Coupled WAVE-VECTIS Simulation of an Intake Restricted Engine

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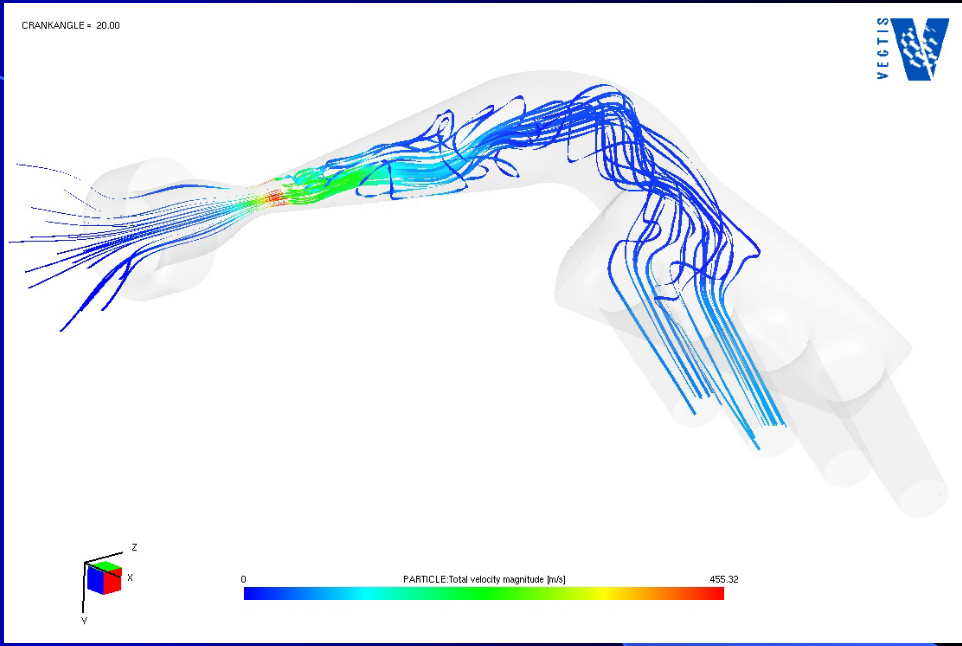
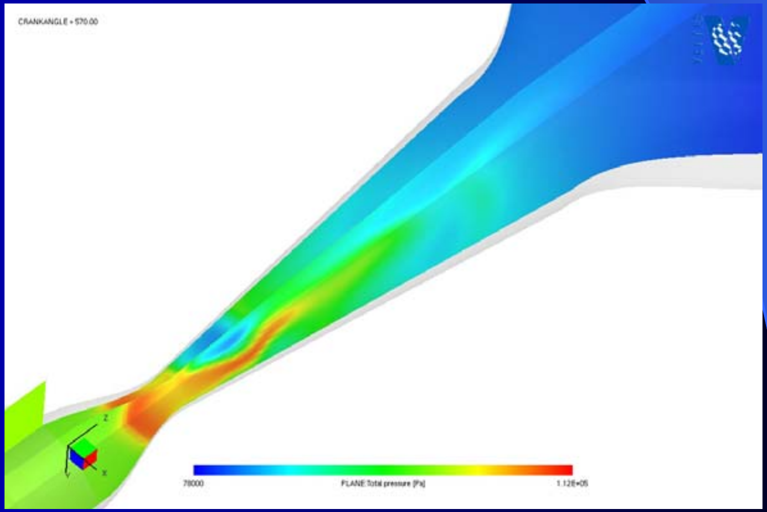
Agenda

- Background
- Project motivation
- Why couple WAVE & VECTIS?
- Model preparation
- Comparison of two intake manifold geometries

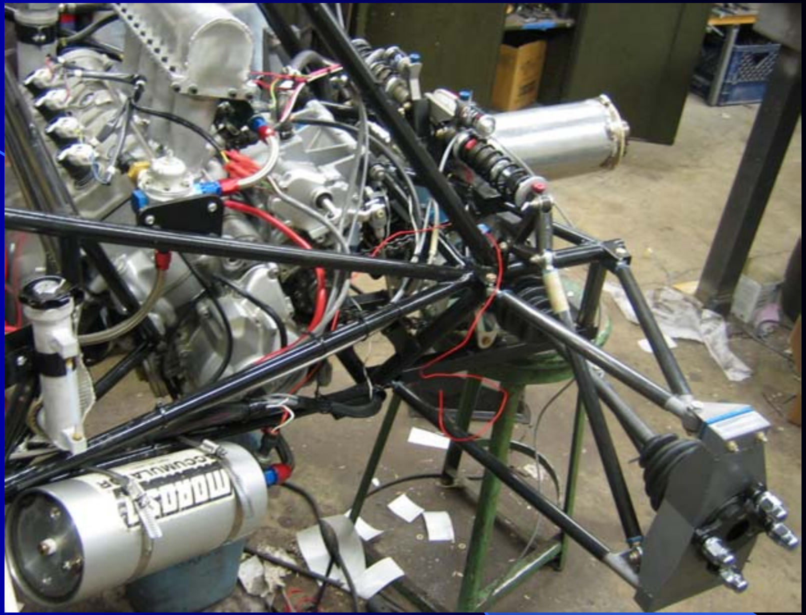


Top Feed 14,000 RPM

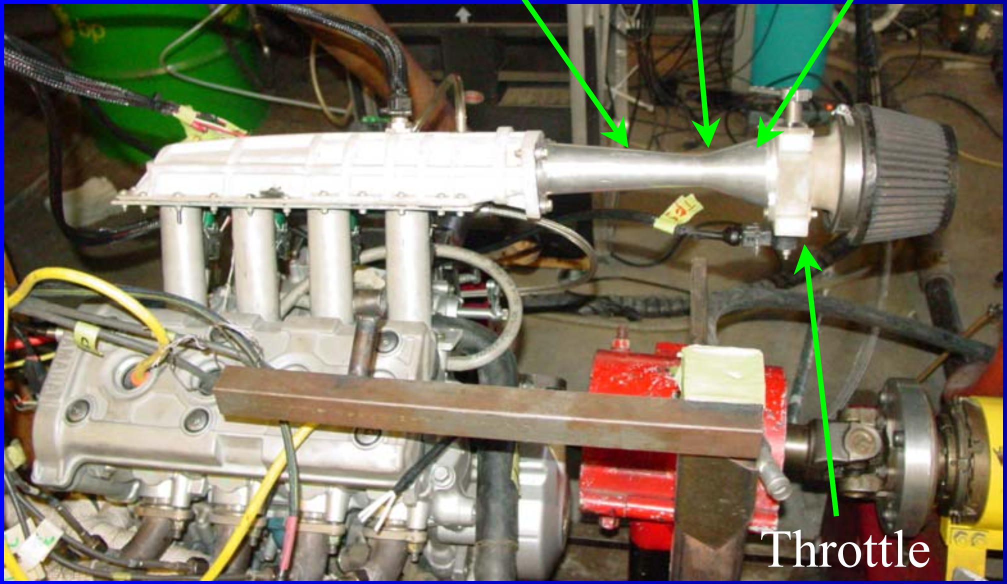


Background

- Engine is used in a small open wheeled racecar for the Formula SAE student competition.
- Formula SAE dictates the use of an intake restrictor with a diameter of 20mm (with gasoline) or 19mm (with E-85).
- Intake restrictor poses greatest impact and challenge to improving engine performance.



Diffuser Throat Nozzle



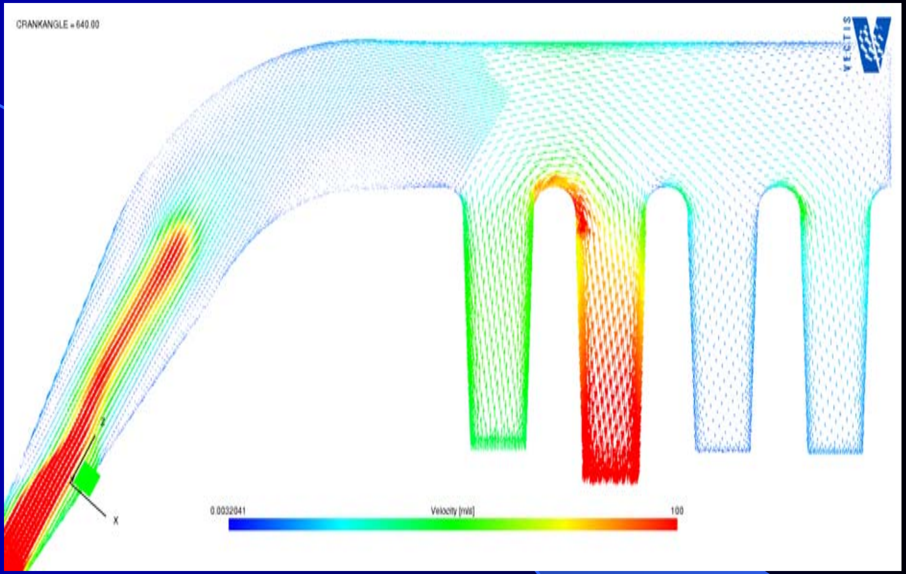
- Engine Specifications:
  - Four Cylinder, Four stroke
  - 600cc Displacement
  - 15,500 rpm redline
  - Bore = 65.5mm, Stroke = 44.5mm
  - 4-2-1 Exhaust Header
  - Sequential Port Fuel Injection (student calibrated)
  - DOHC, 4 valves per cylinder
  - Compression Ratio = 12.4:1
  - Fuel – Gasoline, 100 Octane

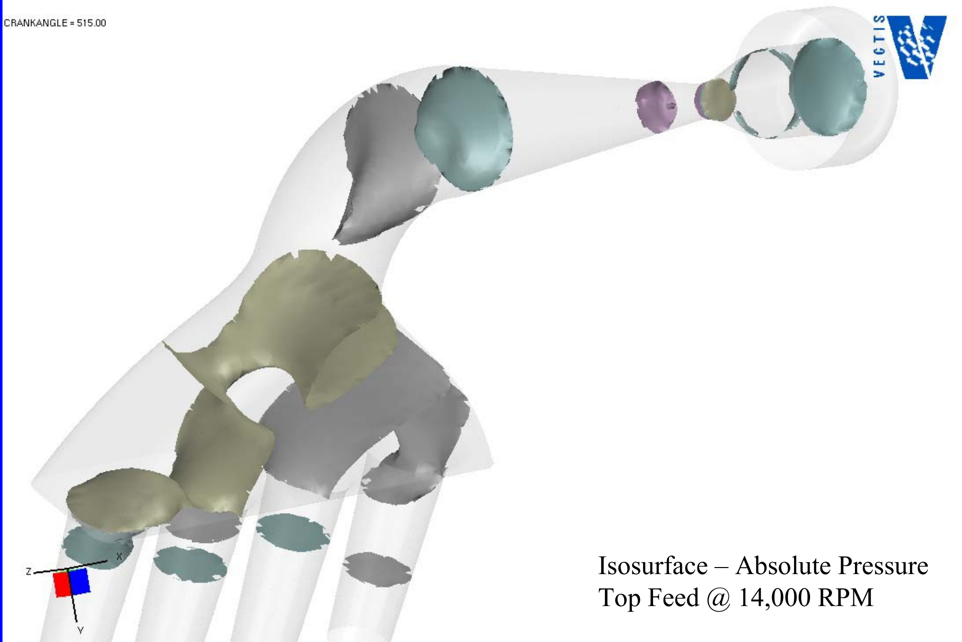
Project Motivation

- Effect of plenum geometry on restrictor performance.
  - Is there significant pressure recovery after the restrictor?
  - Does the plenum geometry play a role on restrictor performance?
  - Where to place flow bends?
- Study 3D flow effects within intake manifold.
- How often during the cycle is the flow really choked?
- Achieve a better general understanding of the flow through the restrictor and intake manifold.
- Improve WAVE model through pressure loss coefficients.

Why Couple WAVE to VECTIS?

- True 3D geometry is properly captured.
- Coupled simulation avoids potentially misleading steady state CFD solutions.
- Flow effects and pressure pulses are more accurately represented in their true 3D nature.



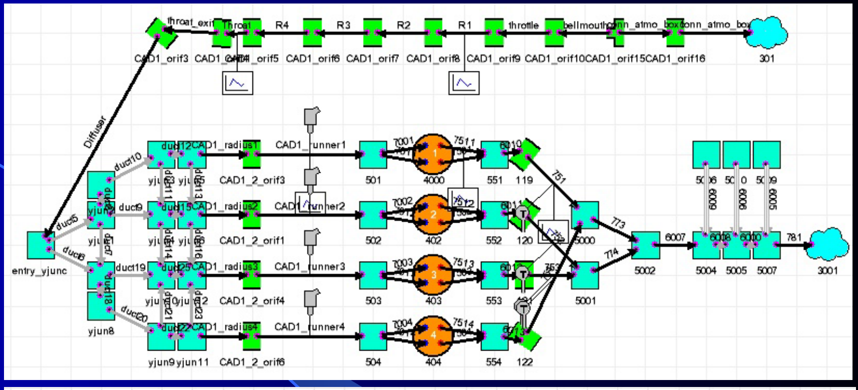


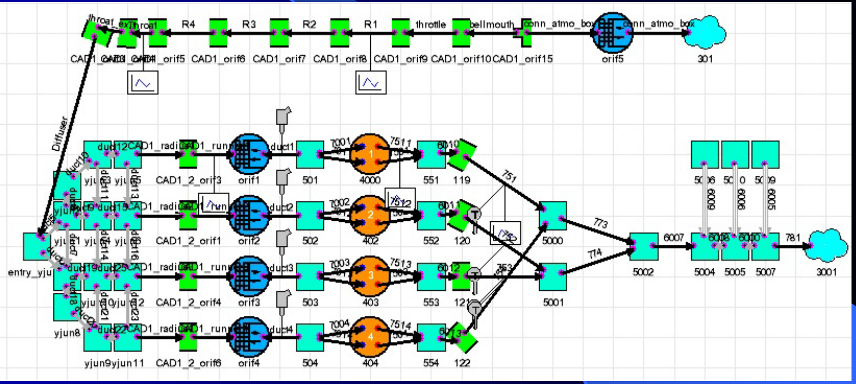
Isosurface – Absolute Pressure
Top Feed @ 14,000 RPM

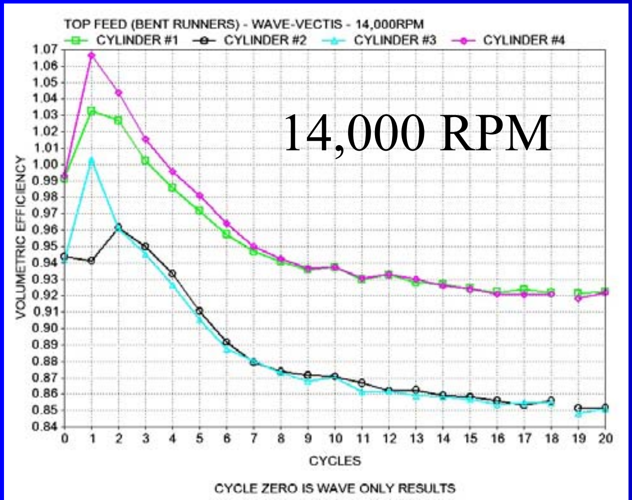
- Less empirical data gathering compared to modeling of a 1D intake geometry.
- Better data visualization with CFD.
- No flow separation possible in WAVE.
- Better prediction of volumetric efficiency imbalances from cylinder to cylinder.

WAVE – VECTIS Preparation & Run Process

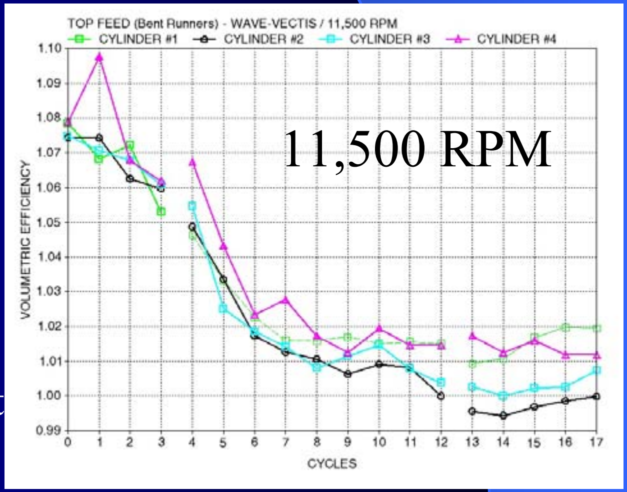
- Generate WAVE only model of the engine.
  - Run over full rpm range.
- Import, Prepare, & Mesh CAD Geometry.
- Link WAVE model to VECTIS using specialized external CFD orifice.
- Move Fuel injector position into WAVE only portion of model.
  - Issue of modeling fuel spray in CFD is avoided.
- Run coupled WAVE-VECTIS simulation.
  - Run at only one rpm point at a time.
  - Run multiple cycles to convergence.





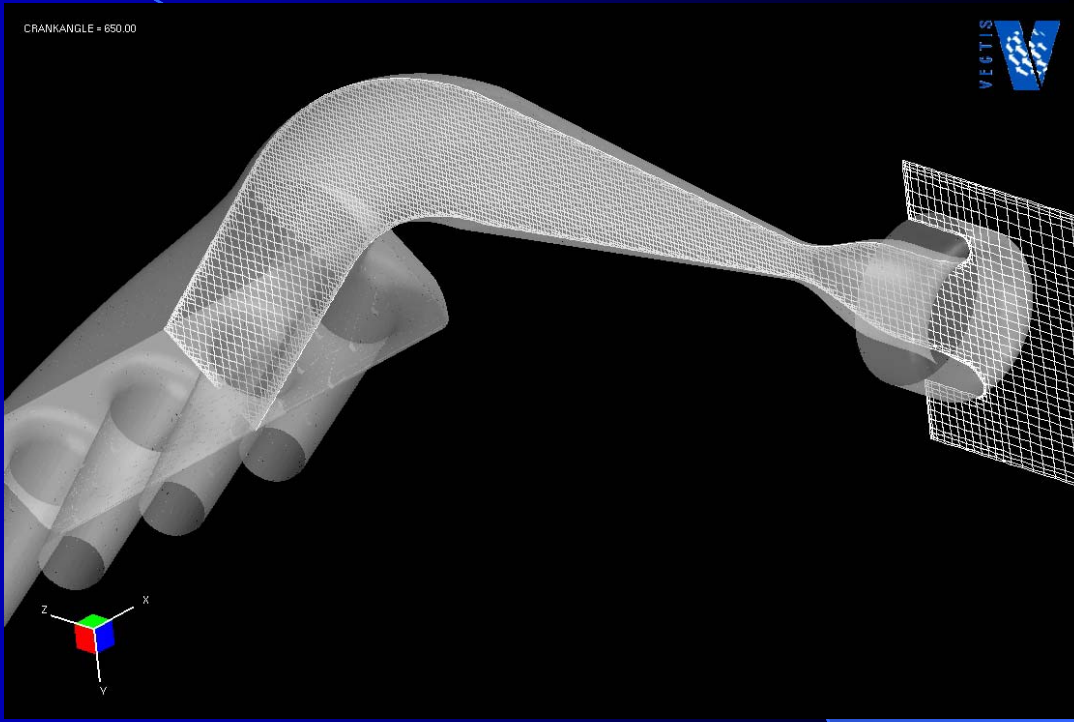


Typical Wave-Vectis Cycle Output



Specific Challenges of Restrictor Imposed on WAVE– VECTIS Solution

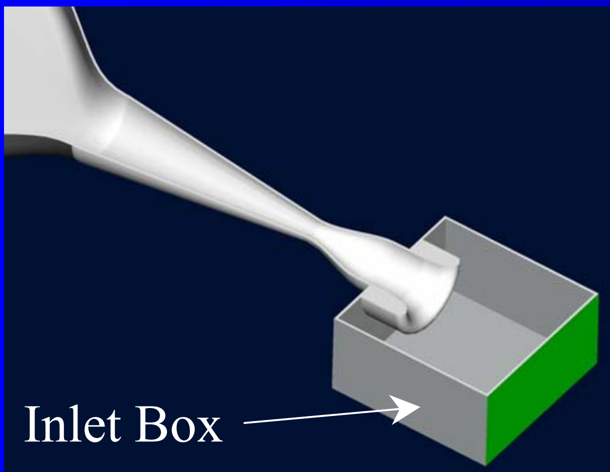
- High RPM & High Valve Overlap
  - More cycles generally required to converge as rpm increases.
  - High rpm of greatest interest on investigating choked restrictor flow.



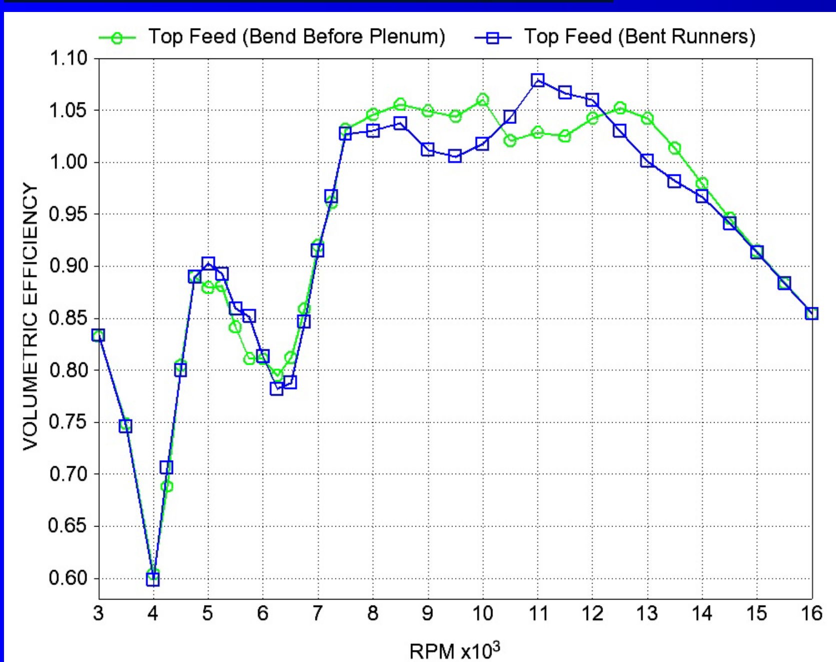
- In order to capture high flow velocities (supersonic) at locations with small geometry, requires…
  - Small time step be taken to keep Courant number reasonable even with implicit solution method.
  - 0.100 to .125 CAD time step at 14,000 rpm.

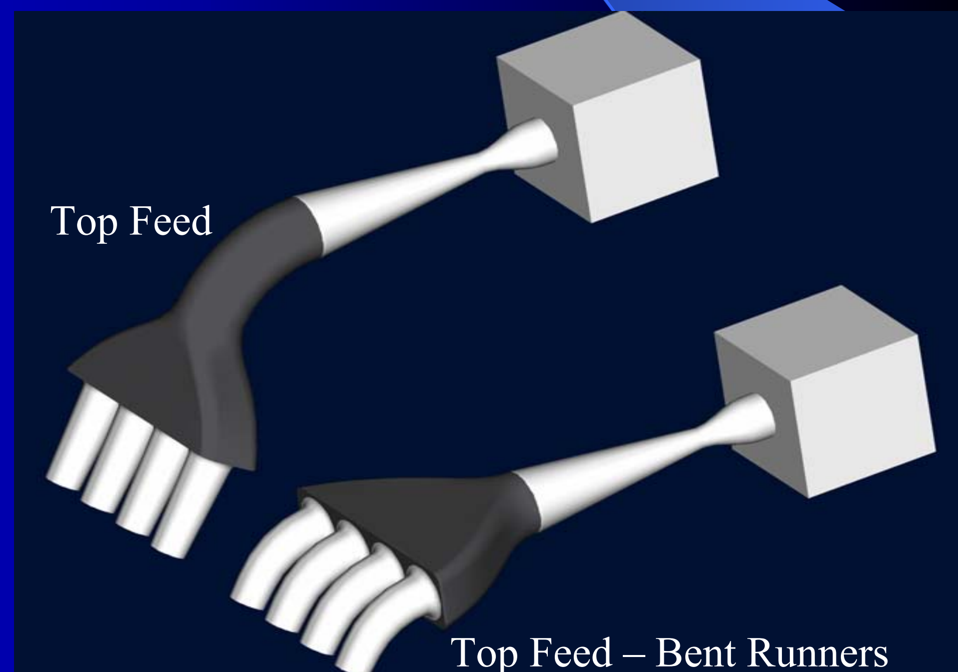
Top/Center Feed Style Intake Manifolds

Sectional View

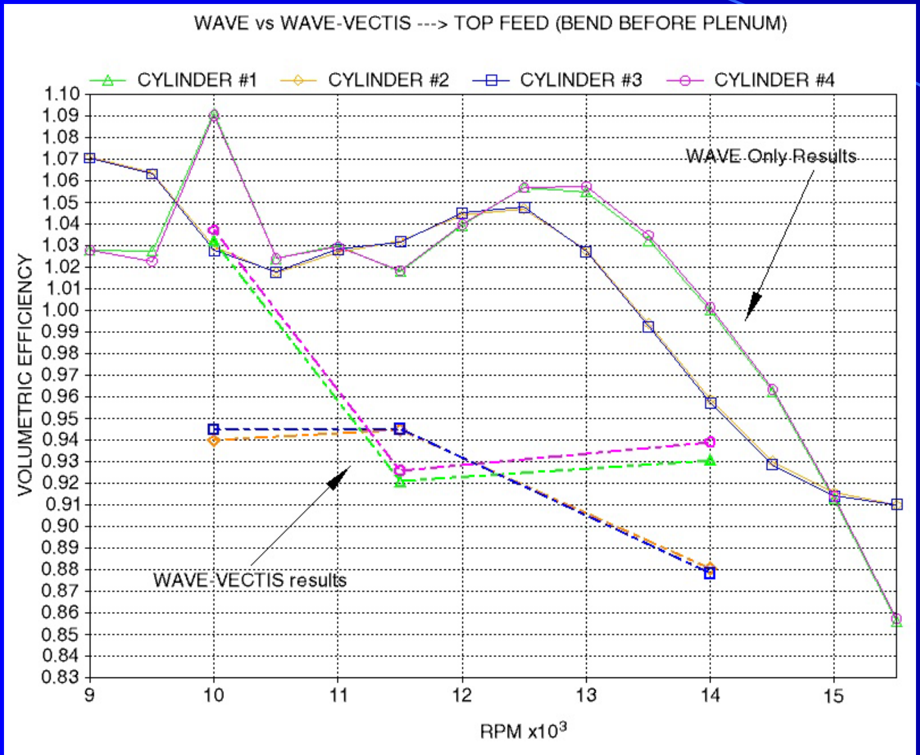


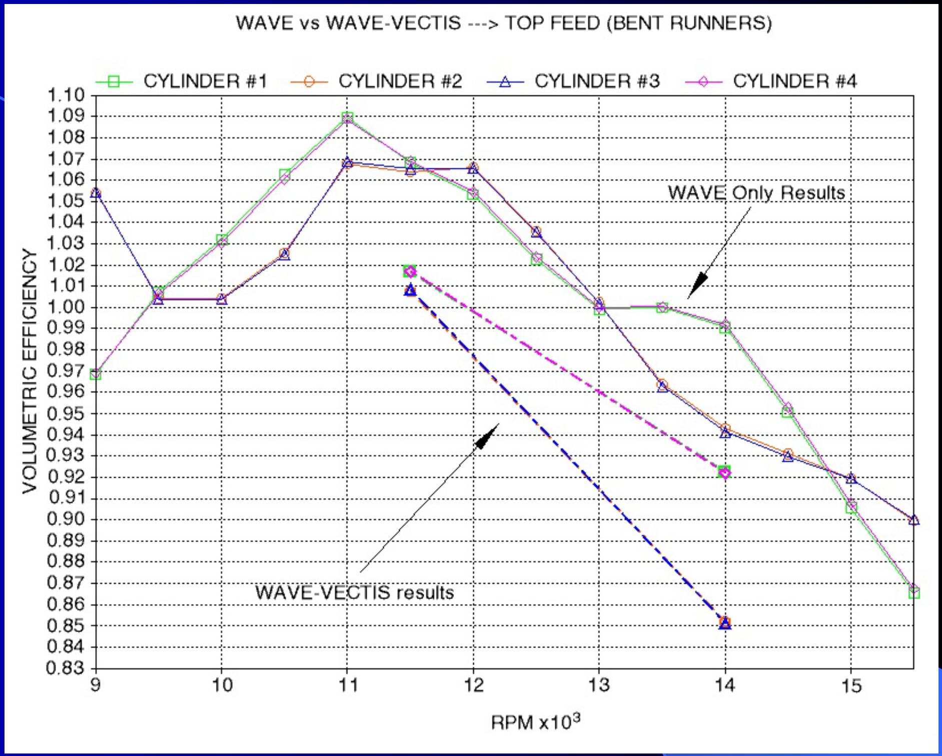
- Manifolds designed to differ in manifold shape only.
  - Same Restrictor and Inlet Geometry.
  - Equal Manifold Volume – between restrictor and intake runners (shaded section represents equal volumes).
  - Runners equal in length, diameter, and taper for both manifolds.
- Both manifolds incorporate a 55° bend somewhere along the flow path.
- Atmospheric inlet box, with volume = 4.1 liters.
- Inlet and outlet boundaries selected where flow is predominantly one dimensional.





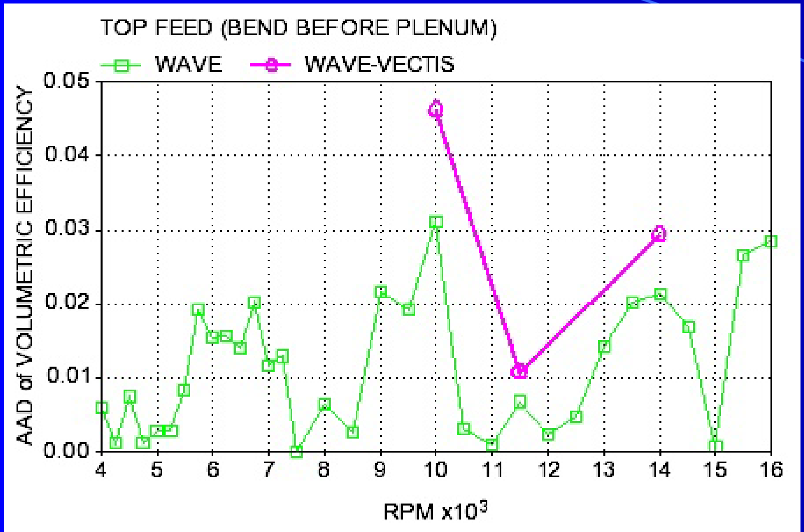
Volumetric Efficiency: WAVE vs. Coupled

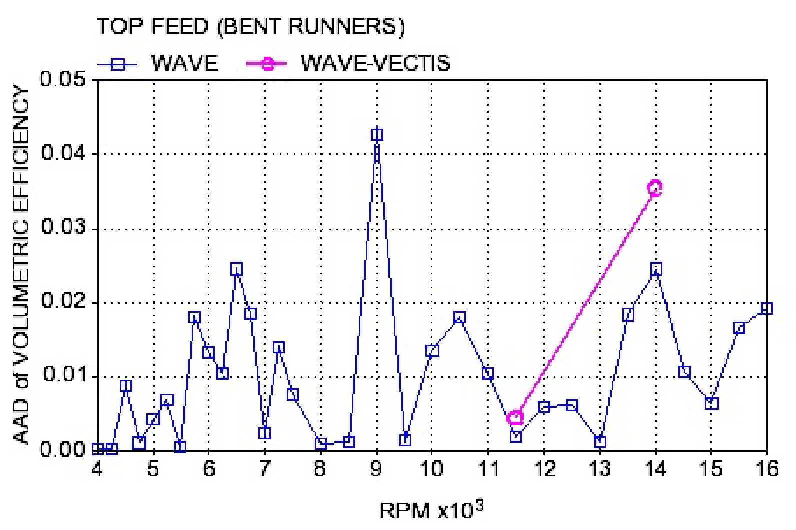




- Spread of volumetric efficiency values are greater with WAVE -VECTIS.
- Good agreement between WAVE & WAVE-VECTIS for cylinder order and grouping of volumetric efficiencies.
- Cylinder grouping: 1&4 / 2&3

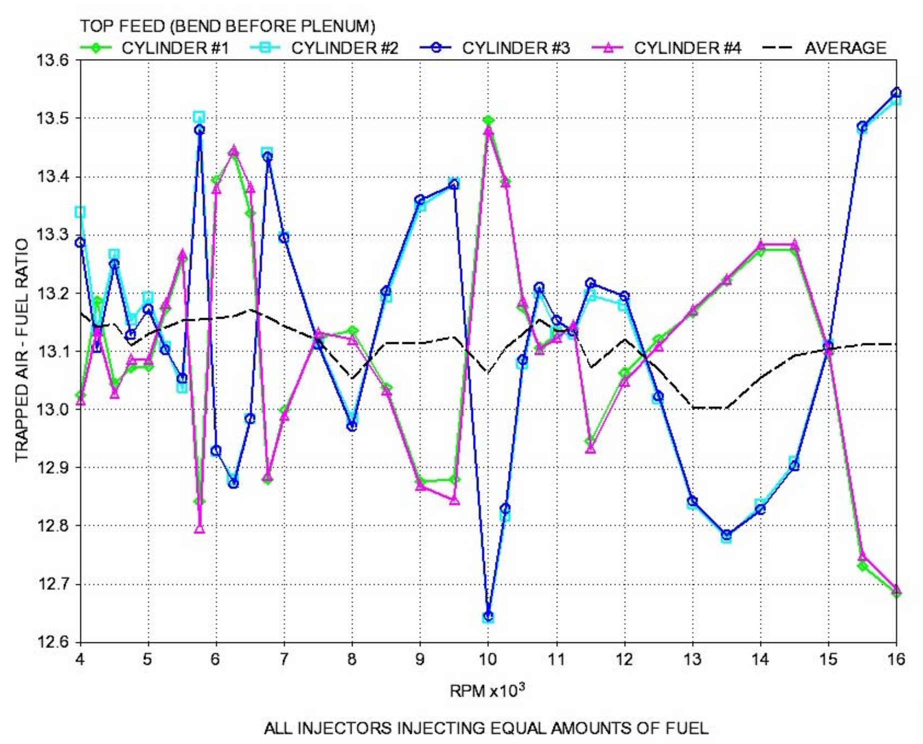
Absolute Average Deviation of Volumetric Efficiency





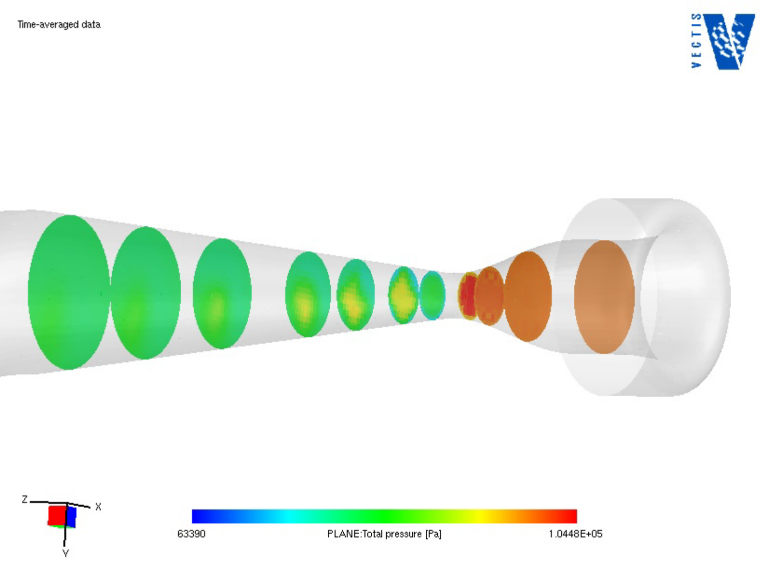
$$AAD = \frac{1}{N}\sum_{i=1}^{N}\left|x_i - \overline{x}\right|$$

- Used as variable to assess VE spread among different manifold designs.
- Better indication of VE spread than standard deviation.
- WAVE-VECTIS typically shows higher AAD of VE.
- Benefits of low AAD of VE
  - Reduced acoustical order content at intake and exhaust orifices.
  - Less time spent calibrating fuel and ignition changes for individual cylinders. Better overall calibration.

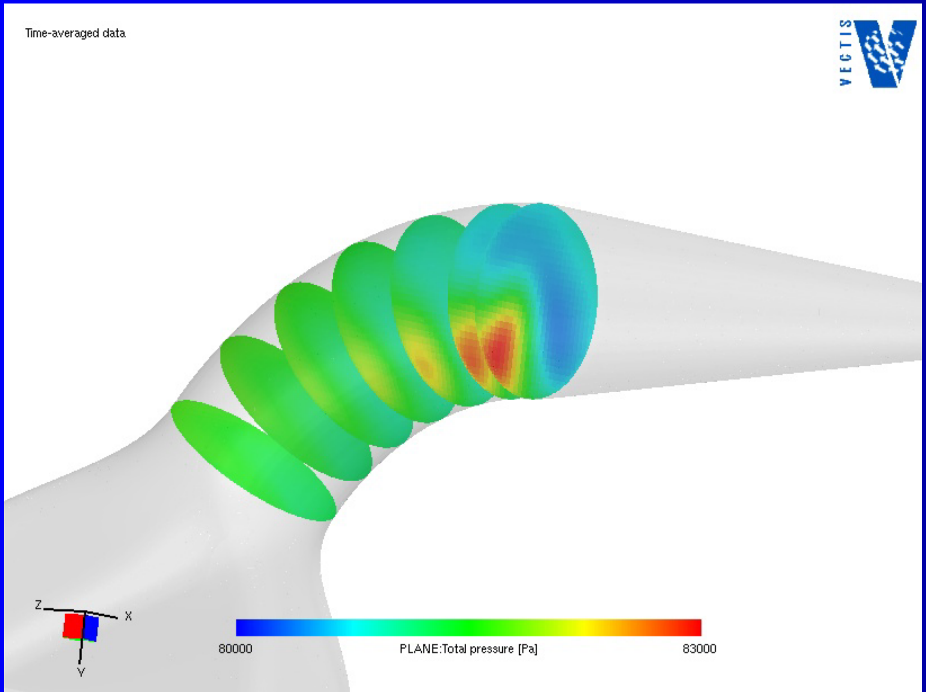


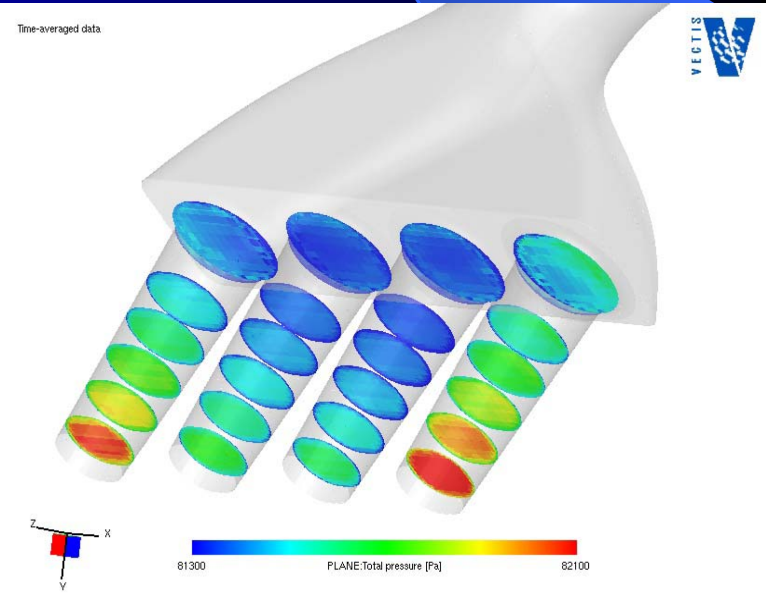
Time Averaged Data

- Time averaged data used to help understand general flow characteristics of an intake.
- Simplifies post-processing but introduces additional challenges.



Top Feed 14,000 RPM

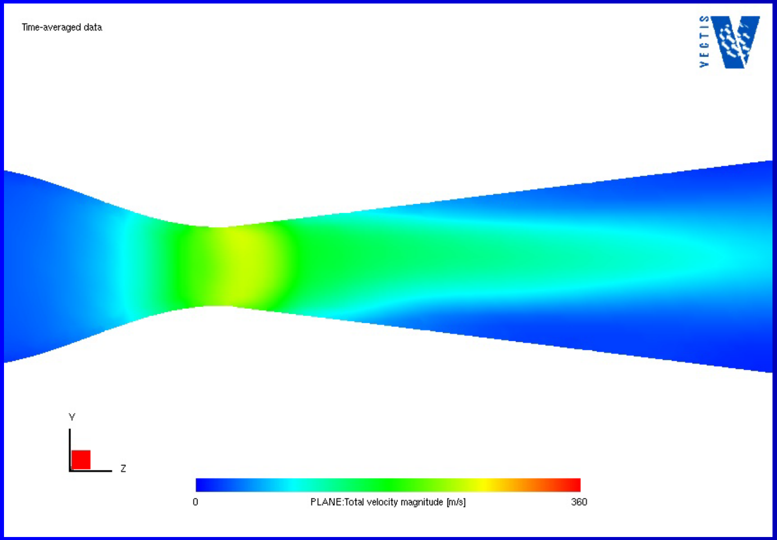




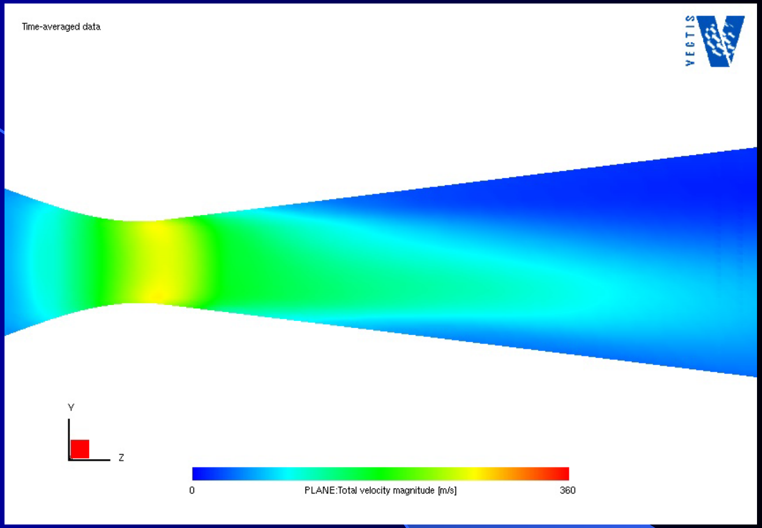
Diffuser Flow Separation (Time Averaged)

Top Feed - Post Diffuser Bend

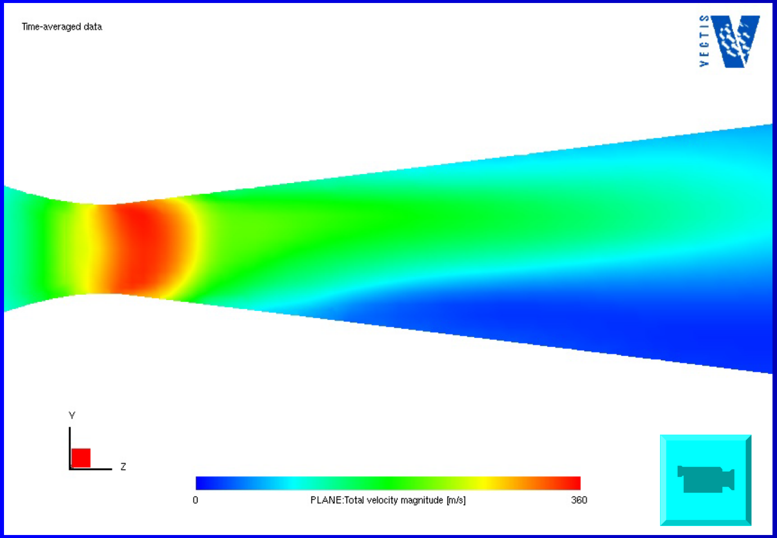
Top Feed - Bent Runners



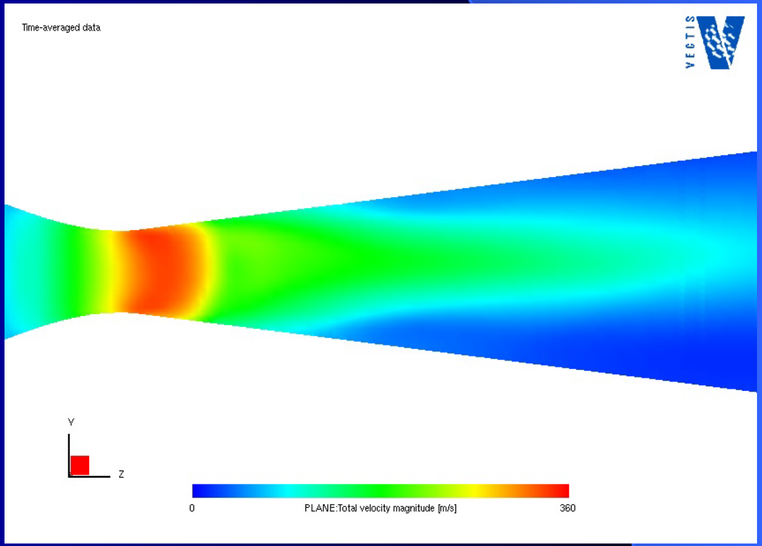
11,500 RPM



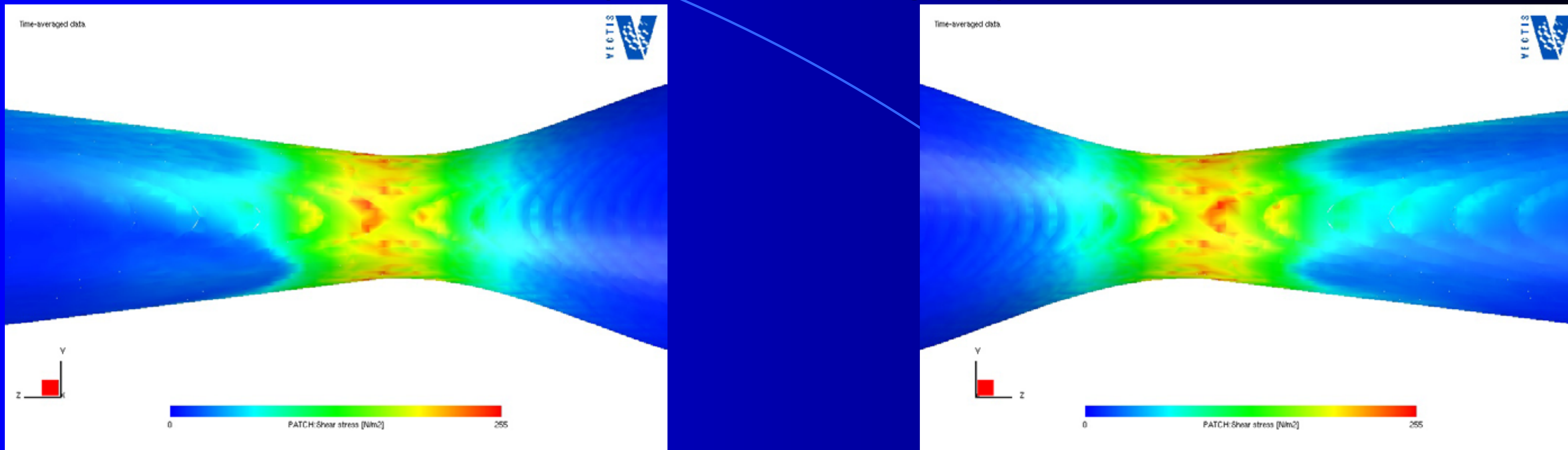
All scale maximums = 360 m/s



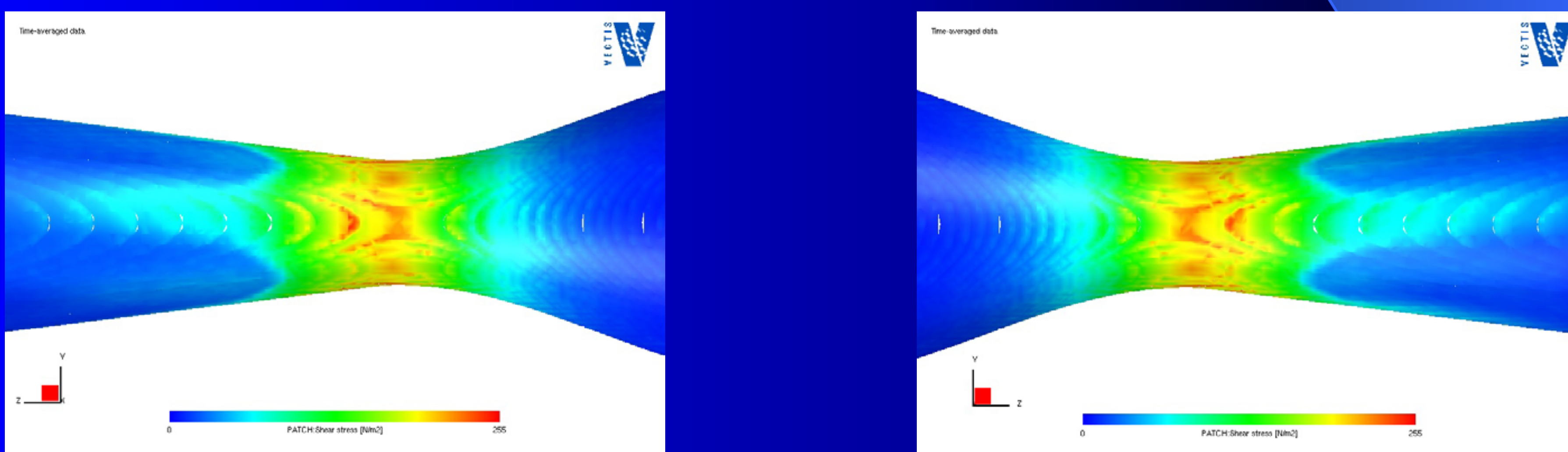
14,000 RPM



Peak Shear Stresses and Frictional Losses
(Time Averaged)

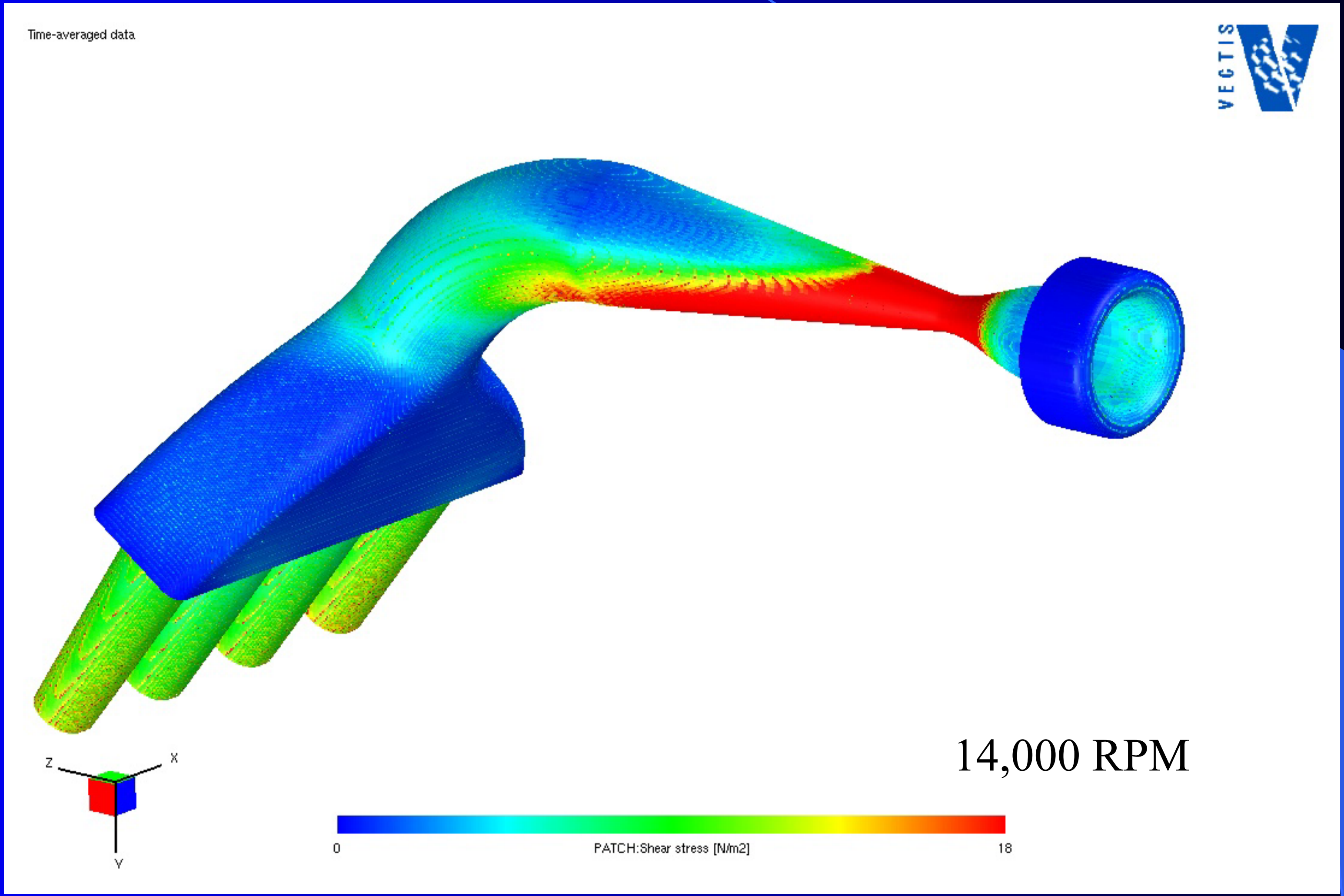


Top Feed with post diffuser bend at 14,000 RPM

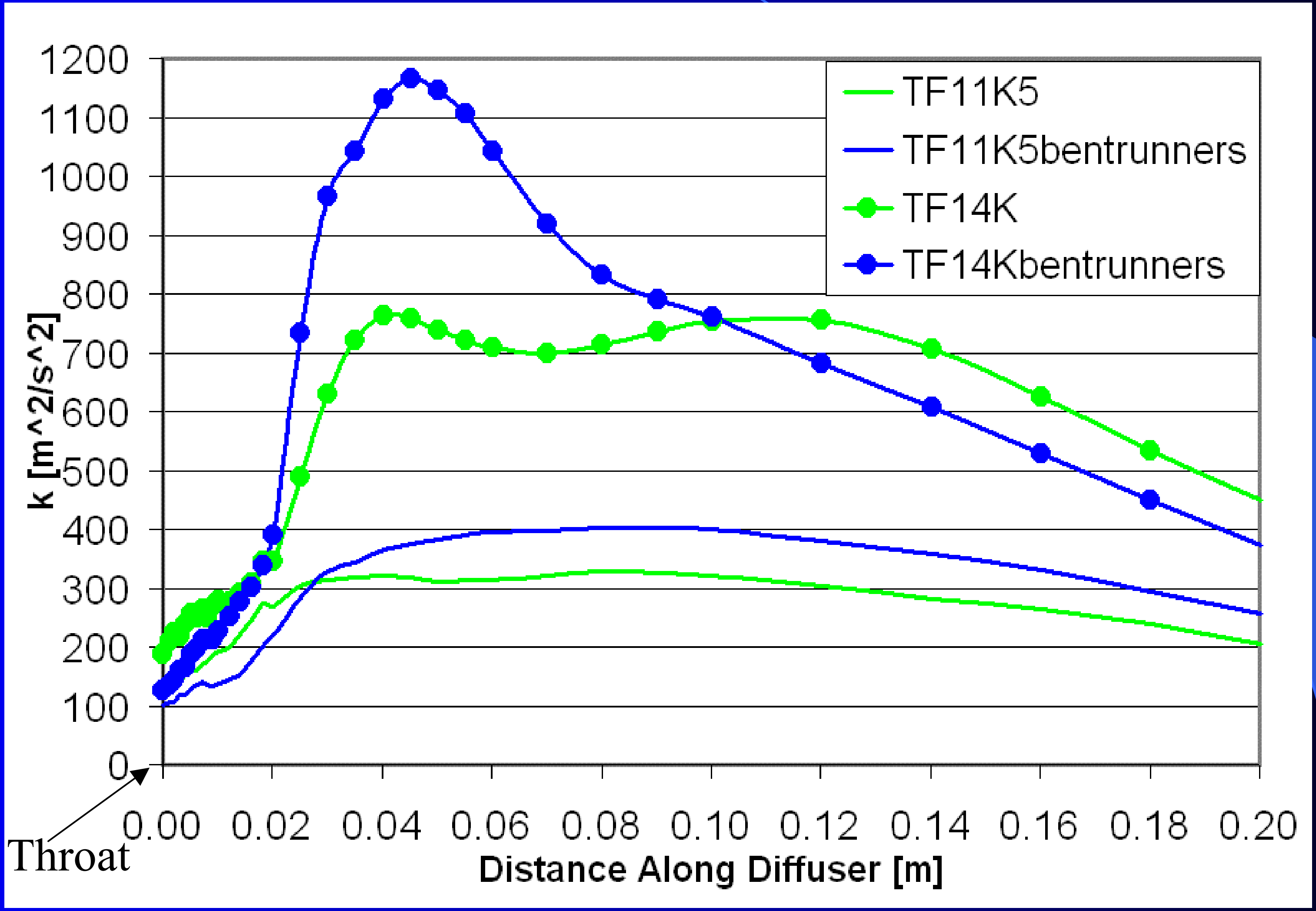


Top Feed with bent runners at 14,000 RPM

Using Shear Stress to Analyze Flow Bend Separation



k-ε Closure Model: Turbulence Generation Along Diffuser



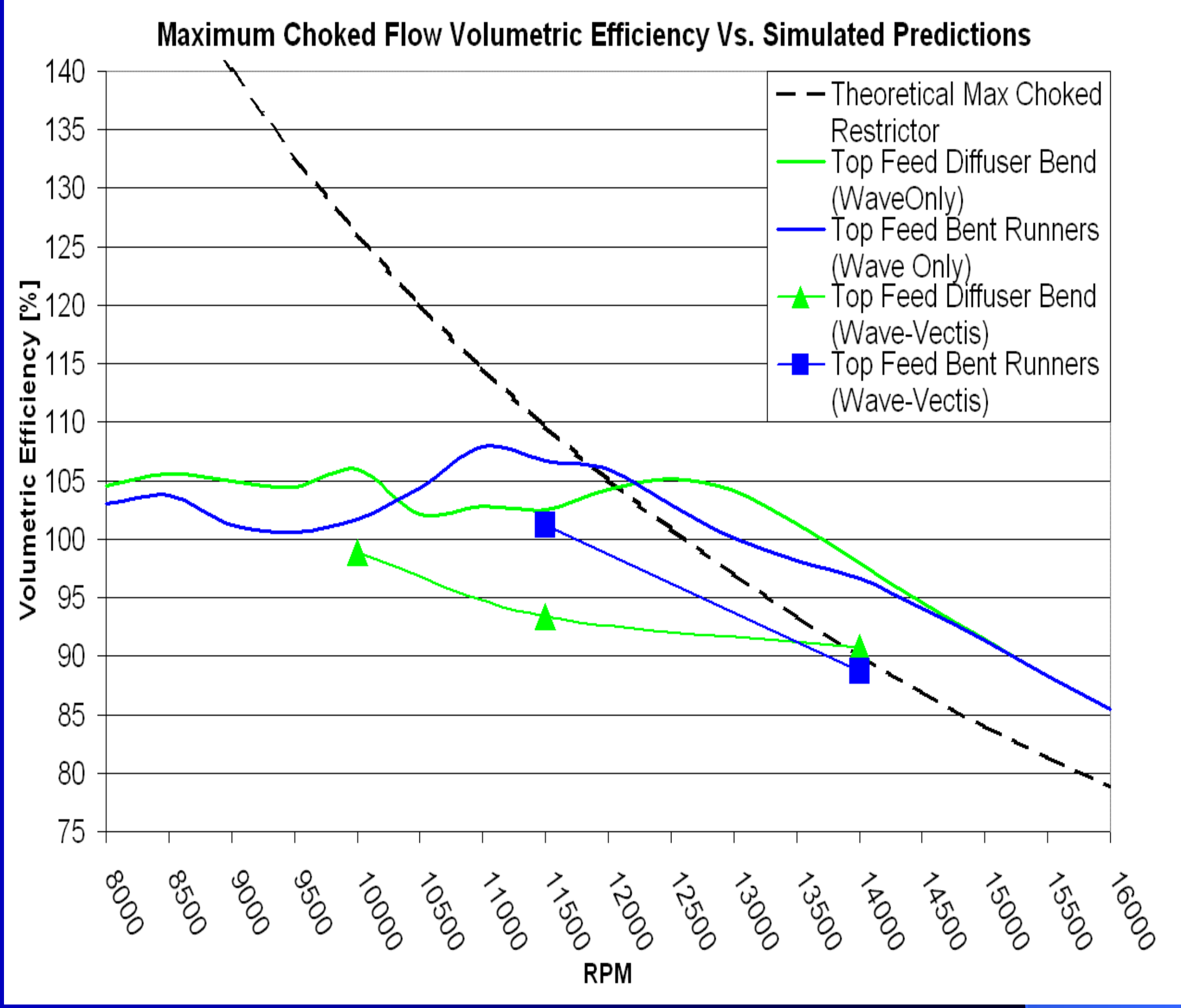
Choked Flow Analysis of Maximum Volumetric Efficiency Potential

- Maximum volumetric efficiency found by choked steady-state isentropic analysis

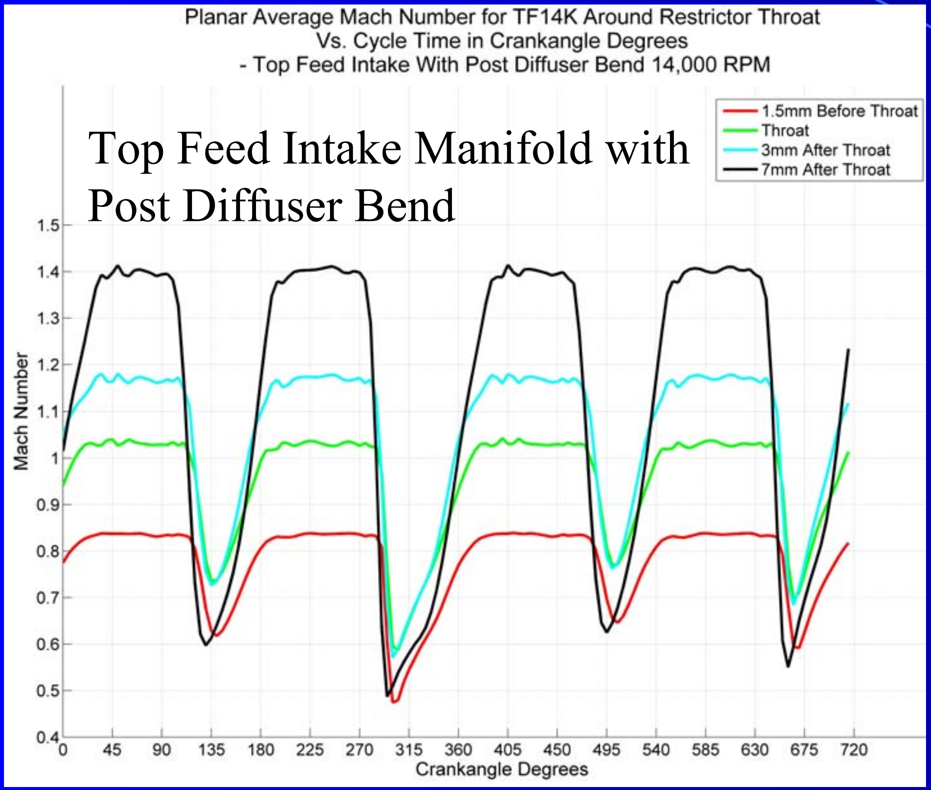
$$\dot{V}_{choked} = \frac{A^*_{throat}\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)} p_0\rho_0}}{\rho_0}$$

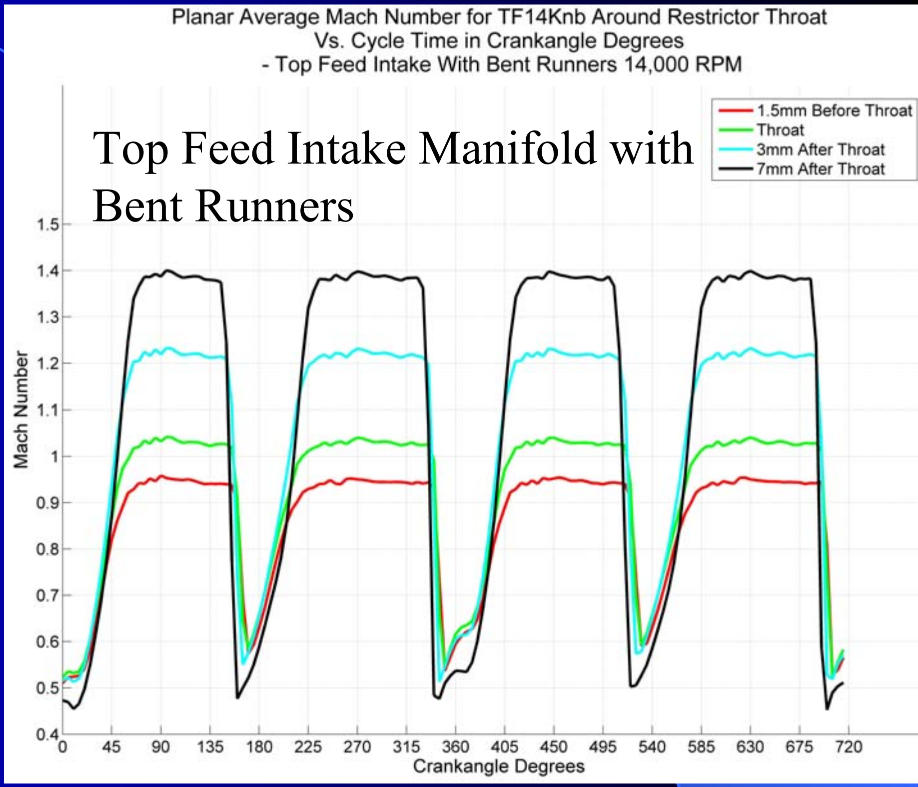
$$\dot{V}_{nom.} = \tfrac{1}{2} * Displacement * CyclesPerSecond$$

$$V.E._{\max} = \frac{\dot{V}_{choked}}{\dot{V}_{nom.}}$$



Mach Number Over One Cycle Near Restrictor Throat - 14,000 RPM

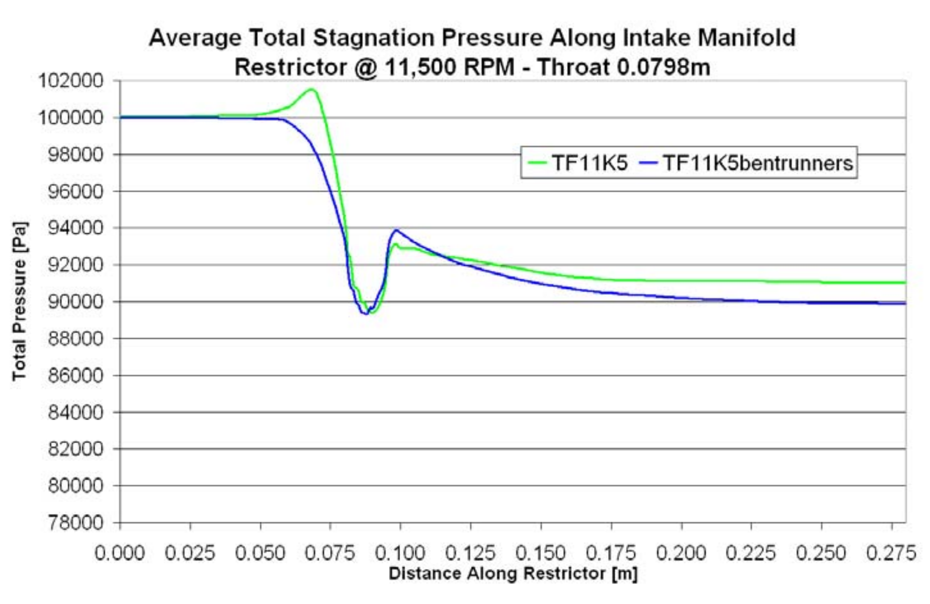


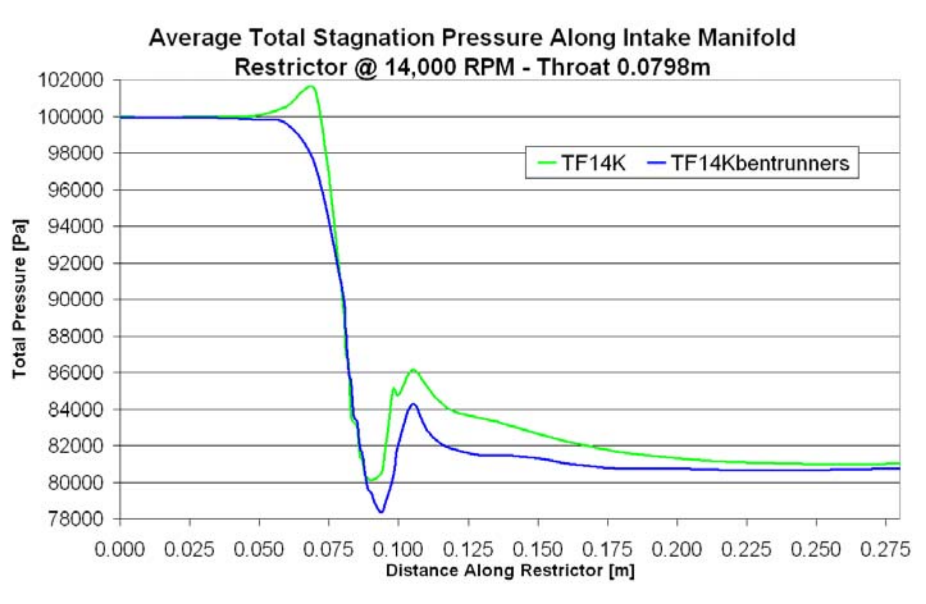


- Choked ~59.7% of the cycle
- Choked ~ 60.2% of the cycle

- Virtually no impact on percentage of cycle choked between intake manifold geometries.
- Near identical amount of supersonic flow in the diffuser. Shock-losses are of similar magnitude.

Total Pressure Drop Across Restrictor (Time Averaged)





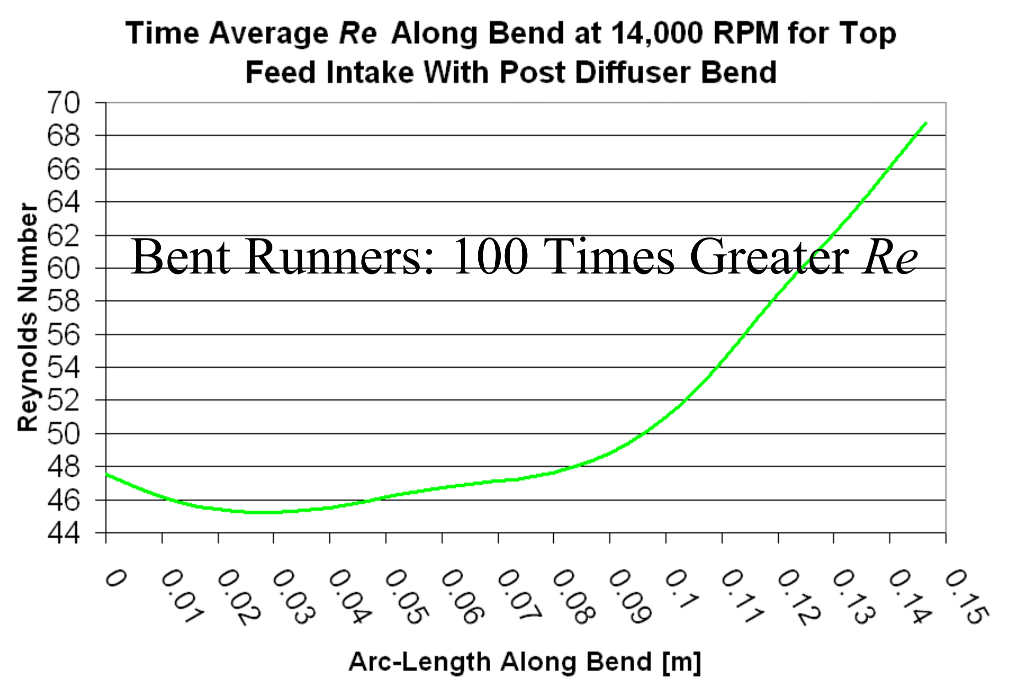
- Differences in total pressure drop across restrictor did not correlate with volumetric efficiency performance of engine.
- Differences in manifold geometry had <2% impact on restrictor total pressure recovery performance.
- Causes of total pressure increases
  - Pulsed flow effects?
  - Effects of non-uniform flow averaging?
  - Low Reynolds Number effects?

Wave-Vectis VE% Predictions

RPM	Post Diffuser Bend	Bent Runners
11,500	93.4%	101.2%
14,000	90.7%	88.7%

Packaging and Performance Compromise

Bend Geometry Features		
Feature	Post Diffuser Bend	Bent Runners
Bend Radius	0.1524 m	0.1016 m
Average Cross Section	0.0727 m	0.0420 m
Bend Angle	55°	55°



$$P.R. = \frac{p_2 + \frac{1}{2}\rho_2 V_2^2}{p_1 + \frac{1}{2}\rho_1 V_1^2} = \frac{p_{o2}}{p_{o1}}$$

Pressure Ratio Across Geometry			
RPM	Post Diffuser Bend	Runner Bend	Straight Runner
11,500	1.0004	1.0029	1.0021
14,000	1.0046	1.0069	1.0053

- Very little difference in pressure losses for different packaging concepts.
- Bent runners should offer better fuel targeting of valve.

Conclusions

- WAVE is a very good tool by itself.
  - Good prediction of individual cylinder volumetric efficiency rankings even with one dimensional assumptions.
  - Still need WAVE to understand full rpm range intake wave dynamics and tuning effects. Quick solution times.
- WAVE-VECTIS is excellent for getting a good understanding of actual pressure losses and their sources. Skin friction, turbulence generation, and separation losses can be analyzed.
- Differences in intake manifold geometry had little impact on diffuser performance.
- Small differences in total pressures losses did not immediately correlate to differences in engine volumetric efficiency.
- Flow through restrictor is not completely choked even at 90% of engine redline.
- Very small variations in engine performance for different placements of flow bend to meet packaging requirements, from a flow loss standpoint.
- Placement of bends can still have a large impact on intake tuning.

Acknowledgements

- Ricardo Sponsorship and Support - Karl John, Patrick Niven, Enrico Bradamante, and Denise Rowe
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- University of Mankato, Mechanical Engineering - Dr. Bruce Jones

Recommended Reading

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