STAGE 7

TRIENNIAL REPORT
1 July 2012–30 June 2015

REVIEW
1 July 1995–30 June 2012

PLANS
1 July 2015–30 June 2018

Chalmers Railway Mechanics – a NUTEK/VINNOVA Competence Centre
Chalmers University of Technology
Mekaniska bromssystem - utveckling och utmaningar
Mechanical braking systems – development and challenges

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Outline

• History of braking
• General on friction brakes
• Illustrative examples
• Challenges
• Concluding remarks
HISTORY OF BRAKING

AFTER THE INVENTION OF THE WHEEL – TOO HIGH SPEED WAS A RISK!

We need brakes!

Horse wagons used block brakes already about 2000 years ago!

Wooden wheel with steel tyre. Braked using lever and wooden block.
Something familiar – Automotive brakes

- Automotive
- Disc brake (~1900)
- Drum brake ~1905 (protected from surroundings)
- Today:
  - Disc brakes (heat management)
  - Drum brakes (trucks: robustness in harsh environments)

First Swedish car 1897, Produced in Surahammar. No brakes. Crashed into mill
Stephenson’s locomotive The Rocket (1829)
- Steam engine – brake by putting in the reverse

Tread (block) brakes
- Express trains ~1860: Brakemen operate manual parking brakes. Instructed by locomotive whistling. Numerous accidents
- Westinghouse Air brake ~1869
  Air pressure controls braking on all wagons along the train. Basically still in use today

Disc brakes ~1950
- Passenger traffic, high speed
Over time a variety of braking systems have evolved. However, friction brakes needed as 1) back-up system for other systems and 2) for emergency braking.
Why is railway braking different from cars and trucks?

- Steel-Steel contact between wheel and rail
  - Low adhesion at contact (order of 0.1)
  - Long stopping distances (order of 1 km)
- Higher axle loads – higher levels of energy
- Highly regulated traffic – safety depends on controls and signals
- Complicated maintenance
  - One train at a time
  - Planned intervals
  - Shrink-fitted components
Basic requirements

- Stop vehicle or control speed on a down-hill gradient
- Consistent braking behavior (wet, snow, leaves)
- Basically all energy is transformed into heat
- Build-up of temperatures must be managed by brake design
- Additionally:
  - Wear
  - Noise
  - Vibrations
  - Environmentally friendly (e.g., particles)

Increasing speeds
Increasing axle loads

\[ W_k = mv^2 \]
\[ W_k = mgh \]
\[ a_{\text{train}} = \frac{F_{\text{friction}}}{m} \]
\[ F_{\text{friction}} = \mu N \]
\[ P = F_{\text{friction}} v \]
Friction

- Frictional behavior is a product of phenomena at the interface between the rotating body and the stationary body.
- Interaction between:
  - Contact pressure
  - Local coefficient of friction
  - Heat generation
  - Wear

We cannot make measurements inside the frictional sliding contact.

Friction brakes often operate at speeds showing so-called frictionally excited thermoelastic instabilities.
GENERAL ON FRICTION BRAKES

Higher contact pressure

Increased frictional heating

Frictionally Excited ThermoElastic Instability

Higher surface temperatures

Thermal expansion

Wear reduces TEI
Stiffness important
Complex interaction!
RAILWAY BRAKING – Illustrative examples

- Rolling noise and friction materials
- Dimensioning temperatures
- Thermal capacity of railway wheels
- Wear of friction materials
- Thermal impact on Rolling Contact Fatigue

*Tread braking examples are given. Several phenomena apply also to disc brakes.*
The Netherlands, mid 1990’s: High levels of **rolling noise** radiate from wagons with cast iron brake blocks!

- Cast iron blocks generate high levels of roughness (waviness, corrugation) on wheel treads
- Legislation on noise levels from rail systems limits number of freight trains per day and night
- Expensive to modify present freight wagons
- Modification of block braking system
  - New block materials – requires modified brake system
  - Cast iron retrofit solutions with new block materials

**New block materials increase wheel heating! Redimensioning of wheels? Other?**
Why high tread corrugation?
Brake rig testing!

Side view of brake rig
• braked wheel at left
• twelve fly wheels

End view with braked wheel

Lucchini Sweden / Surahammar
• Brake rig measurements of temperatures on wheel tread

A general good correlation between generated temperature patterns during braking and resulting tread roughness after cooling down

• Cast iron blocks:
  - instant development of hot spots
• High levels of roughness after few stops
• Cast iron material is transferred from block to tread causing high roughness levels

• Composition and sinter blocks:
  - hot spots after a long time (minutes)
• Low levels of roughness (also polishing effect)
• No material transfer to tread
Temperature field in wheel causes ...

... axial flange deflection – change of wheelset gauge

Risk of derailment

... tensile residual stresses in rim after cooling down

Risk of crack growth and wheel fracture
FE model of wheel and block

- Axisymmetric model of wheel and block
  - fast calculation
  - block parameters modified to account for true block length
- Brake power $Q_{\text{brake}}$ is predetermined
- Heat flux generated at contact
  $$q_{\text{brake}} = \frac{Q_{\text{brake}}}{BL_b}$$
- Heat partitioning between block and wheel by introducing heat resistances $R_b$ and $R_w$

$$q_w = \frac{T_b^{\text{cont}} - T_w^{\text{cont}}}{R_w + R_b} + \frac{R_b}{R_w + R_b} q_{\text{brake}}$$

$$q_b = \frac{T_w^{\text{cont}} - T_b^{\text{cont}}}{R_w + R_b} + \frac{R_w}{R_w + R_b} q_{\text{brake}}$$

Requires calibration using experiments to determine:
- heat resistances $R_b$ and $R_w$
- convection cooling parameters
Model of heat conduction through wheel-rail contact

Perfect-contact model
Surfaces in contact instantly assume common temperature

Modified-contact model
Film is present between surfaces in contact and controls heat conduction
Constant conductance of film
Experimental studies
Wheel – block interaction: – controlled drag braking rig tests
Wheel – rail – block interaction: controlled drag braking rig tests
Wheel – rail – block interaction: field testing

Brake rig testing

Field testing Coal Line, South Africa

Part of test train–view from measurement wagon (100 coal wagons are trailing)

Temperatures of wheel rim, disc and block are measured
Numerical examples – heat partitioning

- 30 kW braking, 100 km/h, ca 30 minutes
- Worn wheel, new brake blocks

- perfect thermal wheel-rail contact
- 15 and 25 tonne axle load

81-94% to wheel with no rail chill
59-71% to wheel with rail chill
23 to 29% of braking heat goes to rail
New brake block materials instead of cast iron

EuroSabot (Sound Attenuation By Optimized Tread Brakes)
EU project 1995-1999 (5.3 M€)
Develop retrofit brake blocks (focus friction)

ERS – Euro Rolling Silently
EU project 2002-2005 (5.8 M€)
Develop retrofit brake blocks (focus friction, fuse function and signalling)

Europetrain
UIC project 2009-2014
Investigate wheel and block wear for new blocks
Possibly train stability problems due uneven tread wear
Thermomechanical aspects – metro wheels

- Mechanical loads
- Thermal loads
- Centrifugal load

+ Residual stresses from heat treatment
  - Wheel and axle assembly

Stresses in railway wheel

What are the dimensioning load cases?

European standards are not for repeated stop braking
Calibration of thermal model
• Rig test at Federal Mogul
• Field test in Shanghai, Line 8

Measure temperatures on wheels and in blocks using thermocouples
Conclusion from field and rig test campaigns

Tread temperatures at end of simulated route (unit: °C)

<table>
<thead>
<tr>
<th>Case</th>
<th>Rail chill (15 tonnes)</th>
<th>No rail chill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rig test</td>
<td>91</td>
<td>107</td>
</tr>
<tr>
<td>Metro guiding axle</td>
<td>104</td>
<td>125</td>
</tr>
<tr>
<td>Metro non-guiding axle</td>
<td>128</td>
<td>159</td>
</tr>
<tr>
<td>Freight</td>
<td>85</td>
<td>98</td>
</tr>
</tbody>
</table>

• In-service: Lowest temperatures for freight and highest for non-guiding axle (metro)

• Rig test (no rail chill) temperatures close to guiding axle temperatures (metro)

• Poor cooling for non-guiding axles

• Importance of knowing the cooling conditions on a specific wagon
Assessment of “Thermal capacity”: what do we need?

1. A calibrated thermal model for the metro applications

2. A material model suitable for elevated temperatures

3. A practical and numerically efficient system for a variety of load cases

4. A proper combined fatigue analysis of the wheel web to estimate life
Material behaviour at elevated temperatures

- Viscoplasticity type with a combination of nonlinear isotropic and kinematic hardening
- Variation of yield stress in the wheel as induced at manufacturing by rim hardening (decreasing the yield by 0.25% per mm depth)
Braking
• Worn wheel (730 mm)
• Speed (80 km/h)
• Deceleration (1.0 m/s$^2$)
• Axle load (16 tonnes)
• 30 stations
• Stop distances (3.0 km)

- EN standard
  - $-1.0 \text{ mm} < \text{deflection} < +3.0 \text{ mm}$
  - $-0.5 \text{ mm} < \text{residual} < +1.5 \text{ mm}$

- Minimum (-0.58 mm)
- Residual (0.25 mm)

Example – Thermal capacity of wheels

![Graph showing thermal capacity of wheels](image)
Limiting braking conditions for stop braking

Worn wheel Stops every 1000 m, 80 km/h

New wheel: Stops every 1000 m, 70 km/h

- Tread (523 °C)
- Residual deflection (1.54 mm) NOT OK!
- Residual hoop stress (+219 MPa)

The wheel with an inclined-straight web is being lifted off from axle. Force that can be transmitted is too low.

NEW WHEEL IS LIMITING!
### Damage evaluation

<table>
<thead>
<tr>
<th>Flange side</th>
<th>Maximum Damage</th>
<th>Maximum Thermal</th>
<th>Life (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δstations [km]</td>
<td>Radius (mm)</td>
<td>Total damage</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>327</td>
<td>$104 \times 10^{-6}$</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>327</td>
<td>$77.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>335</td>
<td>$94.9 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

- Different locations for the highest damage from mechanical loads and thermal loads.
- Web fatigue not a problem for repeated stop braking unless unfortunate wheel design where high thermal and mechanical damage is at same location.

Study on fully worn down wheels – substantial less damage for new wheels

9/14/2016

Chalmers
Example – Wear of friction materials

Modelling of local interaction at contact

\[ q_{\text{local}}(t) = \mu p_{\text{local}}(t) \nu \]

Coupled temperature-displacement simulations. Thermoelastic materials

Element length along contact is typically 0.3 mm.

Brake block mounting stiffness is varied

Temperature dependent wear rate
Determined by pin-on-disc tests
Example – Wear of friction materials

Variation of pressure, temperature and wear over brake block width

Organic composite OC1 $E_{\text{block}} = 1.9 \text{GPa}$

$E_{\text{block}} = 15 \text{ GPa}$
Example – Thermal impact on rolling contact fatigue

Stop braking:
160 km/h and 130 km/h
20 tonnes axle load
0.8 m/s²

Tread cracks develop for braking with sinter blocks.
No cracks after 40 cycles for organic composite block at 160 km/h
Sinter block gives banded contact induced by frictionally induced thermoelastic instabilities and locally "high" tread temperatures. Organic composite brake blocks gives no banded contact and "low" tread temperatures.
FE modelling

Thermal model with prescribed banding patterns

Elastoplastic model (20-625°C)

Traction introduced in contact area

Fatigue of tread: Strain ratcheting damage is assessed

Thermal simulation

Wheel-rail contact "Indentation"

Heat partitioning

Wheel

Rail

Thermomechanical simulation

Example – Thermal impact on RCF
Thermal analysis – stop brake 120 km/h

Temperature distributions at instants in time corresponding to highest surface temperatures in case S1 (left) and case S5 (right).
Braking from 120 km/h.

Temperature at centre of the rolling contact for braking from 120/ km/h when using Organic composite brake blocks - S1 Sinter material brake block - S5.
Markers indicate time instances at which the two contact load passages are considered in thermomechanical analyses.
RAILWAY BRAKING – Challenges

Mix of brake systems on modern trains

• Computer controlled braking system that flexibly can distribute the braking power between the different braking subsystems (ElectroDynamic (ED) / Tread brakes / Disc brakes)

• At ED malfunctioning or at emergency, the mechanical brakes will take a larger part (or all) of the braking effort.

• What is optimum blend of brake sub-systems?
Assessment of ThermoMechanical Fatigue at high temperatures

Fatigue of wheel, treads, axle mounted brake discs and wheel-mounted brake discs

- Material model calibration for TMF situation (not isothermally)
- Material models calibrated for multiaxial behavior
- Rate dependent material models
- Unified TMF criterion
Brake squeal and rolling noise from “low-stress” freight wheels

Upcoming European legislation (Technical Specifications of Interoperability) will enforce noise reductions from wheels and brakes.

This will be especially problematic for “low stress” freight wheels, which because of high thermal loading, have a flexible wheel web.
“New” LL-type (cast iron retrofit) brake block materials

Local tread deformation
Tread roll over on freight wheels caused by new blocks

Winter conditions
Organic composite blocks- ice and snow
Inconsistent braking behavior
Nordic problem
RAILWAY FRICTION BRAKING

Concluding remarks

• Interesting and challenging field
• Spans a several areas of research
• Always demands for higher speeds and / or axle loads
• Working in close collaboration with industry
• Enjoyable / Rewarding / Frustrating experimental work mandatory