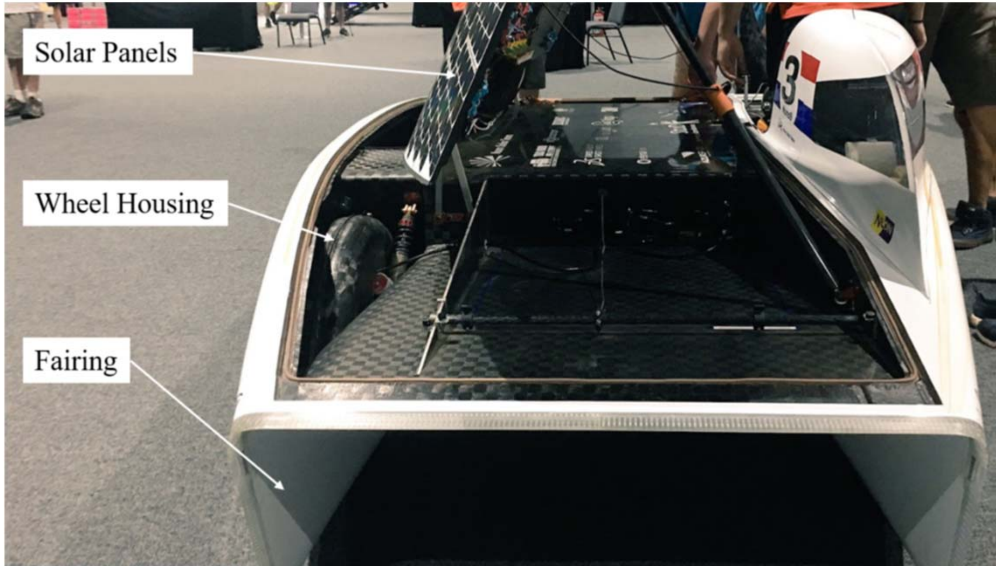
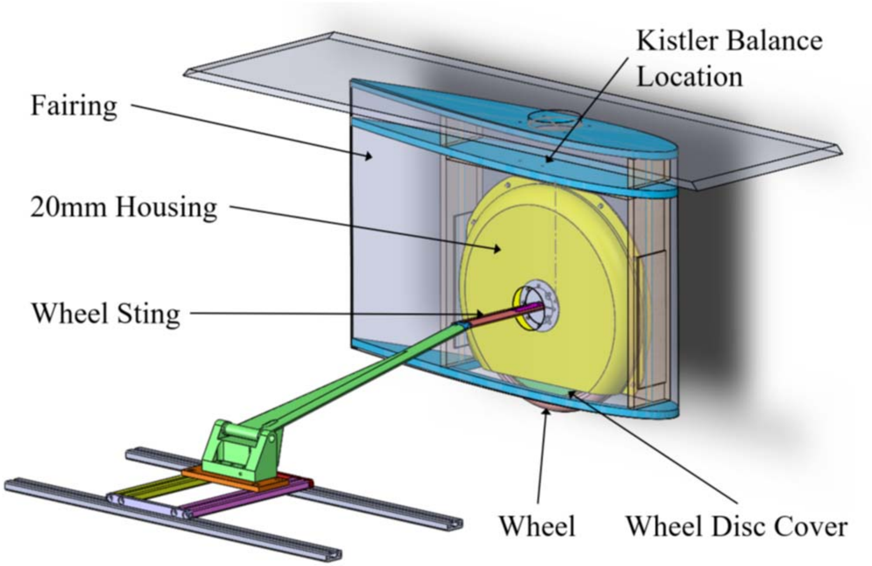
Aerodynamic Development of DUSC 2019

- Wheel Inner Housings
  - Used by several teams
    (but not on Durham cars…)
  - Tight fitting wheel housings within the wheel fairing
  - Move with the suspension and steering



Aerodynamic Development of DUSC 2019

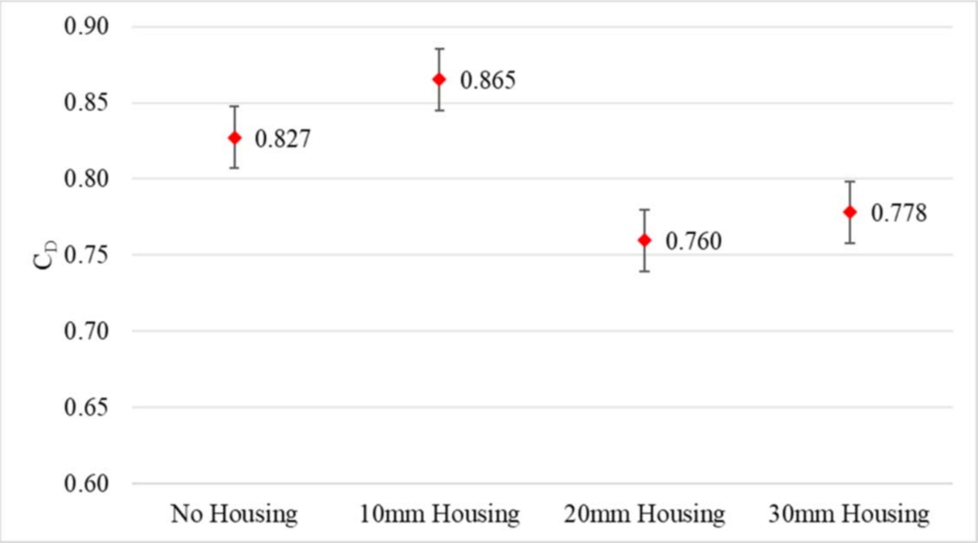
- Wheel Inner Housings
  - CFD & Wind Tunnel investigation at full scale as capstone project



From [8], initial work by [9]

Aerodynamic Development of DUSC 2019

- Wheel Inner Housings
  - CFD & Wind Tunnel investigation at full scale as capstone project
  - Wheel housings can provide a drag saving
  - The gain is ΔC_D=-0.067 based on wheel frontal area which is ~ $\Delta C_D A$=-0.01m^2 on the vehicle.
  - A tight fit is good, but too tight a fit can increase drag relative to not having an inner housing.



From [8]

Outline

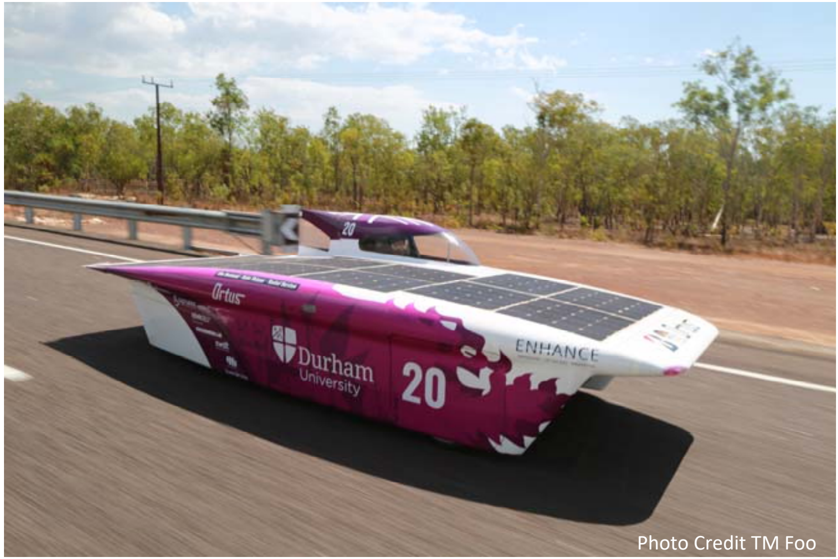
Solar Car Aerodynamics Fundamentals

Vehicle Conceptual Design

Aerodynamic Development of DUSC 2019

Build

Test & Compete



Build

- Positive patterns machined in modelboard
  - ~1000 hours machining time
- Pattern pieces assembled & painted
- Sanded and Polished
- Wet-Layup of Fibreglass-Epoxy Moulds
- Cure in Vacuum Bag
- 8 Piece Main Mould
- Monocoque Chassis
  - Carbon (+Kevlar) Skin, Rohacell Core
  - Pre-preg with vacuum cure in oven
  - Chassis ~40 kg, whole car: 175 kg

Durham University

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https://twitter.com/i/status/1149350505853923328

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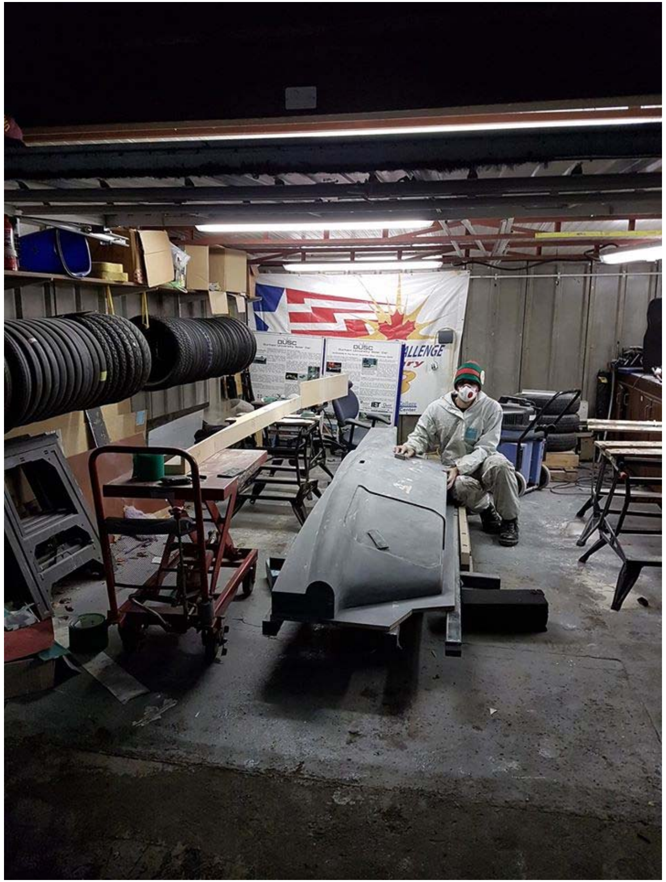

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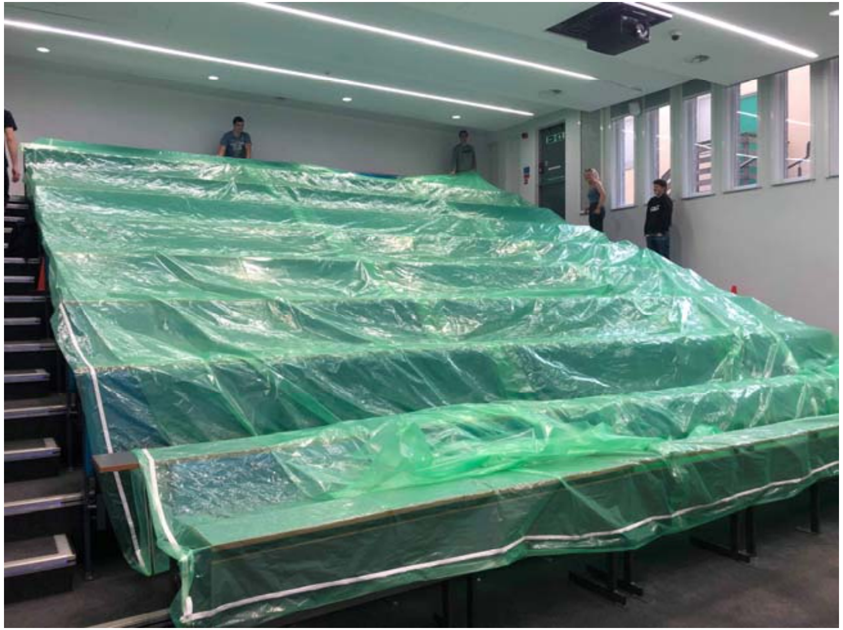

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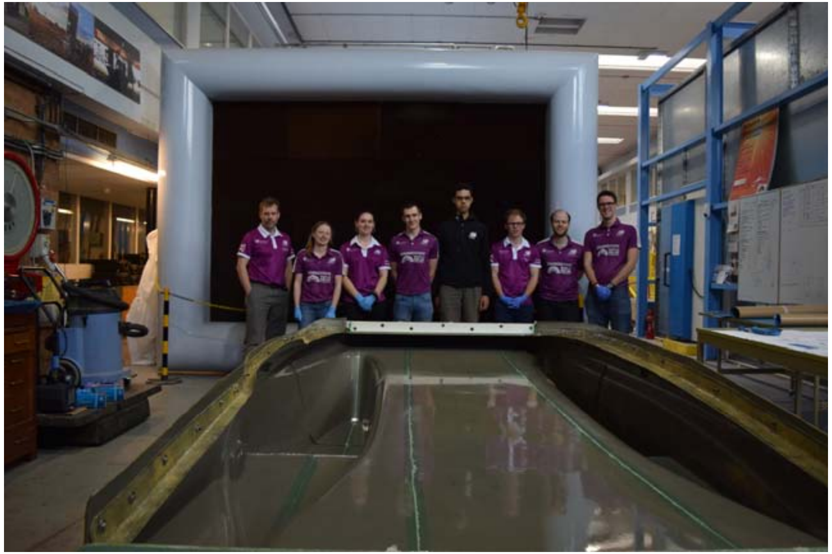

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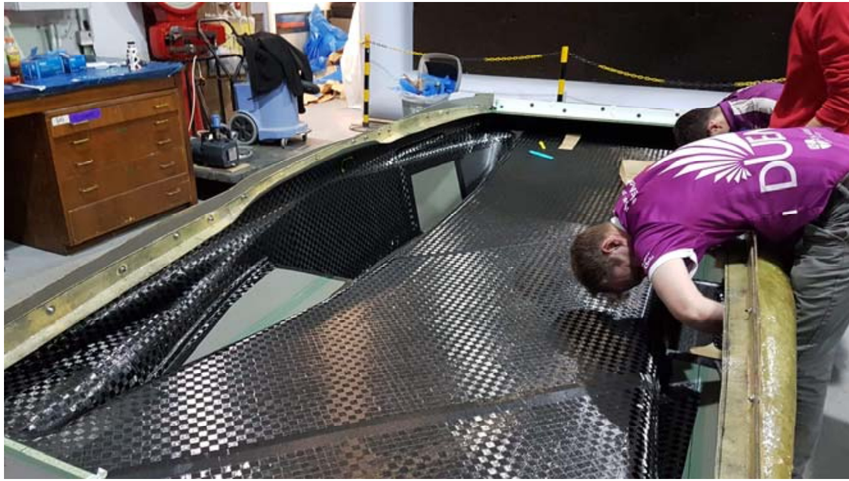

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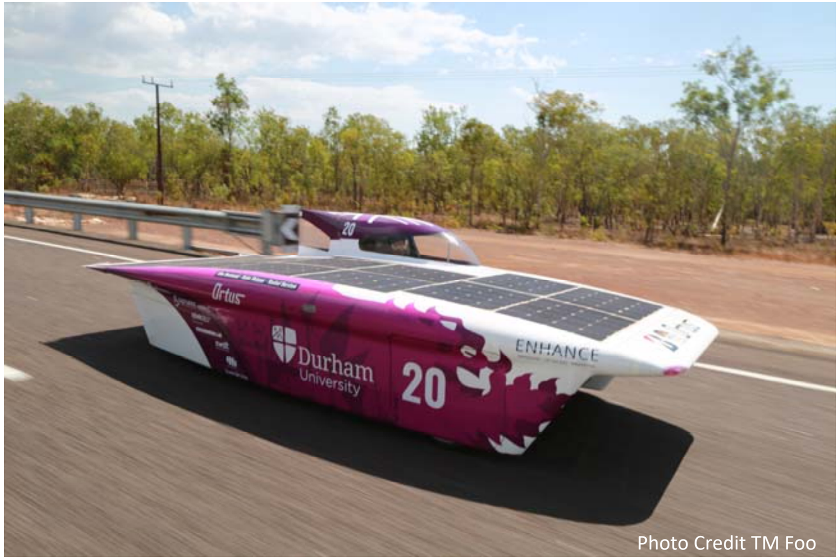

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Test and Compete

- Testing at Bruntingthorpe Proving Ground
- Ship / Fly to Australia
- Hot-Weather Testing

  at Gunn Point Road, NT, Aus.
  - Confirmed C_DA
- World Solar Challenge
  - Drove North Coast to South Coast, just short of Adelaide...
  - Ranked 14th.

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References

1. Williams, J., Aerodynamic Drag of Engine Cooling Airflows With External Interference, SAE Vehicle Aerodynamics SP-1786, 2003-01-0996, Society of Automotive Engineers, 2003.
2. Hoerner, S, F, Fluid Dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance, 1965.
3. University of Minnesota, Solar Car Aerodynamics & Body Design, IEF Solar Car Conference 2015. https://www.americansolarchallenge.org/ASC/wp-content/uploads/2015/04/2015-Solar-Car-Conference-Aerodynamics.pdf .
4. Tamai, G, The Leading Edge: Aerodynamic Design of Ultra-streamlined Land Vehicles (Engineering and Performance), Bentley, 2009.
5. Stemmler, A, Aerodynamic Design and Analysis of a Challenger Class Solar Car, University of Stuttgart Masterarbeit, undertaken at Durham University, 2018.
6. Abbott, IH and Von Doenhoff, AE, Theory of Wing Sections, Dover Books,1960.
7. Fung, J, Solar car aerodynamic evaluation and development, Master's Thesis, Durham University, Department of Engineering, 2016.
8. Wilderspin, J, Wheel and Tyre Aerodynamic Streamlining for Ultra-Low Carbon Vehicles, Master's Thesis, Durham University, Department of Engineering, 2020.
9. Dagkoulis, G, Wheel and Tyre Aerodynamic Streamlining for Ultra Low Carbon Vehicles, Master's Thesis, Durham University, Department of Engineering, 2019.

More Information

- http://www.duem.org
- https://www.dur.ac.uk/engineering/
- https://twitter.com/DUEM_Electric
- DUEM_electric @DUEM_electric
- https://www.youtube.com/channel/UCCEutnq5g_Lq2fbb7VHG5bQ

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IEF Solar Car Conference 2021

Aerodynamic Development of the 2019 Durham University Solar Car

Prof. David Sims-Williams