Advanced Brake Systems and Undercarriage Aerodynamics

Glenn Grant
Pacific Northwest National Laboratory

Heavy Vehicle Systems Optimization
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Project Objective

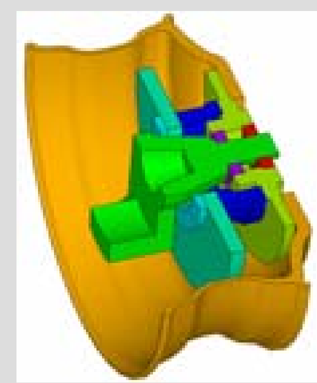
To assess the potential of alternate disc brake system designs and technology concepts to improve energy efficiency, performance, and vehicle safety and stability

Motivation

<u>Heavy vehicle brakes are on the edge of change</u>

Current cast iron drum / phenolic pad systems are near their limits of performance. Higher speeds, higher GVW, 30% decrease in the vehicle drag from parasitic loss (aerodynamics and other) will tax them even further

Federal regulation, the need for shorter stopping distance, higher energy efficiency, and lower life cycle cost will eventually drive brake systems to change



What will new systems look like, and how can they be evaluated?

Heavy Vehicle Systems Optimization

Advertisement from Brake Tier 1 : from Haldex brochure

There is a fixed amount of energy required to stop a 80,000 lb vehicle. As new brake systems become more compact, lighter weight and higher performance, they will likely run hotter.

Thermal management is a key issue

This will require:

- Accurate thermal/stress modeling
- Understanding of under vehicle and in-wheelwell airflow to model heat generation and heat flow
- a systems approach to thermal and stress issues not just material substitution

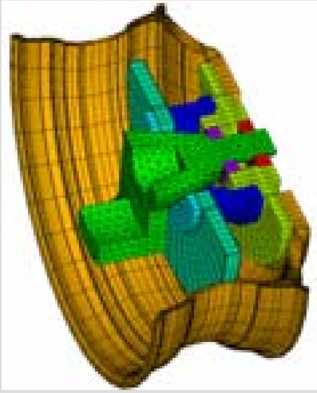
System optimization will yield:

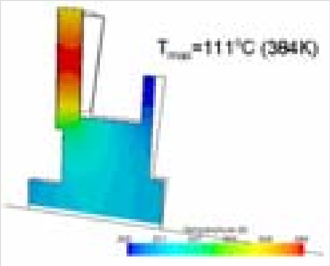
Higher performance
Lighter weight
Lower life cycle cost

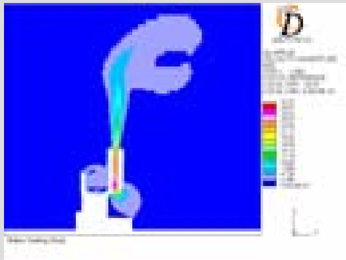
Approach

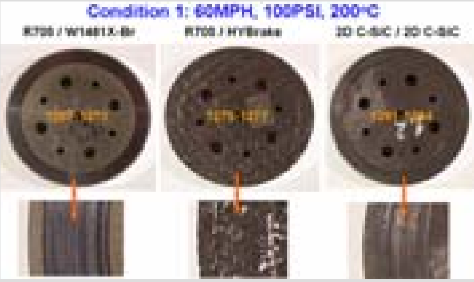
- **Develop computational tools to evaluate the impact of new brake materials and designs on brake cooling, underhood temperature, and overall vehicle thermal management**
  - Understand effects of next generation brake materials and designs on heat generation and flow
  - Understand contribution of brake system to undercarriage thermal management
  - Corner module critical temperatures in hub and wheels
  - Input to heavy vehicle, PSAT-like simulation tools

- **Experimentally investigate low inertia, lightweight brake materials and brake designs**
  - Investigate by thermomechanical and wear testing, new material systems that could:
    - Increase energy efficiency (allow compact systems with low rotational inertia)
    - Increase safety, decrease stopping distance, and increase controllability
    - Increase operational efficiency (low life cycle cost by high wear resistance)
  - Use the material data as input to the thermal model to evaluate effects of tested materials on overall vehicle thermal management









Relevance to 21CT Goals

- ***"Promote research to reduce parasitic losses to achieve significantly reduced energy consumption"***
  - Efficient, compact lightweight brake systems enable fuel economy savings through lower inertial loads and vehicle mass
    - Est. 0.8% fuel savings on vocational vehicles[1]
    - Est. 0.5% fuel savings on long-haul trucks[2]
- ***"Promote the development of technologies to improve truck safety, resulting in the reduction of fatalities and injuries in truck-involved crashes."***
  - Increased braking performance, stability and control will help meet future regulatory limits on stopping distances (FMVSS 121)
- ***"Promote the validation, demonstration, and deployment of advanced truck and bus technologies, and grow their reliability sufficient for adoption in the commercial marketplace."***
  - Increased reliability and durability means less frequent maintenance and repair and more time spent delivering goods to market
  - Increased competitive market position for U.S.

[1] US DOT FHA Highway Statistics – www.ops.fhwa.dot.gov/freight/freight_analysis
[2] Annual Energy Outlook 2005 DOE/EIA-0383(2005)

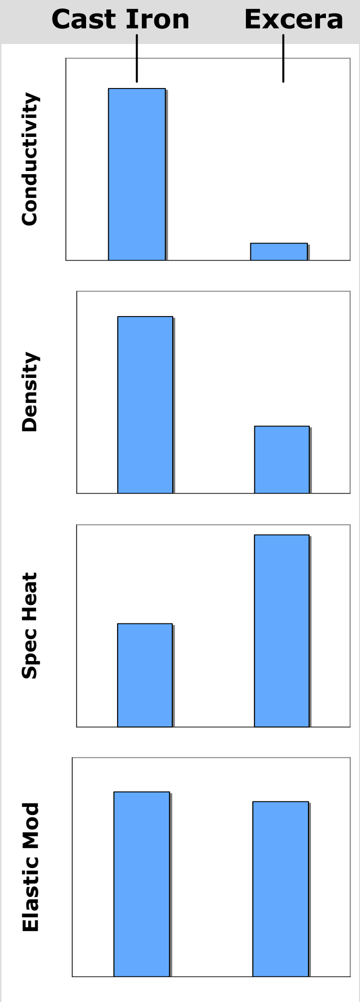
FY05 Technical Accomplishments

- CFD and FEA models developed that track braking energy transients and heat generation, and predict conduction and heat flow
  - Design, geometry, and material properties as inputs
  - Predicts effects of materials and designs on the brake surface temperature and resulting heat transfer to vehicle corner module
- New friction materials evaluated
  - Cermets, C-SiC-Cu composites, friction stir processed materials
  - Friction, wear, mechanical, and thermal performance characterized

Technical Accomplishments
1. Computational model

Motivating factors

- **Next generation braking systems will run at higher temperature and loads due to:**
  - Optimizing brake system efficiency & mass reduction
  - New aero shapes can reduce cooling air to brakes
  - Future reduced stopping distance requirements
- **New materials and designs need to be screened for performance over expected duty cycle to determine limiting conditions**
  - Multiple stopping/deceleration cycles
  - Drag-braking to maintain speed on steep grades
  - Panic stop after heavy braking coupled with extended stop (high temperature soak)
- **Brake components must stay within structural / thermal material and design limits**



Parametric models allow us to explore these questions in virtual space and can make experimental development more efficient

Technical Accomplishments
1. Computational model

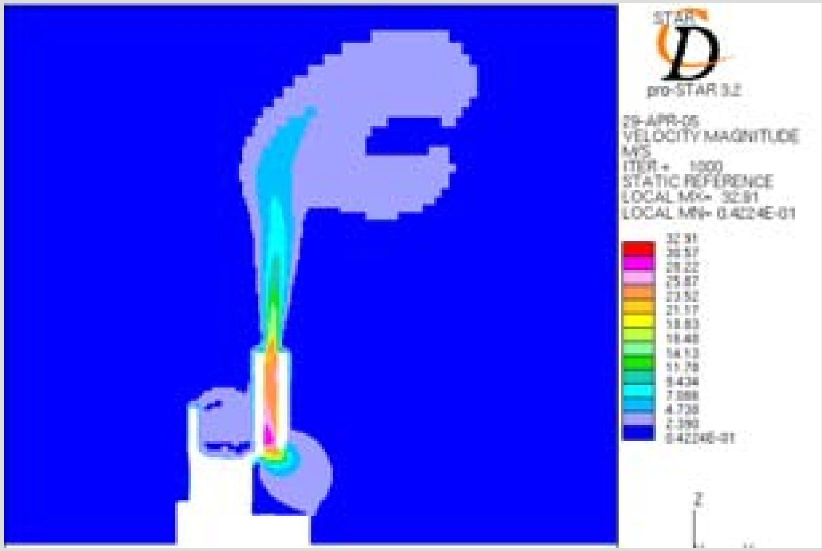
Parametric Evaluation Approach

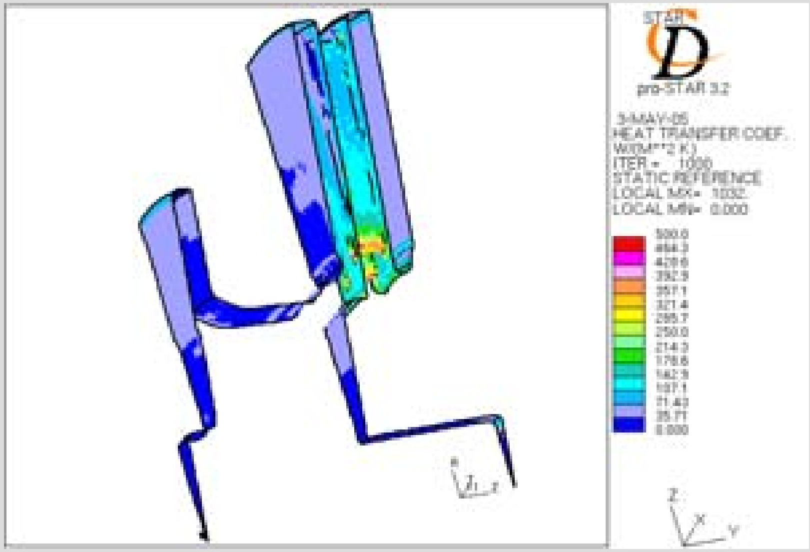
Step 1: CFD

- Use computational fluid dynamics (CFD) to simulate heat transfer characteristics
  - Start of hard braking transient from cruise speed
  - High temperature soak following braking transient
- Currently using CD-Adapco codes StarCD® and StarCCM+®

CFD Thermal-Fluid model explicitly represents:

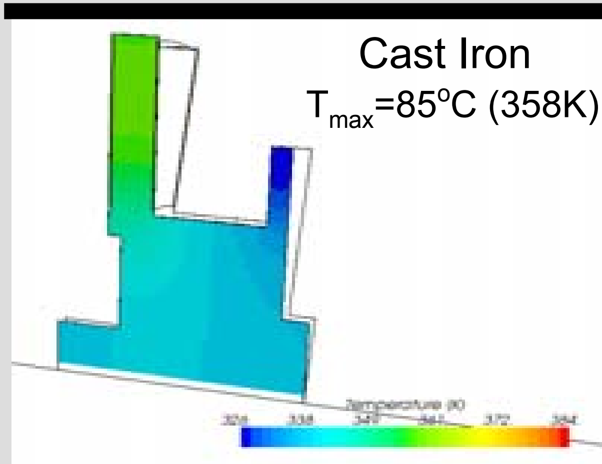
- Forced & free convection (moving & still)
- Simple conduction
- Thermal radiation



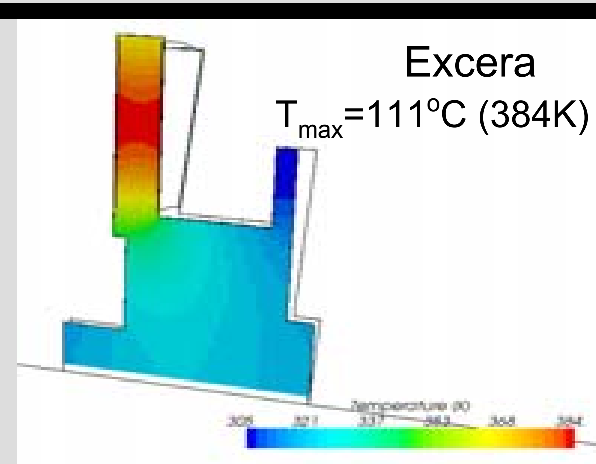


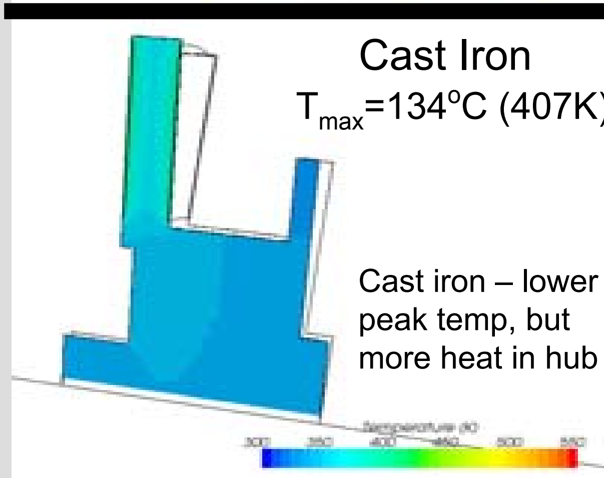
Technical Accomplishments
1. Computational model

Example
Solid Disc CFD model for two materials: cast iron and a cermet

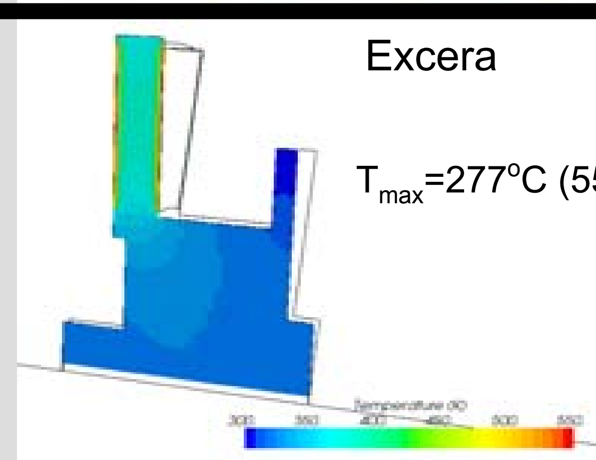


Steady State Solution for Constant Descent





Transient Solution midway through Stopping Duration



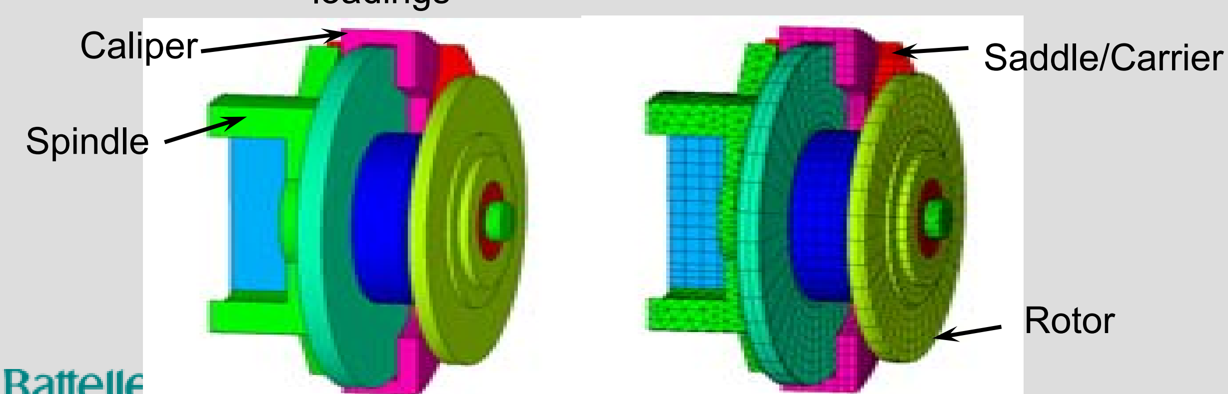
Cermet rotor – high peak temp but less heat in hub

Technical Accomplishments
1. Computational model

Parametric Evaluation Approach

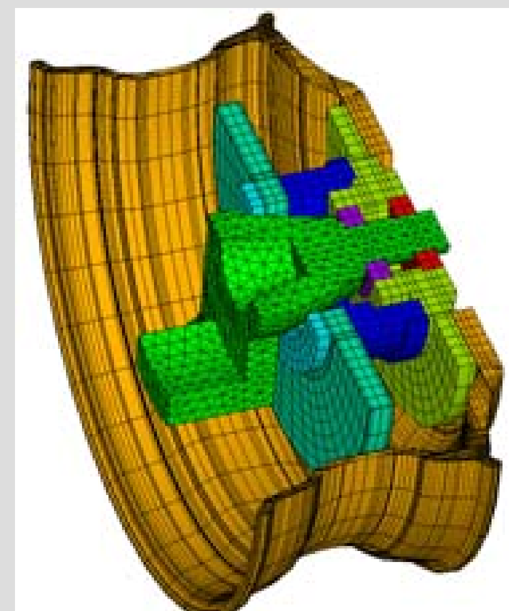
Step 2: FEA

- Use finite element (FE) structural code (ANSYS) to compute temperature & stress distributions
  - Apply convective loss coefficients from Thermal-Fluid model
  - Apply thermal boundary conditions yielded from CFD evaluation
  - Applying other "braking specific" loading conditions
    - Friction heat generation and thermal expansion
    - Rotor torsion induced between rotor attachment & caliper friction loading combination
    - Caliper clamping pressure & rotor attachment loadings



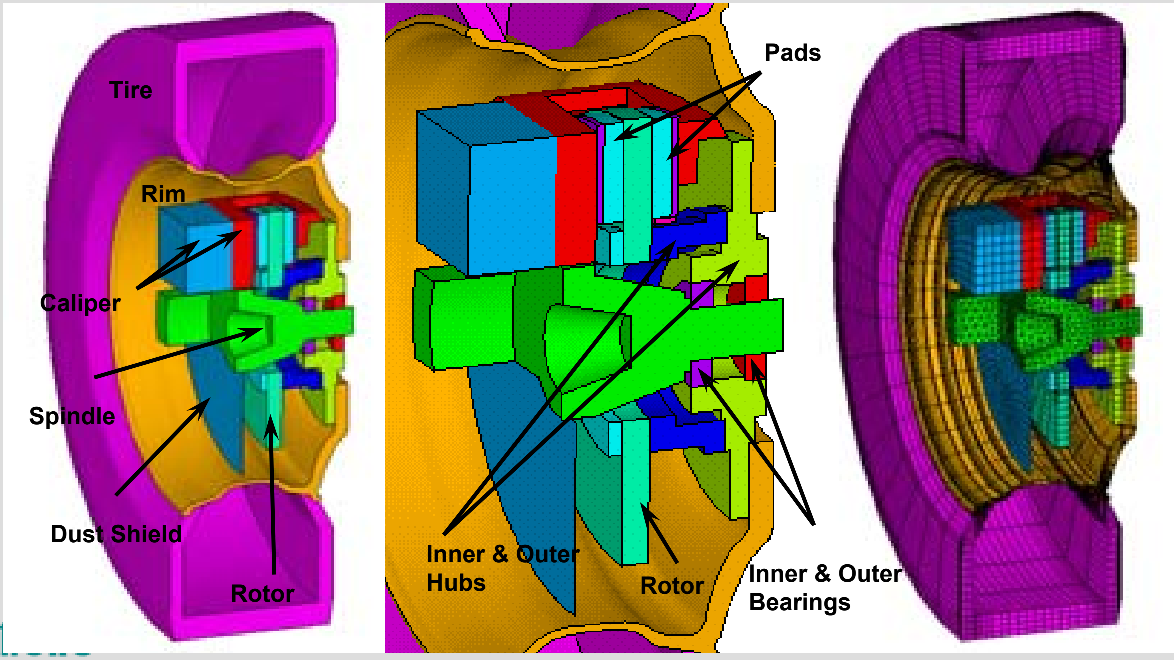
FE Thermal-Structural model explicitly represents:

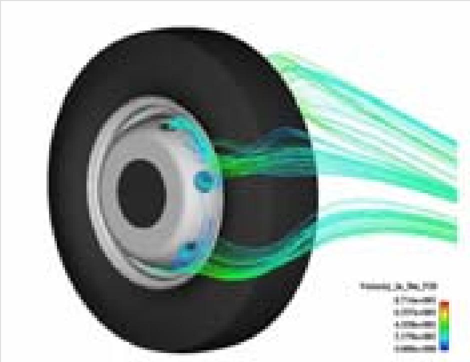
- Multi-component conduction
- Multi-component thermal radiation exchange
- Structural load combinations



Technical Accomplishments
1. Summary of computational modeling

- Solid model provides realistic geometry
- Each "component" can be specified with different material properties
  - Predicts temperatures and heat flux in corner-module components during a braking event
  - Allows for a systems-based design approach
- Under-carriage and wheel-well air flow knowledge is critical, and needed !
- Mass, rotational inertial, and heat transfer output can will be used to calculate parasitic energy loss
  - Model output can be incorporated into PSAT-like total vehicle efficiency models to predict consequences of new designs and materials





SAE TECHNICAL Paper 2003-01-3600, Numerical Simulation of the Flow in Wheel Systems, Cesareo de La Rosa Siqueira, T-Systems do Brasil Ltda, Helio Fragoso, Volkswagen do Brasil Ltda

Technical Accomplishments

2. Evaluation of Advanced Friction Pairs

- Large weight savings and tolerance to high temperature environments may not be met by current cast iron / phenolic pad systems
- New friction materials may be required
- Friction Pair Testing
  - Numerous friction pairs composed of new materials have been tested for friction and wear performance
  - Lightweight composites - cermets and MMCs

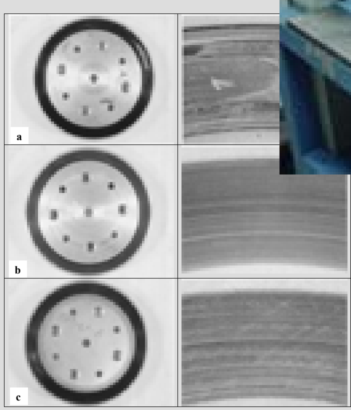
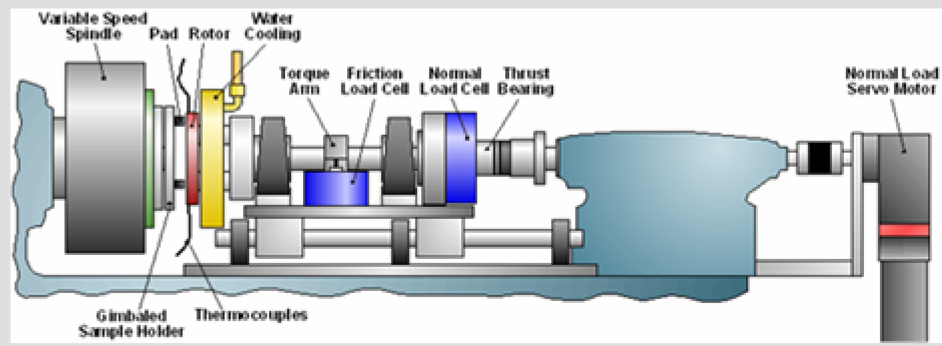


Fig.10. See next page.

Wear tester at PNNL



Wear tester at Rockwell Science Center

Technical Accomplishments

2. Evaluation of Advanced Friction Pairs

Testing for different braking scenarios and materials

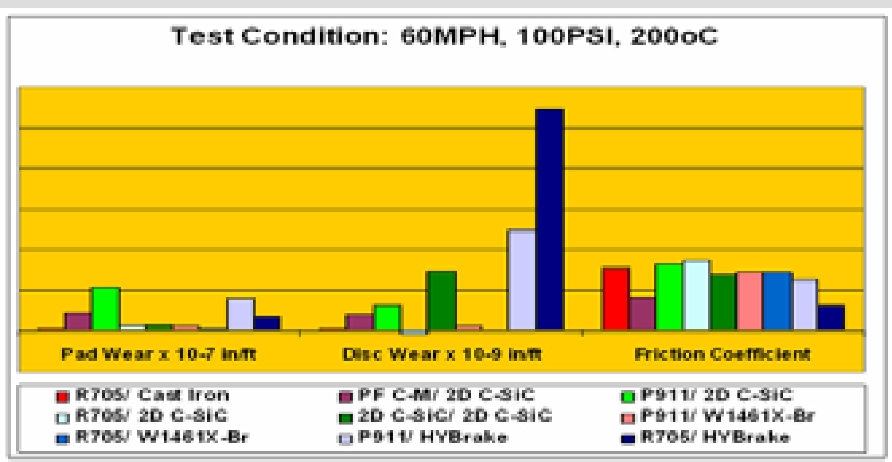
- Materials investigated
  - Rotors
    - Cast Iron (baseline)
    - C/SiC – polymer-based ceramic reinforced
    - C/SiC/Copper - graphite cloth w/ SiC and Cu matrix
    - reaction processed cermet 50SiC / 35Al2O3 / W1461-XBr
    - FSP Surface engineered cast iron
  - Pads
    - Arvin Meritor R705 (baseline)
    - Performance Friction Carbon Metallic
    - Porsche/Brembo Ceramic
    - 2D C/SiC
    - Cermet

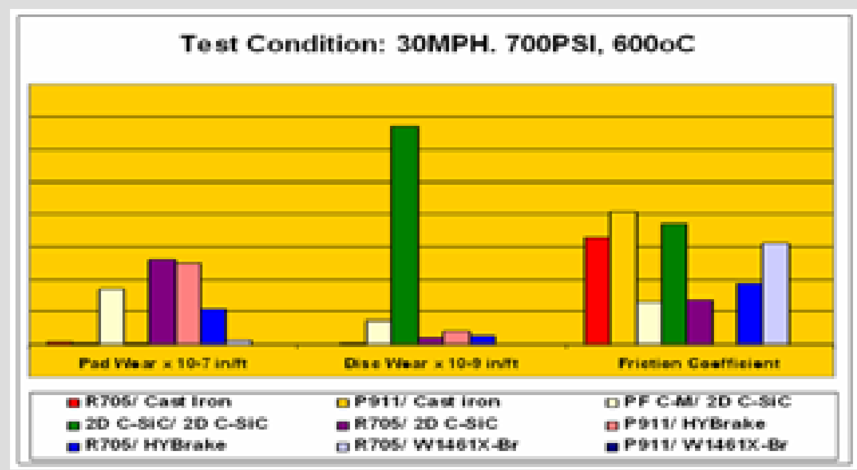
- Thermomechanical testing
  - Provide input data for modeling development
  - Mechanical testing:
    - wear rate
    - friction coefficient
    - compressive strength
    - modulus, etc
  - Thermal property data
    - CTE
    - Conductivity
    - emissivity

Technical Accomplishments

2. Evaluation of Advanced Friction Pairs

- Typical Vehicle Operating Conditions
  - On-highway (mostly snubs, with occasional stops)
    - moderate to high speeds
    - low brake pressures
    - low brake temperatures
  - City bus and vocational vehicles (frequent stops and starts)
    - low to moderate speeds
    - low to moderate brake pressures
    - high temperatures
  - Mountain descents (long brake applications)
    - low to moderate speeds
    - moderate to high brake pressures
    - high brake temperatures

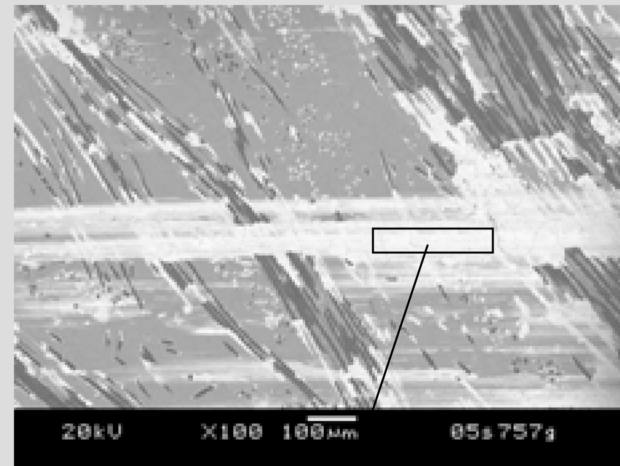


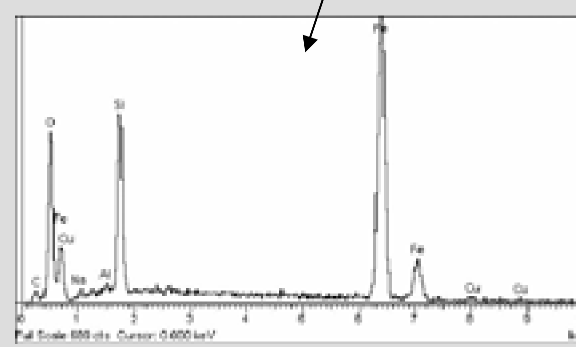


Tribology Characterization

- Material performance is as important to overall system design as rotor geometry – impacts durability and warranty for OEMs

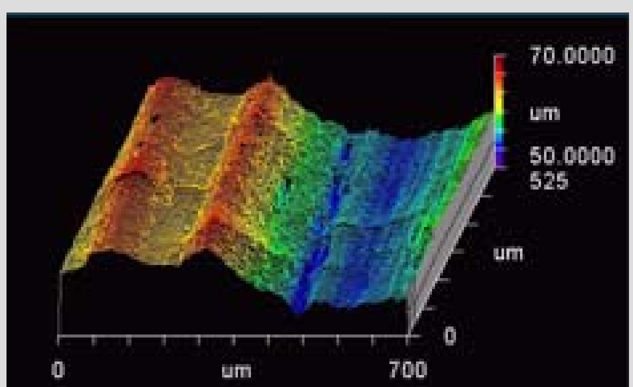
Typical wear tracks for cermets and C/SiC rotor materials





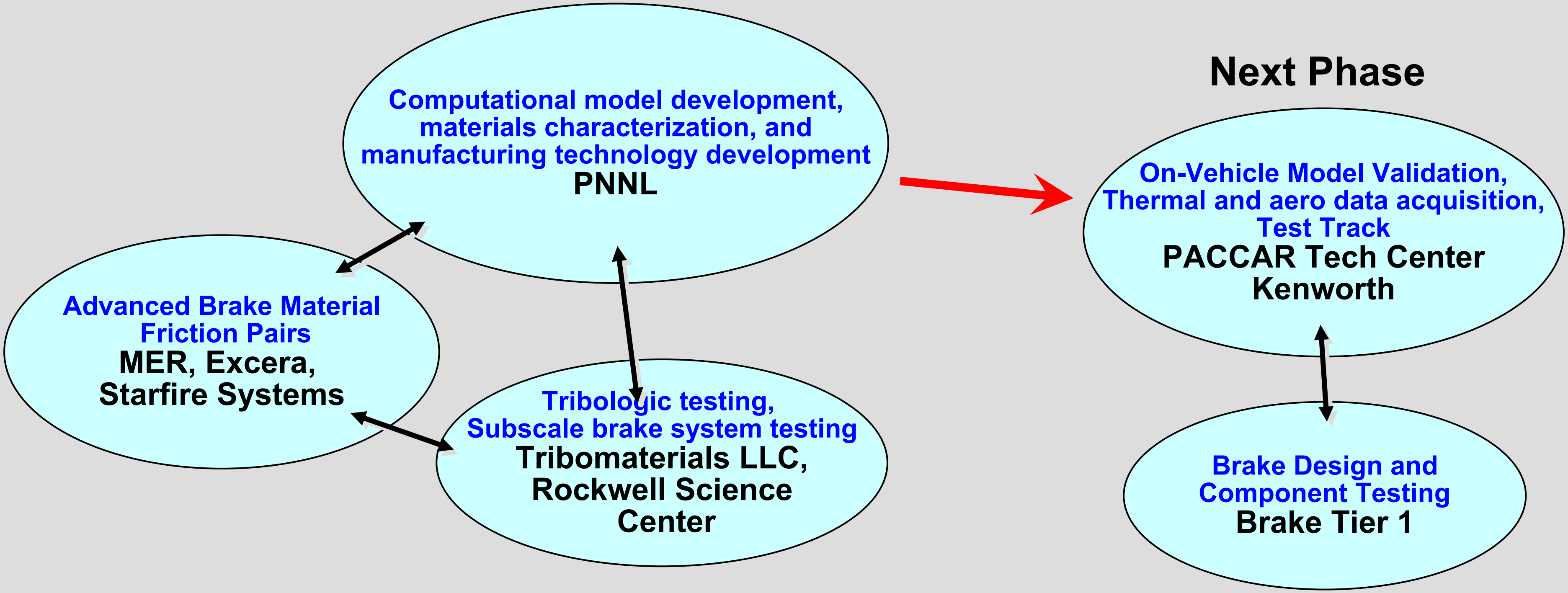
Characterization of transfer layer indicating high amount of iron present that have been transferred from the pad

3-D plot from the surface profilometry measurements illustrating the topography of a tested rotor surface



Technology Transfer / Collaborations

- Team comprised of truck OEM, national laboratory, brake and material suppliers
  - Leverage systems level knowledge and integration, as well as full-scale evaluation capabilities of OEM (PACCAR, others?)
  - Leverage computational science, materials characterization and manufacturing technology development capabilities of PNNL
  - Leverage brake system design knowledge and manufacturing expertise of Brake Tier 1
- Develop design tools with industry partners to insure relevance to commercialization
- Make modeling and simulations tools available to contribute to heavy vehicle performance simulation tools



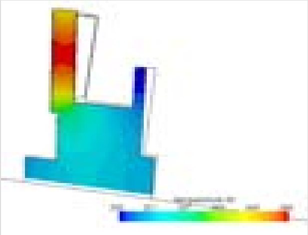
Proposed Future Scope

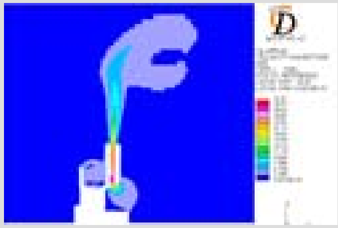
- Incorporate detailed undercarriage CFD (PNNL, leverage LLNL (and others) aero data) to develop better convection and thermal transfer model
- Validate thermal, stress, and air flow models in wheelwell and around brakes with instrumented sub-assemblies (PACCAR test track, PNNL, LLNL?)
- Further down-selection on appropriate lightweight friction materials (PNNL, Tribo Materials, suppliers)
- Design an economical, lightweight, and an innovative brake system that can be demonstrated to improve performance and energy efficiency (In conjunction with Truck OEM and Tier 1 brake suppliers)
  - Target vocational vehicle
- Identify alternate energy absorption/conversion and heat management/rejection methods (regenerative, inductive, piezoelectric or thermoelectric energy recovery, etc.)

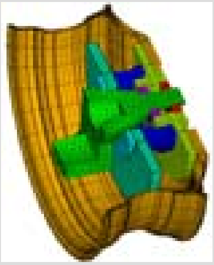
Summary

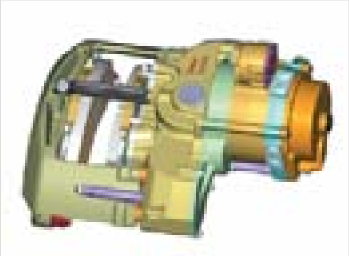
A direct result of reducing parasitic losses will be higher demands on the brake system. New brake materials, designs and concepts will be needed to meet future goals

- Thermal and structural models allow exploring the effects of new materials and designs in virtual space
- Parametric brake system models can provide input to overall vehicle energy efficiency models by providing corner module static and rotational mass with new lightweight designs.
- Lightweight, high performance braking systems have an opportunity to contribute directly to the **21CT and Vehicle Systems Optimization goals:**
  - Increased energy efficiency
  - Decreased parasitic losses through mass reductions
  - Improved knowledge of vehicle undercarriage and wheel-well aerodynamic flow for heat management
  - Improving truck safety through the development and optimization of technologies for better stability, control and braking performance.









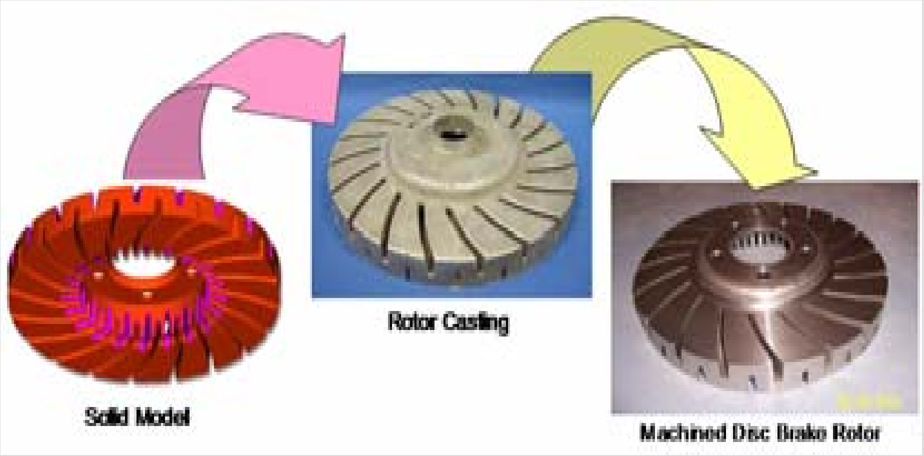
Backup Slides

Energy Calculations

A typical cast iron drum weighs 112 lbs (50.8kg). Weight reduction alone has a demonstrable effect on fuel consumption for a heavy vehicle, especially those with severe stop-and-go duty cycles, like urban delivery and transit buses (due to high rotational inertia in a heavy vehicle brake). It has been estimated that these high duty cycle heavy vehicles will see a 3.4% reduction in fuel consumption per 2204 lb weight reduction1. The new materials proposed in this study, in a disc brake configuration, are estimated to be in the 25lb to 30lb range, representing a savings of up to 87 lbs per brake for the braking surface component alone (not including other scaled down components such as lighter weight calipers and hubs.) For a typical 6-brake urban delivery or bus (Class 6-7-8) this is a potential weight savings of 522 lbs, leading to a projected fuel consumption reduction of about 0.8%. In 2002 these vehicles accounted for 10,305 million gallons of fuel.[2]

Although the fuel savings from weight reduction has less of an effect on long haul Class 8 trucks (1.2% change in consumption per 2200 lb weight reduction1) their total energy consumption is much higher than buses: 2.13 million barrels per day oil equivalent. Energy savings (reduction in fuel consumption) due to weight reduction in the braking system for a typical 10-brake Class 8 could be as high as 0.5%. In 2002 Class 8 long haul tractor trailers consumed 26,451 million gallon of fuel. The 2002 US energy consumption for commercial light truck, transit buses, and Class 8 trucks (urban delivery and long haul) was 5.21 Quads (Quadrillion BTUs). [3] Energy savings due to brake system optimization could be as high as (0.0058)(5.21)=0.0302 Quads or 3x1013 BTUs. (about 5.3 million barrels per year oil equivalent).

[1] (NRC-CNRC Technical Report TP 13892E, 2002)
[2] US DOT FHA Highway Statistics –
www.ops.fhwa.dot.gov/freight/freight_analysis
[3] Annual Energy Outlook 2005 DOE/EIA-0383(2005)



PNNL FreedomCAR / ALM Brake Program: Lightweight Aluminum Metal Matrix Composite Disc Brake Rotor

- Rotor designed specifically for aluminum MMC
- Die cast from AA-A359 alloy with 20% silicon carbide particles (359/SiC/20p)
- Lightweight rotor is 3.32 kg; a **60% weight savings** over the 8.44 kg cast iron production rotor
- Improved fuel economy projection of **0.25 mpg** due to weight reduction and lower inertial forces
- Significantly improved rotor wear and environmental degradation resistance, with the potential as a ‘life of vehicle’ component

New material cost arguments

All the brake materials selected are currently more expensive than the baseline cast iron, but all are fabricated by methods that could be translated to bulk processing and reduced part cost at high volume. Current estimates of market conditions suggest that 20% of the heavy vehicle market is very sensitive to weight reduction. It has been estimated that in this specialty market, the premium paid for weight reduction could be as high as 3$/lb[3]. In the mass truck market this number may be closer to $1.50/lb, indicating any new material proposed will be subjected to very stringent demands on cost differential if weight reduction alone is the only consideration. However, another factor that may play heavily into the economics of looking at advanced material replacements of cast iron is the life cycle cost and performance. Many materials provide combinations of high friction coefficient, particular heat transfer characteristics or increased wear life that can favorably affect system life cycle cost. A 50% increase in wear life for instance will double to interval between rotor change-outs and can affect the economics for those vehicle sensitive to down time.

[3] NRC-CNRC Technical Report TP 13892E, 2002