Appendix E Numerical simulation of wheel and block temperatures and hypothesis on ice deposition on blocks

Background

The standard UIC 541-4 prescribes that the locomotive driver should regularly condition the brakes by introducing short brake applications during winter conditions. In the following, simulated temperatures of wheels and of brake blocks are studied by use of numerical simulations of braking with organic brake blocks J822 and sintered brake block C333. The employed variations of power and speed for condition braking were extracted from measurements at winter field tests by Transportstyrelsen in winter 2020-2021.

In order to achieve useful predictions of block temperatures, which are rather sensitive to the detailed modelling of heat partitioning between blocks and wheel, this modelling is tuned by use of measured brake block temperatures at Becorit brake bench tests. This is feasible since brake block thermal properties were measured at RISE[1]as part of the present project.

Thermal modelling of tread braking

A thermal model of railway tread braking developed within CHARMEC[2] is utilised for calculations of wheel and brake block temperatures. Thermal simulations are based on having prescribed variations of brake power and speed.

Block(s) and wheel are coupled via a contact interface that controls the heat generation and also the heat partitioning between block and wheel. Heat transfer from the rolling wheel into the rail is considered. The thermal model has one set of parameters that has been calibrated using results from field studies and another set for brake rig conditions. In the following, field conditions are simulated, with relevant convection cooling parameters and rail chill [Ref. 10]. Rail chill is calculated based on an axle load 5 tonnes.

The model developed for simulating thermal interaction of wheel, blocks and rail during braking and after braking at cooling down was developed as part of the doctoral dissertation [Ref. 10] and a short review is given here. An axisymmetric finite element model of wheel and brake blocks is used to achieve short calculation times allowing for analyses of wheel and block temperatures of a train in revenue service. The heat input at the wheel-block interface is calculated, prior to analysis, from train data based on the assumptions of constant coefficient of friction and a uniform contact pressure between block and wheel. The heat partitioning between wheel and block(s), is controlled by introducing thermal resistances at the contact interface, and the heat transfer from wheel to rail is controlled by introducing a thermal conductance at the contact, see Figure 1. The heat flux generated at the interface q^{brake} is partitioned between the wheel, q_{w}, and the block, q_{b}, as

[1] Research Institutes of Sweden, Borås, Sweden
[2] Chalmers Railway Mechanics

$$q_{\mathrm{w}} = \frac{T_{\mathrm{b}}^{\mathrm{cont}} - T_{\mathrm{w}}^{\mathrm{cont}}}{R_{\mathrm{w}} + R_{\mathrm{b}}} + \frac{R_{\mathrm{b}}}{R_{\mathrm{w}} + R_{\mathrm{b}}} q^{\mathrm{brake}} \tag{1}$$

$$q_{\mathrm{b}} = \frac{T_{\mathrm{w}}^{\mathrm{cont}} - T_{\mathrm{b}}^{\mathrm{cont}}}{R_{\mathrm{w}} + R_{\mathrm{b}}} + \frac{R_{\mathrm{w}}}{R_{\mathrm{w}} + R_{\mathrm{b}}} q^{\mathrm{brake}} \tag{2}$$

Here $T_{\mathrm{b}}^{\mathrm{cont}}$ and $T_{\mathrm{w}}^{\mathrm{cont}}$ [°C] are contact temperatures of block and wheel, respectively, and R_{b} and R_{w} [°C /(W/m^2)] are heat resistances at contact. Heat transfer from wheel to rail is analysed assuming perfect thermal wheel-rail contact. For rolling contact and the same thermal material properties in wheel and rail, the heat $Q_{\mathrm{wr}}^{\mathrm{perfect}}$ [W] transferred from wheel to rail is then taken as

$$Q_{\mathrm{wr}}^{\mathrm{perfect}} \approx -6.99 \frac{b\lambda}{\sqrt{\kappa}} \left(T_{\mathrm{w0}} - T_{\mathrm{r0}}\right) \sqrt{\frac{av}{8\pi}} \tag{3}$$

Here a and b [m] are semi-axes of the contact patch (a is in direction of rolling), λ [W/m °C] thermal conductivity, κ [m^2/s] thermal diffusivity, v [m/s] train speed, T_{w0} [°C] wheel tread temperature and T_{r0} rail temperature. This expression gives an upper limit for the heat transferred from wheel to rail. The heat transfer for constant wheel and rail temperatures can be calculated numerically by integrating the heat flux over the contact area. The rail chill is implemented in the FE-models via the rail chill parameter $Q_{\mathrm{wr}}/\Delta T$ (thermal power transferred from wheel to rail per unit difference in surface temperature) which is transformed to convection cooling applied to the area of wheel-rail contact.

Cooling by convection and cooling by radiation are modelled using classical formulae. For the wheel, a convection model is employed that accounts for radial variation of the heat transfer. The convection cooling parameters employed at modelling for in-field conditions.

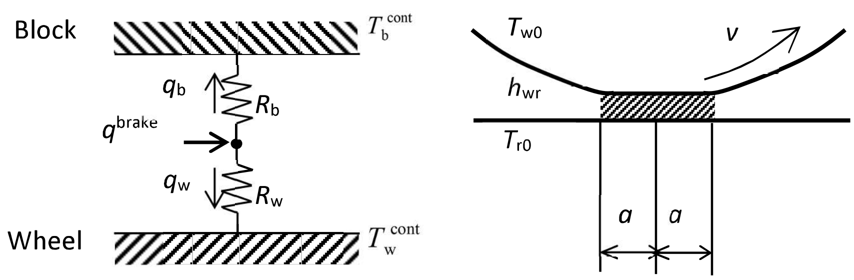

***Figure 1** Thermal resistances at wheel and block contact are used to partition heat between wheel and block (left). Contact between wheel and rail-wheel with film (thermal conductance) at contact (right).*

Tuning of brake block – wheel heat partitioning

The thermal properties of brake block J822 and C333 were determined in dedicated measurements[3] as part of the present project, see

Table **1**. To tune the heat partitioning parameters for these two brake blocks, measured data from reference testing of them were used. To this end, power and speed variations were extracted, see Figure 2, and used in the thermal model of tread braking. Temperatures were extracted from the numerical results at the thermocouple position 10 mm from the brake block contact surface and at mid-block thickness. The heat partitioning parameters R_w and R_b were modified to achieve calculated results that mimicked the measured ones, see Figure 3. Note that no formal calibration was performed, only an adjustment of the values to achieve similar temperatures.

***Table 1** Thermal properties of friction materials*

	Conductivity [W/m K]	Specific heat [J/kg K]	Density [kg/m^3]
J822	0.96	1040	2083
C333	51.7	550	4750

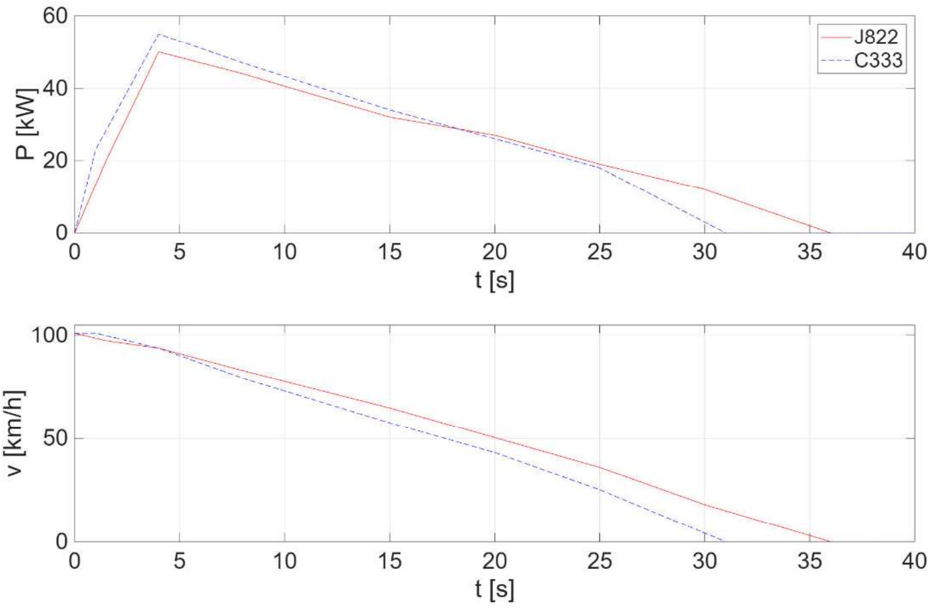

***Figure 2** Extracted variation of power and speed during reference braking for blocks J822 and C333.*

[3] Hasan Sokoti, Thermal properties of two friction materials, RISE, Borås Sweden, December 2025

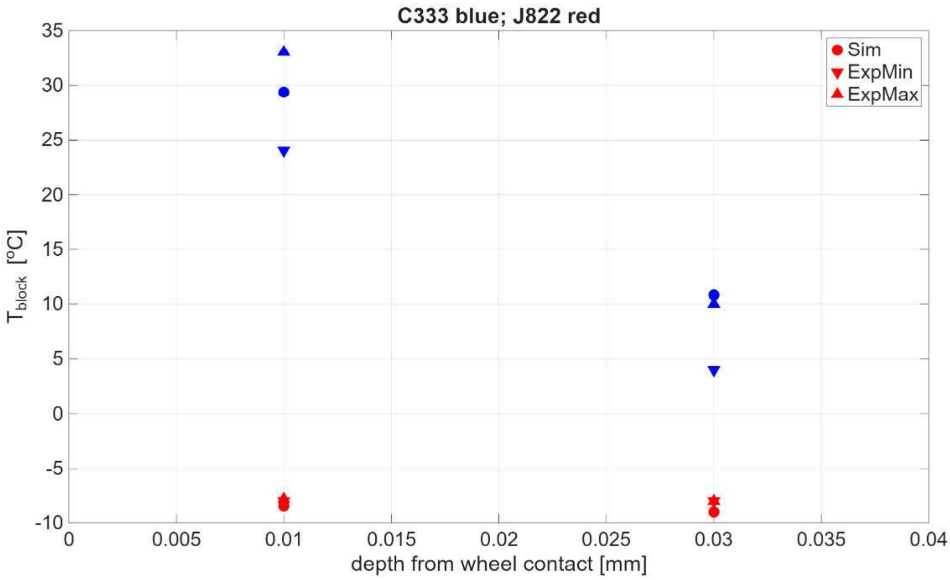

***Figure 3** Calculated and measured brake block temperatures for brake blocks J822 and C333 at end of stop.*

Simulation of train driver brake conditioning according to UIC 541-4

An example of speed and power variations were extracted from the 2021 field tests arranged by Transportstyrelsen, see Figure 4. A generic freight wheel was simulated at semi-worn diameter (867 mm) and new wheel diameter (920 mm), for an axle load of 5,0 tonnes. Simulations are performed for two assumed ambient temperatures: -10 °C and -20 °C.

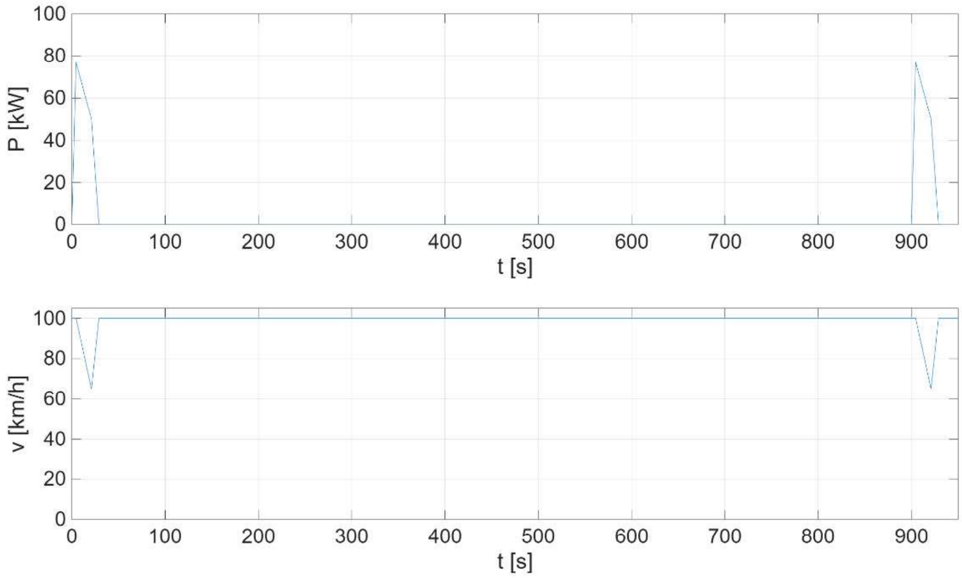

Figure 4 *Extracted variation of power and speed from 2021 field tests of winter braking performance using LL brake blocks. A short application of brake force is introduced every 15 minutes.*

The resulting temperatures of wheel and brake blocks are shown in Figure 5 for all the ten repeated cycles of brake conditioning, and in Figure 6 the temperatures of the last cycle is shown. According to these results, calculated using the heat partitioning model that has been tuned using measured brake block temperatures, it is found that the brake block C333 has a similar, or higher temperature than the wheel, with temperatures reaching between 50 °C and 70 °C. For brake block J822, the opposite is found, with the brake block always being colder than the wheel, with maximum block temperatures reaching +10 °C when performing brake conditioning at -10 °C.

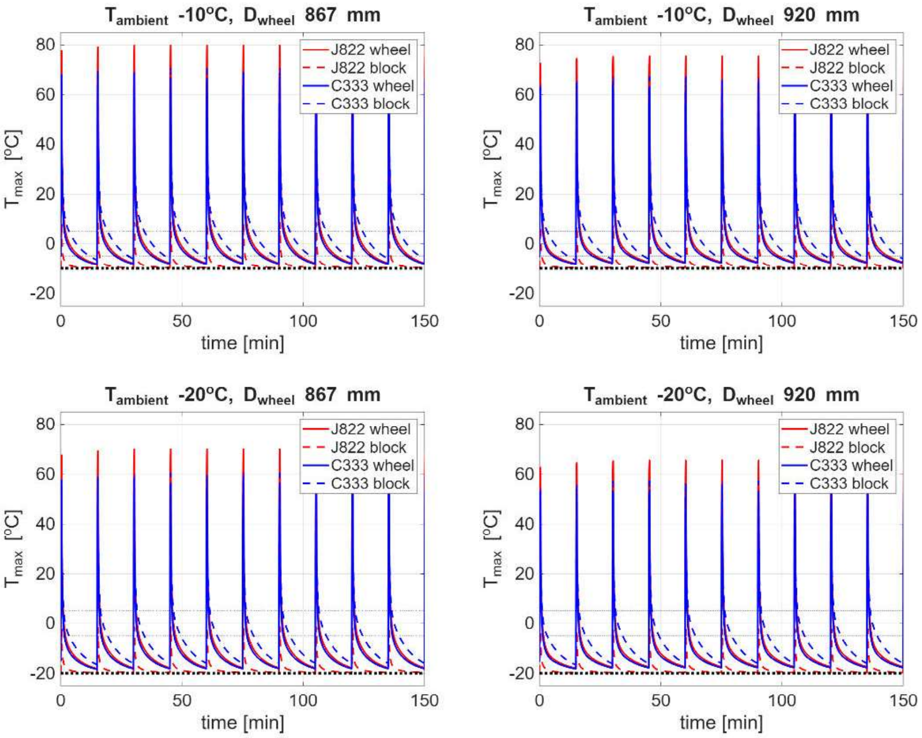

***Figure 5** Calculated maximum temperatures of wheel and brake blocks for 10 simulated repeated cycles of brake conditioning. Horizontal dashed black line indicates ambient temperature. Dotted black lines have been inserted at -5 °C and at +5 °C*

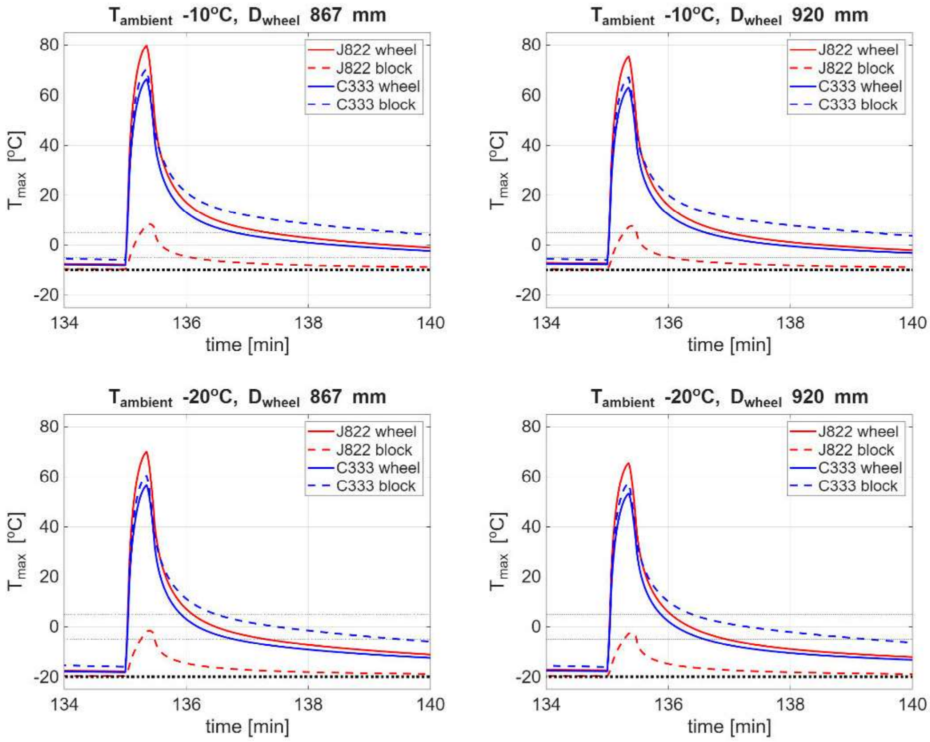

Figure 6 Calculated maximum temperatures of wheel and brake blocks for the last of the 10 simulated repeated cycles of brake conditioning. Horizontal dashed black line indicates ambient temperature. Dotted black lines have been inserted at -5 °C and at +5 °C.

Brake block ice deposition hypothesis

For ice to be deposited on the brake block friction surfaces, fluid water must be available, and the brake blocks need to be at a temperature noticeably below 0 °C for the water to solidify into ice, which is a process that consumes large quantities of energy. Solidification enthalpy of water is 334 kJ/kg, which can be compare the heat capacity of water being 4,18 kJ/kg°C or 1,04 kJ/kg°C for the J822 brake block. Whirling snow around a wagon / the wheels can readily be melted by the "hot" wheel during a period following brake conditioning for both brake block types. The water on the tread of the rotating wheel will then spray around the wheel and partially distribute onto the brake block contact surfaces.

If we make some crude assumptions on temperature limits for ice deposition on the blocks:

- that a wheel temperature of at least +5 °C is required for melting snow and,
- that a brake block temperature of below -5°C is required for the water to solidify (freeze).

We then find from Figure 6 that:

- For brake block J822, for an ambient temperature of -10 °C, we can see that there is a period of 76 seconds for ice deposition on the blocks for a semi-worn wheel and 56 s for a new wheel. For an ambient temperature of -20 °C the time for ice deposition is 38 and 35 s respectively for the semi-worn and the new wheel.
- For brake block C333, which is never colder than the wheel, there is no time for ice deposition on the brake blocks.

Using the above hypothesis on temperature limits, we can also conclude that 1) an ambient temperature of -5 °C can never produce ice on blocks since the blocks will always have at least a marginally higher temperature than this. Moreover, it can be noted 2) that the time for ice deposition on the blocks is longer at the higher ambient temperature of -10 °C than at -20 °C. This points towards that it is not a problem that becomes worse as temperature drops very much. Both these observations are in line with locomotive driver experience.

The here performed numerical simulations point towards that the temperatures of the brake blocks during brake conditioning, that depend on the thermal material properties of the brake block material and the heat partitioning with the wheel, can be important for build-up of ice on brake block contact surfaces. They can tentatively explain why brake performance loss caused by ice on friction surfaces, which winter brake bench tests reported here have proven to be catastrophic for braking distances, is an uncommon / unknown phenomenon for the sintered material C333. Corollary, they can tentatively explain how ice can deposit on the contact surface of the organic J822 brake blocks.