JOHN DEERE

Electric Turbo Compounding…

A Technology Who's Time Has Come

- Carl T. Vuk
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ADVANCED ENGINEERING

OUTLINE

- System Architecture
- Review of Hardware Elements
- System Analysis
- Test Results
- Application Recommendations
- Conclusions
- Future Work
- Questions

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Electric Turbo Compounding:

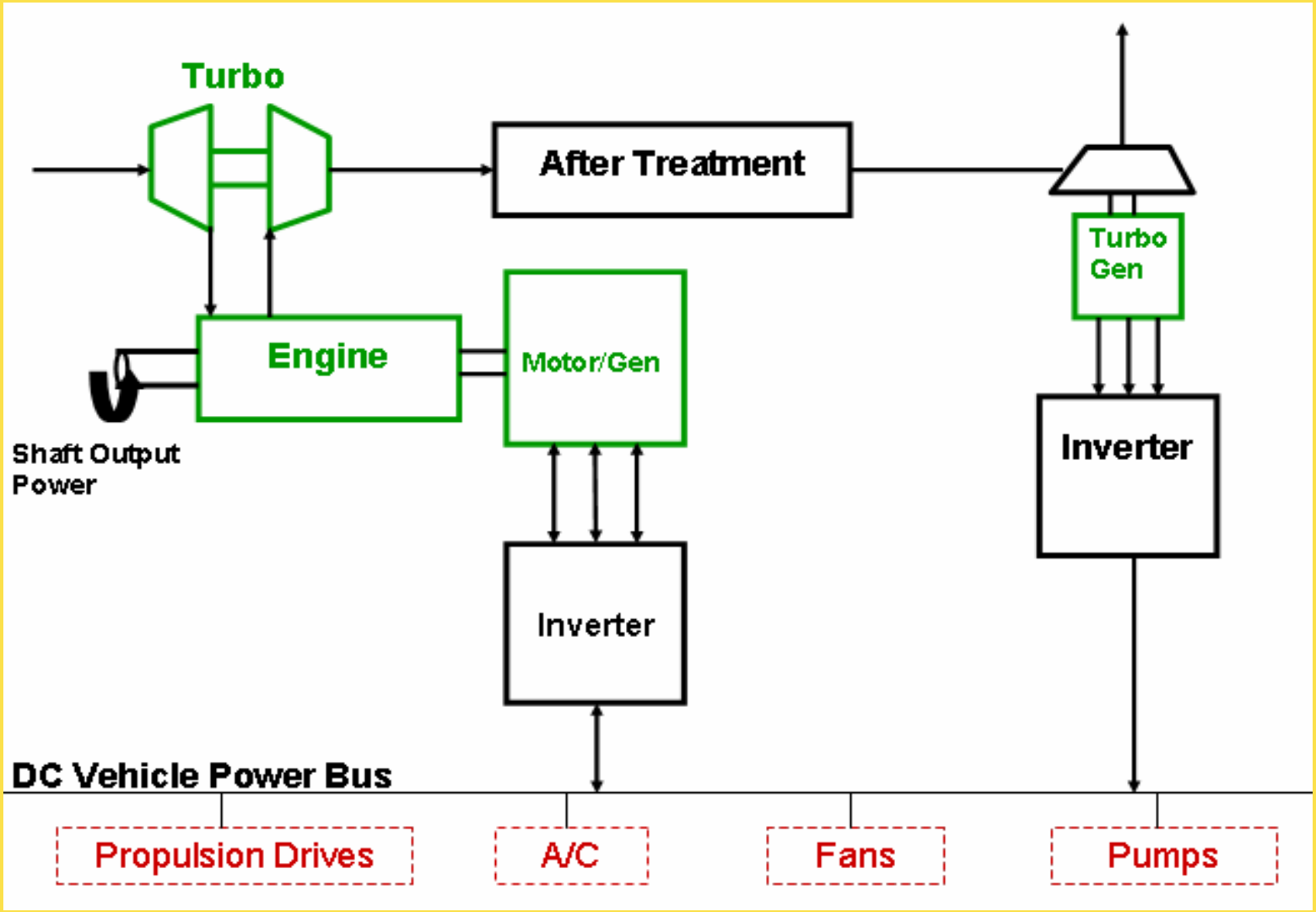
- ***A System That Converts Waste Exhaust Energy to Shaft Work, using a Turbine, and Couples it Back to the Engine, Electrically***

ADVANCED ENGINEERING

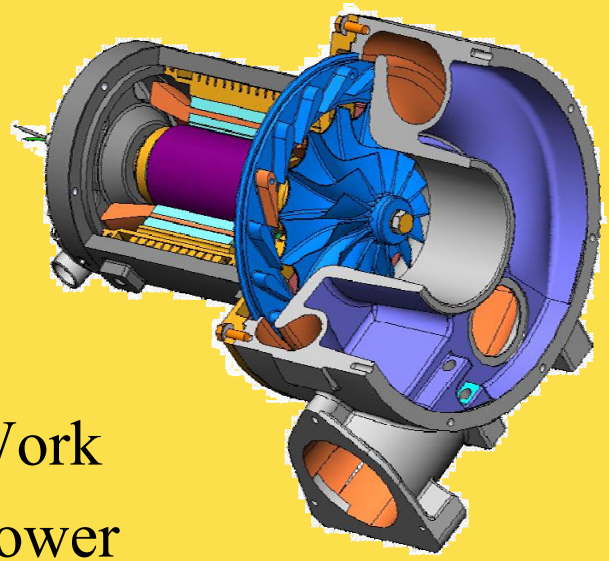
Why Turbo Compounding ?

- Today's Engines Reject 40% of the Fuel's Energy in the Exhaust Gas Stream. The Exhaust is an Excellent Source of High Grade Heat, And it's Free!
- Turbo Compounding Technology is Available and Proven With Mature System Costs in the Order of $50/kW.
- The Technology Provides Power Growth, Improved Fuel Economy, and Reduced Emissions.

System Architecture

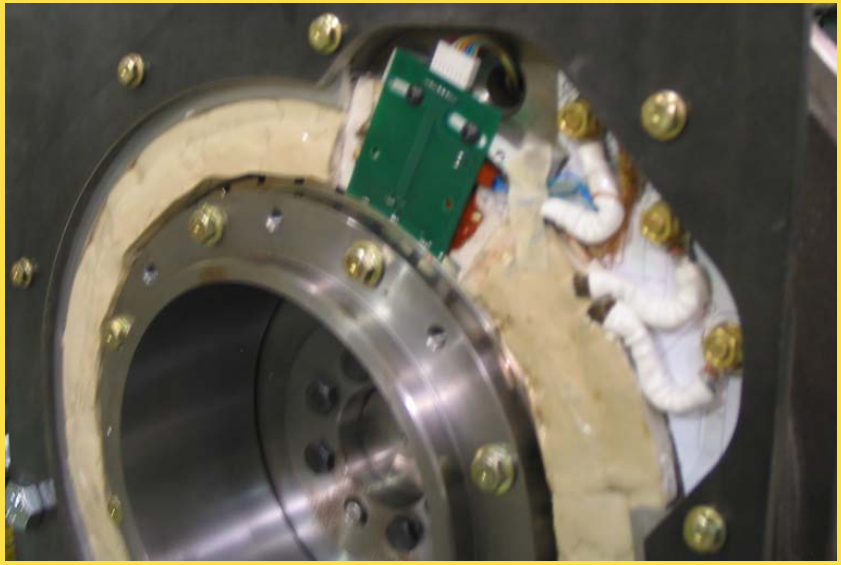


Turbo Generator



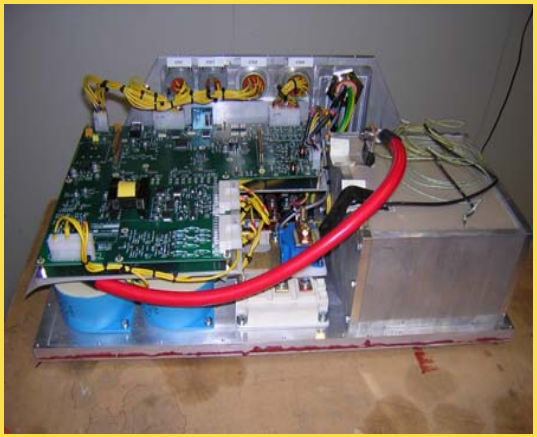
- Converts Exhaust Energy into Shaft Work
- Converts Shaft Work into Electrical Power
- Simple Architecture
- Very High Efficiency
- Known Technology
- Cost Effective Design

Motor Generator



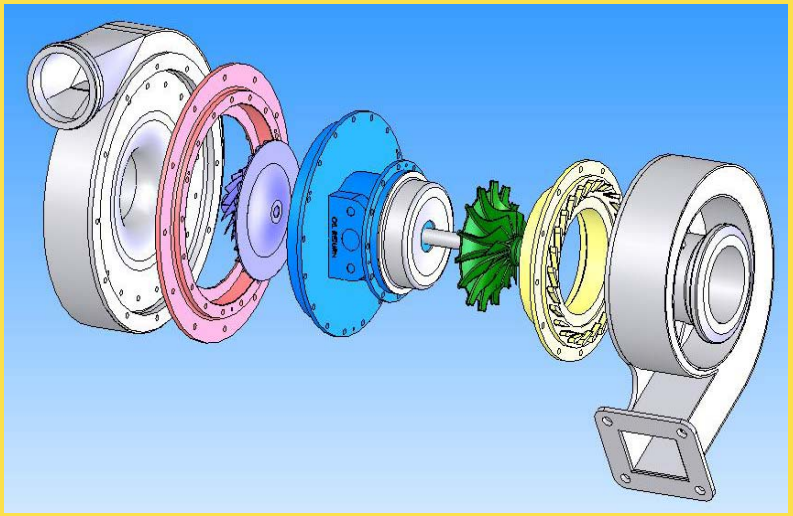
- Generates When Turbo Gen Can Not (Generating Mode)
- Couples Turbo Gen Power Back to Engine (Motoring Mode)
- Flywheel Mounted for Compact Packaging
- Simple Low Cost Machine Using Known Technology
- High Efficiency BPM Technology

Power Electronics



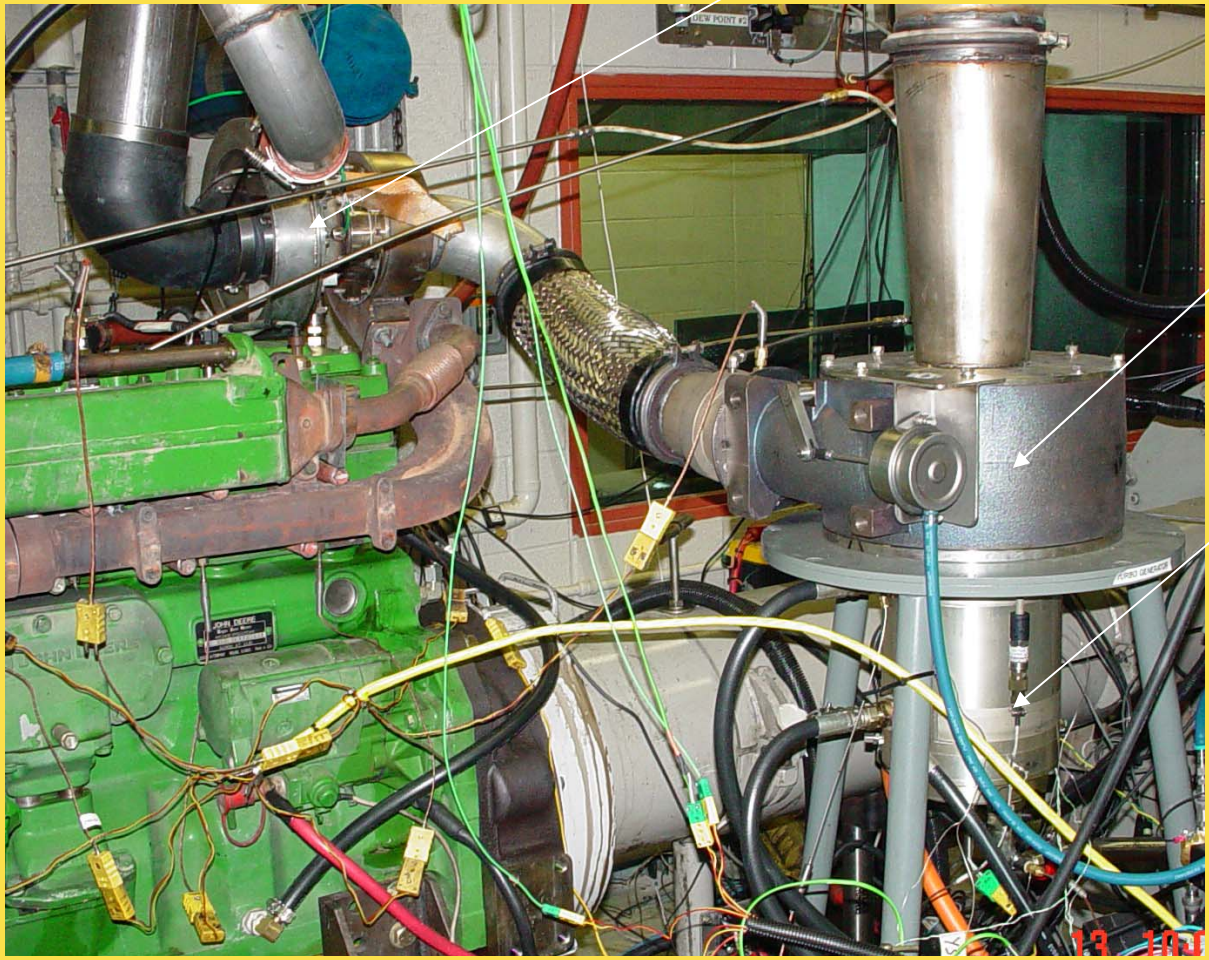
- Controls Turbo Gen Speed and Delivers DC Power
- Manages Motor Gen to Regulate BUS Voltage
- Very High Efficiency Over Operating Envelope
- Cost Effective Components
- Liquid Cooled

Advanced TurboCharger



- High Pressure Turbine
- Significantly Upgraded Efficiency
- Fixed Geometry Turbine Nozzle Vanes
- Vaned Diffuser (Compressor)

Dyno Test Setup



Two Stage Architecture

- Independent Control of Turbo Machinery Elements
- Modest Pressure Ratios
- Interstage After Treatment
- Allows for Simple Turbo Machinery
- Improved Transient Response

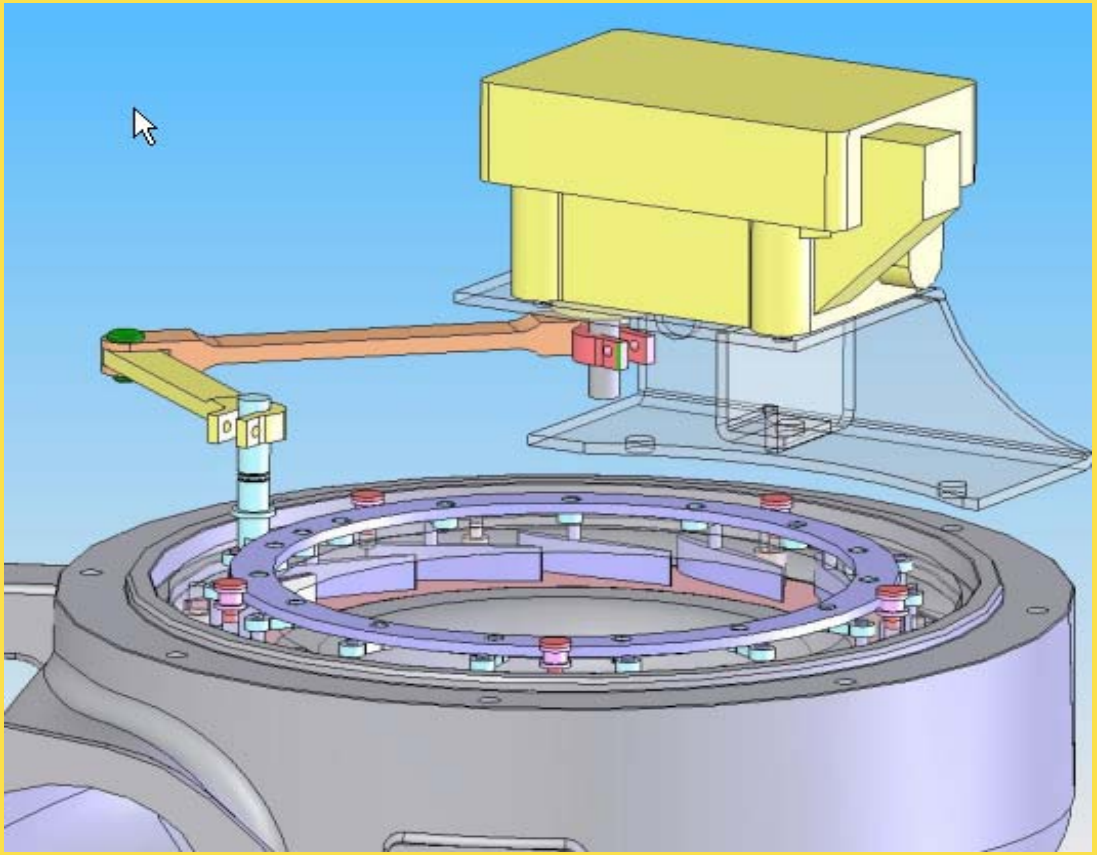
Electric Coupling

- Power Turbine Speed Control Optimization
- Efficient Power Recirculation w/o Fluid Coupling
- Packaging Flexibility
- Motor Generator Supports Vehicle Electrification

Variable Geometry Turbines

- VG TurboCharger Not Needed to Drive EGR
- VG Power Turbine - Option
  - Provides Direct Control of Turbo Compounding Output
    - Increases Part Load & Part Speed Output
    - Potential Control of Engine Air Flow & Transient Response
- Fixed Geometry Power Turbine – Option
  - Better Efficiency at Full Load
  - Reduced System Complexity
  - Lower Cost

Variable Vane Mechanism (Power Turbine)

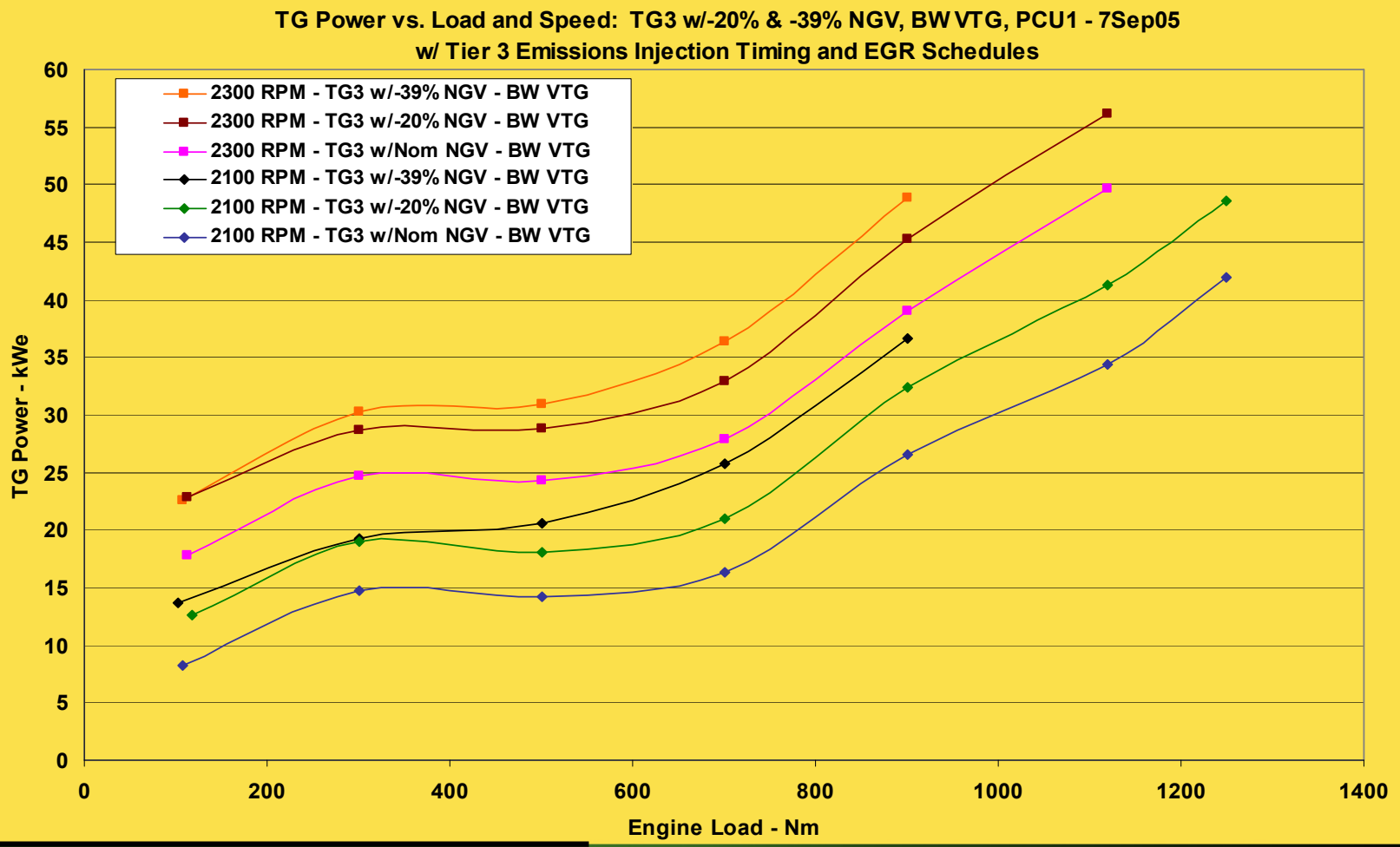


Variable Vane Mechanism (Power Turbine)

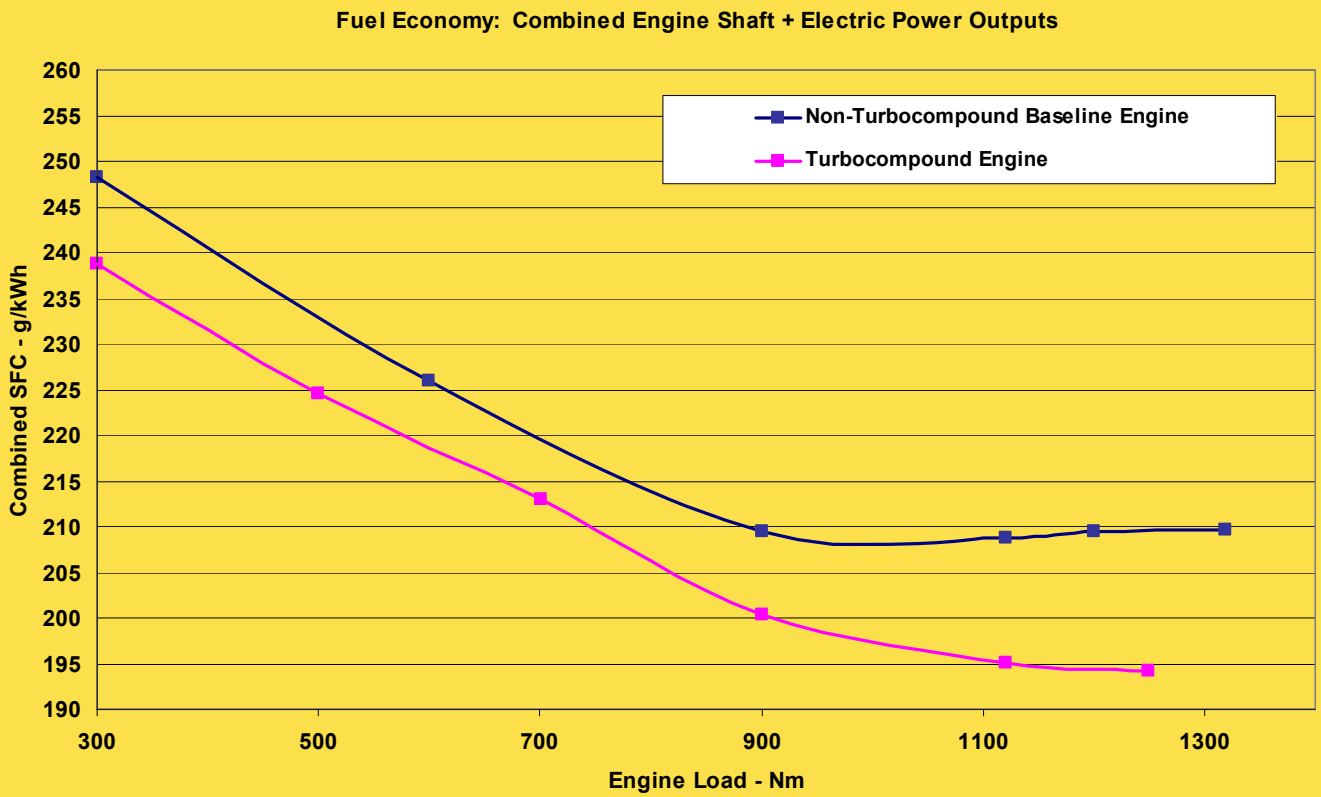
Motor Generator Optimization

- Efficiency Must be High (95%) in Operating Envelope
- Packaging is Critical For Common Design and Minimal Vehicle Disruption
- Every Application is Different. Assuming Will Not Produce Optimal Results

Engine Test Data (Output Characteristics)



Engine Performance Data (Fuel Economy)



Application Targets – Turbo Compounding

- High-Duty Cycle Steady State Operation Maximizes Benefit
- High Annual Usage Improves Payback
- Vehicle Electrification Helps Justify Added Cost
  - Motor/Gen Needed Even w/o TurboCompounding
  - More Efficient to Use Electrical Power in Vehicle
- Power Growth
  - Valuable in Some Applications
  - Allows Smaller Higher Duty Cycle Engines in Applications Not Needing Power Growth

Ideal Applications

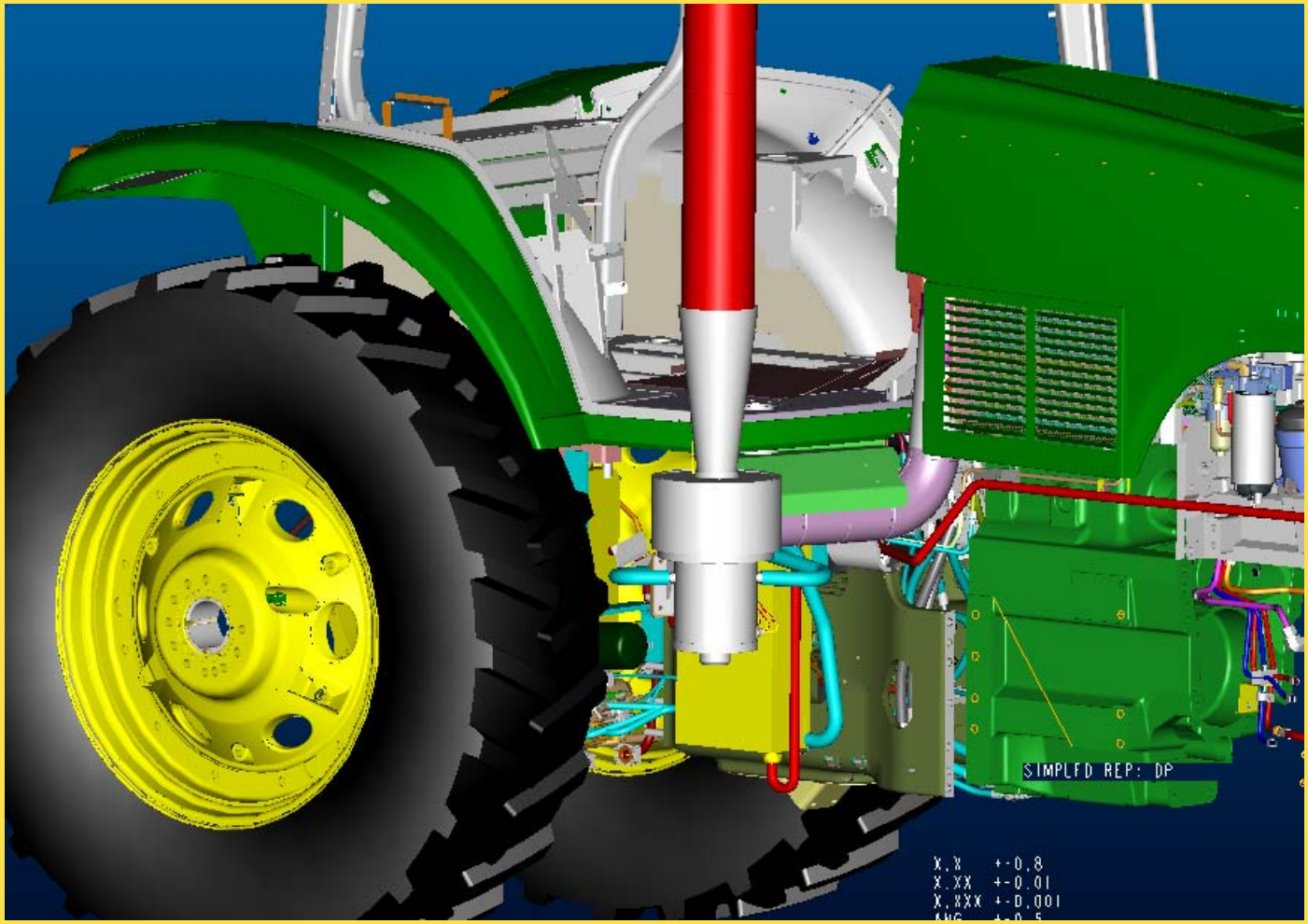
Large Tractors

Row Crop Tractors

Combines

Trucks

Tractor Mounted Turbo Generator



Hardware Integrated in Tractor

Deere 9L Engine in International Truck

Conclusions:

- 20% Power Growth Has Been Demonstrated With Little Adverse Impact On The Engine. Higher Output is Possible.
- Fuel Economy Improvements of 10% Have Been Demonstrated at Tier 3 Conditions
- Turbo Compounding is Compatible With Emissions and Appears to Provide Benefit
- An Electrically Coupled Two Stage Architecture offers Control, Efficiency, Emissions, and Packaging Benefits. It Also Supports Electrification.
- System Costs Suggest Commercialization Potential

Future Work

- Evaluate Benefits of the Variable Geometry Power Turbine
- Characterize Performance Benefits in Vehicles
  - Deere Tractor
  - On-Highway Truck
- Expand Scope to Include Larger Engines
- Develop Next Generation Hardware
  - Optimize for Tier 4

Acknowledgements

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Questions ?