

Experimental investigation of the effects of operating factors on the internal temperature of ultra-large tires using direct measurements at the Muruntau open-pit mine

Umidbek Yusupov

umidyusupov20161978@gmail.com

Tashkent State Transport University

Gayrat Ubaydullayev

Tashkent State Transport University

Barno Kenjayeva

Tashkent State Transport University

Quvondiq Urinbayev

Tashkent State Transport University

Research Article

Keywords: Off-the-road tire, TKPH, haul truck, longitudinal grade, axle-load transfer, TPMS, open-pit mine, Muruntau

Posted Date: October 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11045643/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Experimental investigation of the effects of operating factors on the internal temperature of ultra-large tires using direct measurements at the Muruntau open-pit mine

Umidbek Yusupov¹, Gayrat Ubaydullaev², Barno Kenjayeva³, Quvondiq Urinbayev⁴

¹Department of "Vehicle Engineering", Tashkent State Transport University, Tashkent, Uzbekistan.

²Department of "Automotive Engineering and Manufacturing Engineering", Tashkent State Transport University, Tashkent, Uzbekistan.

³Department of "Transport Logistics", Tashkent State Transport University, Tashkent, Uzbekistan

⁴PhD Student, Department of "Vehicle Engineering", Tashkent State Transport University, Tashkent, Uzbekistan.

¹Corresponding author

E-mail: ¹umidyusupov20161978@gmail.com, ²gayratubaydullaev1948@gmail.com, ³barno_o@tstu.uz,

⁴quvondiq3991@gmail.com

Abstract. This paper investigates the effects of operating factors on the thermal condition of 50/80R57 Bridgestone MasterCore VREM E1A tires installed on Komatsu 860E-1K haul trucks under the sharply continental climatic conditions of the Muruntau open-pit mine in Uzbekistan. Full-scale field tests were conducted on five haul trucks operating with payloads of 225–230 t. The internal tire temperature was measured directly using needle-type thermocouples at nine control points located near the tread–breaker interface. The thermocouple measurements were comparatively evaluated against data obtained using an infrared pyrometer and the KODA monitoring system. The results showed that temperatures in the tire shoulder zones were 3–7°C higher than those in the central tread region, while the rear tires operated at temperatures averaging 5–8°C higher than those of the front tires. Multiple regression models incorporating haul distance, operating speed, longitudinal road grade, and ambient temperature explained 97.6% of the variation in front-tire temperature and 90.5% of the variation in rear-tire temperature. Under operating conditions characterised by an ambient temperature of 36°C or higher, a mean speed of approximately 15 km/h, and a longitudinal road grade of approximately 4%, each additional kilometre of haul distance increased the internal tire temperature by an average of 2.79°C. The calculated haul distance corresponding to the critical temperature of 105°C was approximately 5.8 km. The implementation of the developed organisational and technical recommendations for improving tire utilisation at the Muruntau mine reduced operating costs by UZS 1013 per kilometre. Based on the estimated annual operating volume, the resulting annual economic benefit amounted to UZS 607.8 million per haul truck.

Keywords: Off-the-road tire, TKPH, haul truck, longitudinal grade, axle-load transfer, TPMS, open-pit mine, Muruntau

1. Introduction

Ultra-large off-the-road (OTR) tires are among the most critical components directly affecting the operational safety, productivity, and technical availability of haul trucks used in open-pit mines [1 – 4]. They differ from other components because of their high cost, rapid wear under severe operating conditions, and the complexity of replacement. According to an analysis of the operating cost structure of haul trucks at the Muruntau open-pit mine of Navoiy Mining and Metallurgical Company JSC (NMMC) for 2025, fuel and lubricants accounted for 34% of total costs, while ultra-large tire costs represented 27% [11]. The latter exceeded the shares of depreciation (17%), labour costs (14%), spare parts and materials (7%), and other expenses (1%). This cost structure indicates considerable potential for improving the economic efficiency of mine haulage through more effective tire management.

A single 50/80R57 tire manufactured by Michelin or Bridgestone for a Komatsu 860E-1K haul truck, as well as a 1200/90R57 tire manufactured by Goodyear, costs approximately USD 60,000–70,000 according to the procurement records and supplier quotations available to NMMC [12]. The 50/80R57 tire size is specified by Komatsu as the standard tire size for the 860E-1K haul truck [10]. Under the severe operating conditions of open-pit mines deeper than 600 m, the service life of these tires is often limited to 4–10 months [13]. Premature tire failure before the specified service life is reached results not only in the cost of purchasing a replacement tire but also in additional losses associated with unscheduled truck downtime, repair operations, disruption of the production cycle, and reduced haulage capacity.

The continuous deepening of the Muruntau open-pit mine, the downward movement of the mining front, and increases in haul distance and vertical lift intensify the mechanical and thermal loads acting on the tires. The sharply continental climate of Uzbekistan further aggravates this problem, as the ambient air temperature may reach +45 to +50°C during the summer [13], [29], [30]. Previous numerical and field studies have demonstrated that vertical load, operating speed, ambient temperature, and transport-cycle length significantly influence heat generation and temperature distribution within ultra-large OTR tires [3], [4]. Long haul routes, high payloads, longitudinal road grades, and frequent acceleration and braking increase heat generation within the tires, while high ambient temperatures restrict the dissipation of accumulated heat into the surrounding environment.

During truck operation, tire rubber is subjected to repeated compression, tension, shear, and bending deformations. Owing to the viscoelastic and hysteretic properties of rubber, part of the mechanical energy associated with cyclic deformation is converted into heat and retained within the thick tread, breaker, shoulder, and sidewall structures [1], [2], [5], [7]. Experimental investigations of OTR tire rubber compounds have confirmed that hysteresis loss depends strongly on strain amplitude, strain rate, and rubber temperature [1], [2]. When the internal temperature exceeds the permissible level, thermal and oxidative aging of the rubber compound accelerates, while the adhesion strength at the rubber–cord interface decreases [8]. These processes increase the likelihood of microcracking, interlayer separation, tread detachment, and carcass damage. Therefore, internal tire temperature is an important diagnostic indicator for evaluating tire condition, thermal loading, and expected service life.

Observations conducted by the Central Mining Administration showed that the vertical load acting on the tires of Komatsu 860E-1K haul trucks varied from approximately 250 to 750 kN, the mean operating speed ranged from 14 to 20 km/h, and the ambient temperature varied from -20 to $+45^{\circ}\text{C}$ [13]. In addition, haul distance and vertical lift, mean longitudinal road grade, transport-cycle duration, turning radius, road-surface condition, rolling resistance, and tire inflation pressure significantly affect the thermal state of the tires [3–6]. The combined and variable effects of these factors indicate that evaluating tire performance solely on the basis of the nominal tonne-kilometre-per-hour (TKPH) rating may be insufficient. Recent studies have therefore proposed correcting nominal TKPH values for actual cycle length, operating speed, tire load, and ambient temperature [4].

Although existing analytical and finite-element models describe the mechanisms of hysteretic heat generation and temperature distribution within tires, their results depend on the tire structure, route geometry, climatic conditions, payload, inflation pressure, and operating regime of a particular mine [3], [5], [6]. The OTRTire-T finite-element model, for example, was validated against mine-site observations and achieved an average prediction error of approximately 8.63%; nevertheless, its applicability remains dependent on the operating ranges and boundary conditions used in model development [3]. Therefore, conclusions obtained from laboratory experiments or numerical simulations should be verified through full-scale measurements under actual operating conditions before being used for operational decision-making.

In practice, tire inflation pressure and cavity-air temperature are continuously monitored using tire-pressure monitoring systems (TPMS), including the KODA system, whereas infrared pyrometers are used for rapid measurement of the external tread temperature. However, these methods do not fully represent the maximum local temperature developed within the rubber structure near the tread–breaker interface. Experimental studies have shown that, under prolonged cyclic loading, internal rubber temperature may exceed the externally measured surface temperature [9]. Moreover, uneven temperature distribution across the tread width and surface cooling after the haul truck stops may lead to underestimation of the critical internal temperature. Thermocouples embedded in the tire structure have been successfully used to validate calculated temperature fields and directly measure temperatures in critical tire regions [7]. Therefore, non-contact monitoring results should be validated against direct measurements performed within the rubber–cord structure using needle-type thermocouples.

The objective of this study was to experimentally evaluate the effects of haul distance, operating speed, longitudinal road grade, and ambient temperature on the internal thermal regime of 50/80R57 Bridgestone MasterCore VREM tires installed on Komatsu 860E-1K haul trucks under the operating conditions of the Muruntau open-pit mine. The study aimed to determine temperature distributions at six wheel positions and nine control points across the tread, compare direct thermocouple measurements with infrared-pyrometer and KODA data, and establish safe operating regimes. The development of position-specific thermal assessment models based on full-scale measurements, together with practical recommendations for reducing excessive tire heating, constitutes the principal scientific and practical contribution of this research.

2. Materials and methods

2.1. Study site and equipment

Field measurements were conducted at the Muruntau open-pit mine in Uzbekistan under sharply continental climatic conditions. The investigated haul routes had one-way haul distances of up to 9 km and mean longitudinal grades ranging from 3.30% to 7.24%. During the field trials, the mean operating speed of the haul trucks varied from 14.32 to 18.34 km/h, while the mean ambient temperature ranged from 3°C to 38°C .

The experimental fleet consisted of five Komatsu 860E-1K rigid-frame haul trucks with garage numbers 381, 382, 384, 386, and 388. The nominal payload capacity of this truck model is 254 t. During the hot-season experiments, the actual payload was maintained at approximately 225–230 t to reduce the risk of excessive tire heating. Haul distance, operating speed, cycle duration, stops, and route elevation profiles were obtained from the trucks' GPS and telematics systems.

The trucks were equipped with 50/80R57 Bridgestone MasterCore VREM E1A radial tires. The investigated tires were new at the beginning of the experiment and had an initial tread depth of approximately 95 mm. Before each test, tire pressure, tread condition, and the absence of visible damage were checked. The cold inflation pressure was maintained at approximately 700 kPa in accordance with the manufacturer's recommendations.

Six wheel positions were investigated: front left (FL), front right (FR), rear left outer (RLO), rear left inner (RLI), rear right inner (RRI), and rear right outer (RRO). This arrangement enabled the thermal behavior of the front and rear tires, as well as the inner and outer tires of the rear dual-wheel assemblies, to be evaluated separately.

Table 1: Field equipment and experimental conditions.

Item	Specification
Truck and payload	Komatsu 860E-1K; 225–230 t during hot-season trial
Tire	50/80R57 MasterCore VREM E1A; new tread ≈ 95 mm
Direct sensor	TASCO TNA-20 with TA410-2 K-type needle probe
Probe geometry	3 mm diameter; 150 mm length
Measurement channel	5–6 mm diameter, drilled to breaker interface
Tread locations	Nine points from outboard to inboard shoulder
Distance regimes	one-way haul distances of up to 9 km
Common exposure	15.17 km/h mean speed; $\approx 4.24\%$ mean grade

Item	Specification
Ambient condition	3–38°C

2.2. Direct internal-temperature measurement

The target variable was the rubber temperature close to the breaker–carcass interface, where cyclic deformation and low thermal diffusivity can produce a local maximum. At each tire, nine channels with a diameter of 5–6 mm were prepared across the tread width. A 3-mm-diameter, 150-mm-long K-type needle thermocouple was inserted until the breaker interface was reached. The nine locations were designated SHO OB, 3/8 OB, 1/4 OB, 1/8 OB, centerline (CL), 1/8 IB, 1/4 IB, 3/8 IB, and SHO IB, where OB and IB denote the outboard and inboard sides.

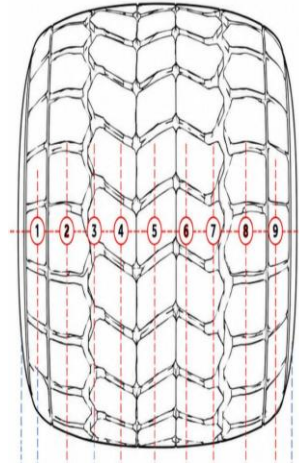


Fig. 1. Schematic of the nine direct measurement points and the needle-probe insertion zone extending to the breaker–carcass interface: 1 — SHO OB (Outer Bead); 2 — 3/8 OB; 3 — 1/4 OB; 4 — 1/8 OB; 5 — CL (Center Line); 6 — 1/8 IB; 7 — 1/4 IB; 8 — 3/8 IB; 9 — SHO IB (Inner Bead).

The direct measurement method was locally invasive and was used for controlled scientific measurements rather than routine fleet-wide monitoring. For the field comparison, the uncertainty of the thermocouple measuring instrument was taken as $\pm 0.1^\circ\text{C}$. Measurements were performed three times per day: in the morning at the beginning of the shift (08:00), at lunchtime (14:00), and in the evening at the end of the working shift (20:00). The haul trucks were stopped in an unloaded condition, and the sensor was promptly inserted into the tire to minimise post-stop cooling effects and accurately measure the internal temperature within the tire structure (Fig.2).



Fig. 2. During the investigation of the internal thermal condition of ultra-large tires.

2.3. Experimental regimes and data reduction

The experimental investigation was designed to evaluate the effects of the principal operating factors on the internal temperature of ultra-large mining tires, namely haul distance, average operating speed, ambient temperature, and average longitudinal road grade. Each factor was investigated in a separate experimental stage while the remaining operating parameters were maintained as constant as practicable. This approach made it possible to evaluate the individual contribution of each factor to the tire internal temperature.

The experimental program consisted of four main stages:

- Stage I – effect of haul distance (3.5 – 8 km);

- Stage II – effect of average operating speed (approximately 14 – 18.5 km/h);
- Stage III – effect of average longitudinal road grade (4 – 7.5%);
- Stage IV – effect of ambient temperature, investigated throughout all seasons over the range of 3 – 38°C.

The nine points characterize one spatial temperature profile and were not treated as nine independent experiments. For regime r and tire position p , the profile mean was calculated as

$$\bar{T}_{rp} = \left(\frac{1}{9}\right) \sum T_{rpi} \quad (1)$$

where T_{rpj} is the direct temperature at tread point j . A separate exploratory least-squares line was then fitted to the three regime means for every wheel position:

$$\bar{T}_p(L) = a_p + b_p L \quad (2)$$

The distance at which the fitted mean reached the site-adopted 105°C screening level was calculated as

$$L_{crit,p} = (105 - a_p)/b_p \quad (3)$$

Because there were only three distance regimes and truck/route assignment was not randomized, R^2 values are reported only as descriptive fit statistics. The slope b_p represents combined distance-related operational exposure and must not be interpreted as an isolated causal effect of distance.

The experimental study comprised a total of 26 operating regimes, including three haul-distance regimes, twelve operating-speed regimes, three longitudinal-grade regimes, and five ambient-temperature regimes.

Because the number of experimental observations was limited, including quadratic terms for all explanatory variables would have resulted in an unnecessarily large number of regression parameters and increased the risk of model overfitting. Therefore, haul distance, operating speed, and longitudinal grade were represented by linear terms, whereas ambient temperature was represented by a linear–quadratic term. Accordingly, the regression model was formulated as follows:

$$T = b_0 + b_1 L + b_2 V + b_3 i + b_4 T_a + b_5 T_a^2 \quad (4)$$

2.4. Comparative analysis of tire temperature measurement methods

Tire temperature was measured simultaneously using a needle-type thermocouple, an infrared (IR) pyrometer, and a KODA/MEMS sensor. The tread-surface temperature measured by the IR pyrometer ranged from 15 to 70°C and was 15–20°C lower than the internal temperature. The tire-cavity air temperature recorded by the KODA/MEMS sensor ranged from 30 to 92°C and was 10–28°C lower than the breaker temperature. The temperature measured by the needle-type thermocouple at the breaker–carcass interface ranged from 40 to 118°C. These results support the use of the needle-type thermocouple as the reference method for assessing the local maximum internal tire temperature.

3. Results

3.1. Temperature rise across haul regimes

To evaluate the effect of ambient temperature on the internal thermal condition of ultra-large mining tires, experimental investigations were conducted throughout all four seasons. In all tests, the haul distance (approximately 6 km), average operating speed (15 km/h), and average longitudinal road grade (4.05–4.21%) were maintained as nearly constant as practicable, while ambient temperature was considered the only independent variable.

The autumn experiments were conducted on 5 November 2025 using a KOMATSU 860E-1K haul truck (garage No. 381). The average one-way haul distance was 5.89 km. The maximum ambient temperature during the test was 22°C, while the daily average temperature was 14°C.

The winter experiments were carried out on 12 January 2026 using the same haul truck No. 381. The operating conditions were comparable to those of the autumn tests, whereas the maximum and daily average ambient temperatures were 9°C and 3°C, respectively.

The spring experiments were performed on 4 May 2026 using haul truck No. 386. During this test, the maximum ambient temperature reached 29°C, with a daily average of 20°C.

The principal summer experiments were conducted on 22 June 2026 using haul truck No. 384. The tests were performed under a maximum ambient temperature of 38°C and a daily average temperature of 33°C.

Because the highest thermal loading of mining tires is generally observed during extremely hot summer conditions, an additional high-temperature experiment was conducted on 19 July 2026 using haul truck No. 388. The operating parameters remained essentially unchanged, whereas the maximum and daily average ambient temperatures reached 45°C and 38°C, respectively.

Based on the data collected under natural operating conditions over an ambient temperature range of 3–38°C, separate analyses were performed for the front- and rear-axle tires in Fig. 3 and 4. The resulting relationships between ambient temperature and tire internal temperature were subsequently presented in the form of individual regression plots for the two axle groups.

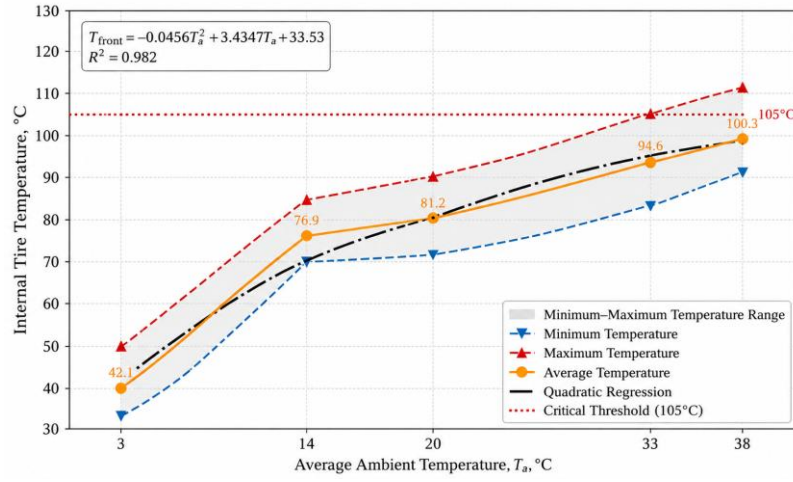


Fig. 3. Effect of ambient temperature on the internal temperature of Front-axle tires.

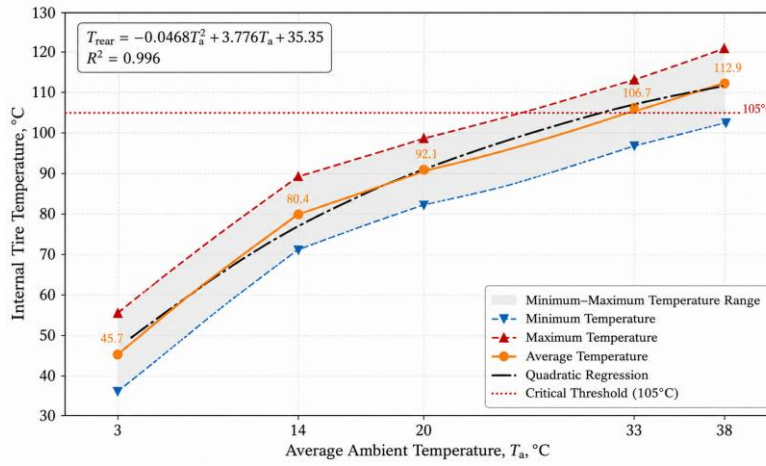


Fig. 4. Effect of Ambient Temperature on the Internal Temperature of Rear-axle tires.

The results demonstrate that ambient temperature has a pronounced influence on the internal thermal condition of ultra-large mining tires. As the average ambient temperature increased from 3°C to 38°C, the average internal temperature of the front-axle tires increased from 42.1°C to 100.3°C, whereas that of the rear-axle tires increased from 45.7°C to 112.9°C. Throughout the investigated temperature range, the rear-axle tires consistently operated at higher temperatures than the front-axle tires, indicating a greater thermal loading of the rear axle.

Under summer operating conditions, the average internal temperature of the rear-axle tires reached 106.7°C at an ambient temperature of 33°C, thereby exceeding the adopted critical threshold of 105°C. The maximum temperature of the front-axle tires reached 105.4°C at 33°C and increased further to 111.2°C at an ambient temperature of 38°C, whereas the maximum temperature of the rear-axle tires reached 121.4°C. These findings indicate that elevated ambient temperatures substantially increase the thermal loading of mining tires and significantly increase the likelihood of exceeding the critical operating temperature, particularly for rear-axle tires.

3.2. Assessment of the effect of haul distance and determination of critical operating thresholds

Field experiments were conducted on 25-26 June 2026 using KOMATSU 860E haul trucks to investigate the influence of haul distance on the internal temperature of ultra-large mining tires. Six operating regimes were considered, with average one-way haul distances of 3.53 – 7.94 km. To isolate the effect of haul distance, the average operating speed (approximately 15 km/h), the average longitudinal road grade (approximately 4%), and the average ambient temperature (33°C) were maintained as nearly constant as practicable throughout the experiments. This experimental design enabled the influence of haul distance on tire internal temperature to be evaluated independently of the other operating parameters.

The measured temperature profiles demonstrated a non-uniform distribution of internal temperature across the tire tread. For all operating regimes, the highest temperatures were consistently recorded in the shoulder regions (SHO OB and SHO IB), whereas the lowest temperatures occurred near the tread center (CL). Depending on the operating regime, the shoulder temperatures exceeded those of the central region by approximately 3–7°C (Fig. 5 and 6).

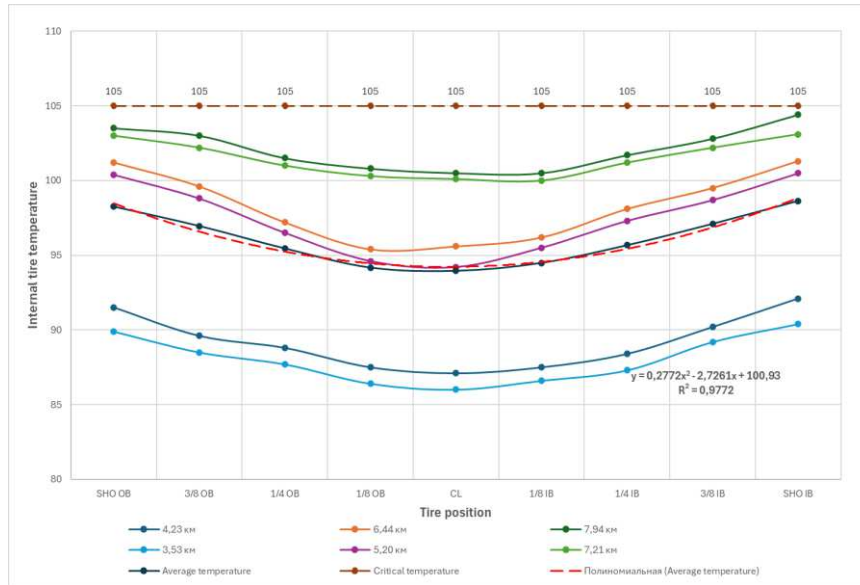


Fig. 5. Internal temperature distribution across front-axle tire positions under different haul-distance operating regimes.

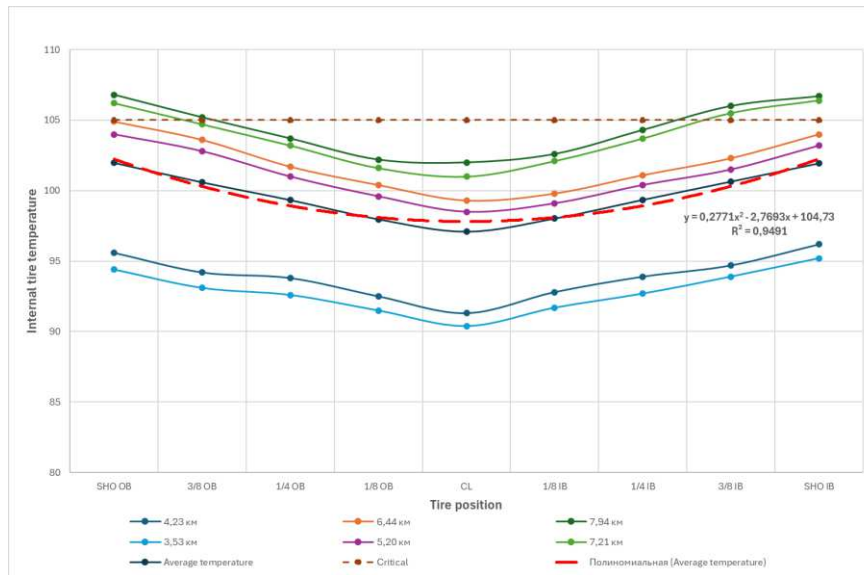


Fig. 6. Internal temperature distribution across rear-axle tire positions under different haul-distance operating regimes.

This phenomenon is primarily attributed to the concentration of lateral shear stresses in the tire shoulder regions caused by cornering maneuvers and road cross slopes on the open-pit haul roads, combined with less efficient heat dissipation from these regions. Furthermore, the right-hand side of the tire tread profile consistently exhibited higher temperatures than the left-hand side for all haul trucks investigated. This asymmetry is associated with the greater frequency of right-hand turns along the haul routes, the relatively small turning radius of some road sections (22 m), and the relatively high road cross slope (5%) within the turning zones (Fig. 7).



Fig. 7. Road sections with turning radii below the recommended design value along the haul routes.

A comparison of the three haul-distance regimes revealed a clear positive relationship between haul distance and tire internal temperature. When the average one-way haul distance was less than 5 km, the internal temperatures of the 50/80R57 Bridgestone MASTERCORE VREM E1A tires remained below the adopted critical threshold of 105°C. At haul distances between 5 and 7 km, the tire temperatures approached the critical operating range, whereas haul distances exceeding 7 km resulted in temperatures above the recommended limit, particularly for the right-front tire. The rear tires consistently operated at higher temperatures than the front tires, indicating a greater thermal load on the rear axle.

Based on the experimental data, the following linear regression model was obtained:

$$T_{in} = 88.87 + 2.79L \quad (6)$$

where T_{in} is the predicted internal tire temperature (°C) and L is the average one-way haul distance (km). The model provided a high coefficient of determination ($R^2 = 0.981$), indicating an excellent agreement with the experimental observations within the investigated distance range (3.53–7.94 km). The regression coefficient indicates that each additional 1 km of haul distance increases the internal tire temperature by approximately 2.79°C under the investigated operating conditions.

Using the site-adopted critical temperature of 105°C, the corresponding critical haul distance was estimated as 5.8 km. This result suggests that, under typical summer operating conditions (ambient temperature approximately 33–36°C, average speed 15 km/h, and longitudinal road grade about 4%), the internal temperature of the investigated tires approaches the critical operating threshold when the average one-way haul distance reaches approximately 5.8 km. Therefore, maintaining haul distances below 5.5 km provides an adequate operational safety margin for the E1A tire specification, whereas longer haul routes should be monitored more closely or equipped with the more heat-resistant E3A tire specification, in agreement with the technical recommendations provided by Bridgestone.

3.3. Experimental investigation and analysis of the effect of average operating speed on tire internal temperature

The Field experiments were conducted on 15–18 June 2026 using three KOMATSU 860E-1K haul trucks (garage N.382, 384, and 388) to evaluate the effect of average operating speed on the internal thermal condition of ultra-large mining tires. The experiments were performed under similar operating and climatic conditions in order to isolate the influence of operating speed. During the test program, the average haul distance (4.81–7.89 km), the average longitudinal road grade (3.30–6.45%), and the ambient temperature (33–34°C) were maintained as nearly constant as practicable. This experimental design made it possible to evaluate the influence of average operating speed independently of the other operating factors.

To establish different speed regimes, three driving conditions were assigned to the operators. The first haul truck was operated at the lowest practicable speed, the second at the normal operating speed, and the third at the highest permissible speed while fully complying with technological and safety requirements. This approach minimized the influence of other operational variables and enabled a direct assessment of the effect of average operating speed on the development of tire internal temperature.

The experimental results demonstrated a consistent increase in tire internal temperature with increasing average operating speed. For the front axle, increasing the operating speed from 14.3 km/h to 18.1 km/h increased the average internal tire temperature from 93.4°C to 107.9°C, corresponding to an increase of approximately 15°C. A similar trend was observed for the rear axle, where the average internal temperature increased from 94.1°C to 110.0°C over the same speed range. Under all operating regimes, the rear-axle tires consistently exhibited higher temperatures than the front-axle tires (Fig. 8 and 9).

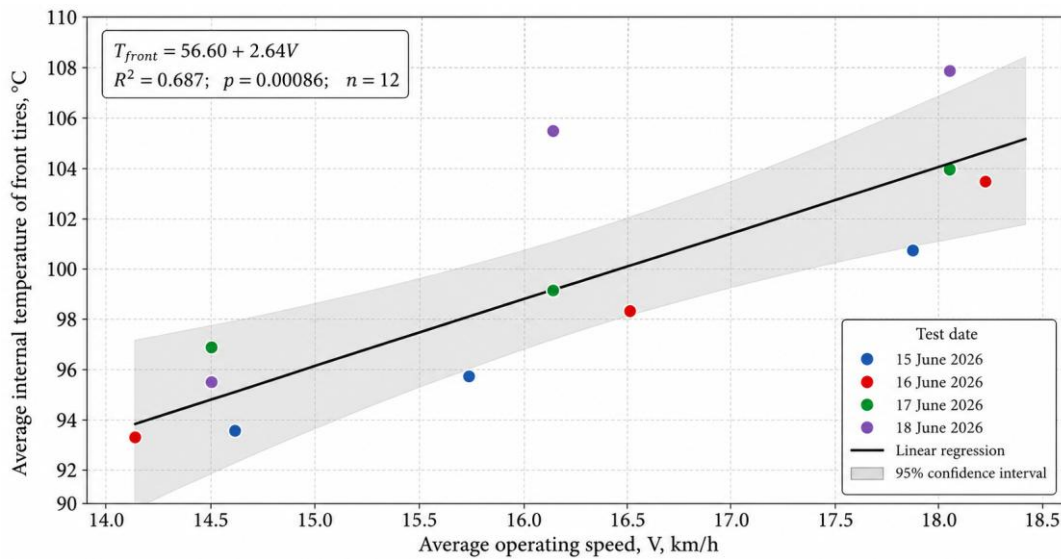


Fig. 8. Relationship between average operating speed and the average internal temperature of the front-axle tires (average ambient temperature 33.5°C).

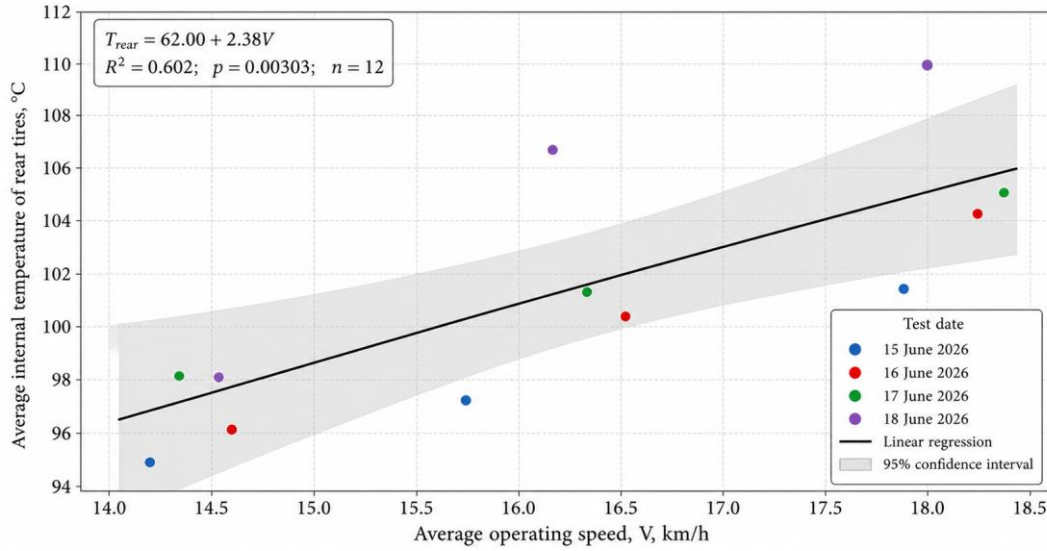


Fig. 9. Relationship between average operating speed and the average internal temperature of the rear-axle tires (average ambient temperature 33.5°C).

Based on the experimental data, linear regression analysis was performed to quantify the relationship between average operating speed and tire internal temperature. For the front axle, the following regression model was obtained:

$$T_{front} = 56.62 + 2.62 \cdot V \quad (7)$$

where T_{front} is the average internal temperature of the front tires (°C) and V is the average operating speed (km/h).

The statistical characteristics of the model ($R^2 = 0.687$, $RMSE = 2.61^\circ\text{C}$, $p < 0.001$) confirm a strong and statistically significant positive relationship between average operating speed and front-tire internal temperature. According to the regression coefficient, an increase in operating speed of 1 km/h results in an average increase of approximately 2.64°C in the internal temperature of the front tires.

For the rear axle, the corresponding regression equation was

$$T_{rear} = 62.0 + 2.38 \cdot V \quad (8)$$

This model indicates that each 1 km/h increase in average operating speed increases the average internal temperature of the rear tires by approximately 2.38°C . Although the temperature sensitivity of the rear tires to speed was slightly lower than that of the front tires, the rear tires consistently operated at higher absolute temperatures throughout the investigation. Under the highest operating-speed regime, the average rear-tire temperature approached 110°C , exceeding the site-adopted critical operating temperature of 105°C .

From a physical standpoint, this phenomenon is associated with the increased frequency of cyclic deformation of the tire structure as rotational speed increases. At higher operating speeds, the number of deformation cycles per unit time increases, leading to greater hysteresis energy losses within the rubber compound. Because the generated heat cannot be dissipated rapidly enough to the surrounding environment, thermal energy accumulates within the carcass and belt regions of the tire, resulting in a progressive increase in internal temperature. This effect is particularly pronounced in the rear-axle tires because of their higher operating loads and consequently greater cyclic deformation.

3.4. Effect of average longitudinal road grade on the thermal condition of mining tires

Field experiments were conducted on 20 June 2026 using three KOMATSU 860E-1K haul trucks (garage Nos. 382, 384, and 388) to investigate the influence of average longitudinal road grade on the thermal condition of ultra-large mining tires. The tests were performed under nearly identical operating conditions, with an average haul distance of approximately 5 km, an average operating speed of 15 km/h, and an average ambient temperature of 33°C (maximum 39°C). During the experiments, the haul trucks operated on road sections with average longitudinal grades ranging 4–7.5%, allowing the effect of road grade to be evaluated independently of the other operating parameters.

The results showed a progressive increase in thermal loading with increasing road grade. At an average grade of 4.12%, the average temperature of the front tires ranged from 91 to 97°C , while the rear tires operated within 96 – 100°C . Increasing the grade to 5.61% raised these values to 96 – 103°C and 101 – 107°C , respectively. Under the steepest condition (7.24%), the front tires reached 105 – 110°C , whereas the rear tires operated within 109 – 114°C . Throughout all operating regimes, the rear axle consistently exhibited higher temperatures than the front axle.

The transverse temperature distributions further confirmed the influence of road grade. At 7.24%, almost all measurement locations on the front tires exceeded the adopted critical operating temperature of 105°C . For the rear tires, the shoulder regions reached this threshold already at 5.61%, while under the steepest condition the entire tread profile remained within 110 – 113°C . The highest values were recorded at the shoulder regions, reaching approximately 109°C for the front tires and 113 – 114°C for the rear tires (Fig. 10 and 11).

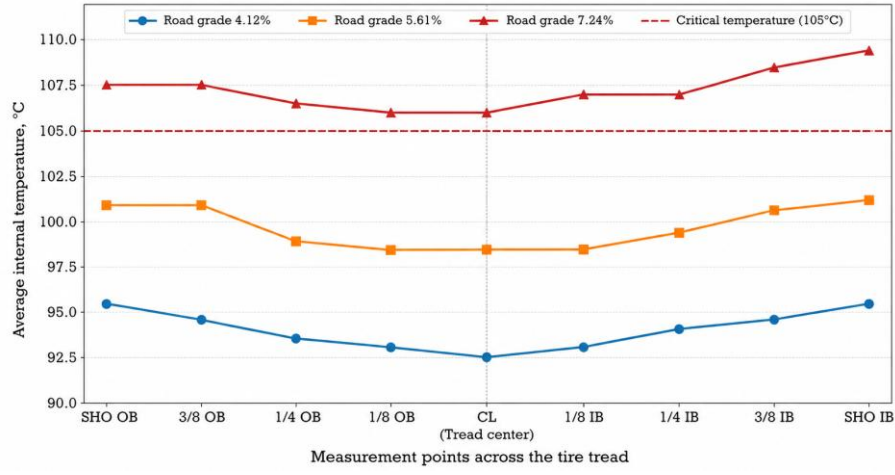


Fig. 10. Internal temperature distribution across the front-tire tread profile under different longitudinal road-grade conditions.

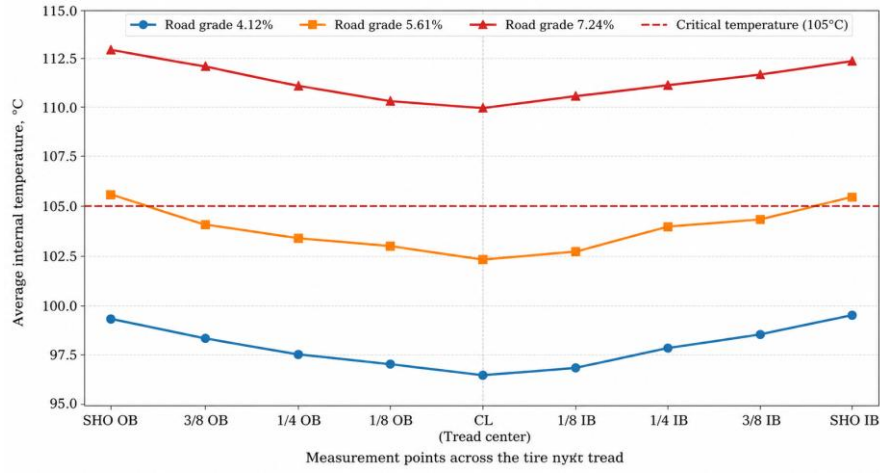


Fig. 11. Distribution of internal temperature across the tread profile of the rear tires under different longitudinal road-grade conditions.

The observed trend is explained by the increase in tractive demand as road grade becomes steeper. Higher gradients require greater driving torque, which intensifies cyclic deformation of the tire structure and increases hysteresis energy losses within the rubber compound. As a result, heat generation exceeds the rate of heat dissipation, leading to progressive thermal accumulation in the carcass and belt regions. Because the rear axle carries a greater share of the vehicle load, this mechanism is more pronounced for the rear tires, substantially increasing the likelihood of exceeding the critical operating temperature under steep haul-road conditions.

3.5 Validation of multivariable regression models developed from experimental results using LOOCV and bootstrap methods

1. Comparison of models for front-axle tyres. linear model:

$$T_{front} = -31,713 + 1,284L + 3,716V + 3,489i + 1,509T_a \quad (9)$$

The goodness-of-fit metrics for this model are as follows: $R^2 = 0,930$; $R_{adj}^2 = 0,899$; $RMSE=4,12^\circ\text{C}$.

2. Comparison of models for rear-axle tyres. Linear model:

$$T_{rear} = -15,403 + 1,869L + 2,807V + 2,893i + 1,603T_a \quad (10)$$

The goodness-of-fit metrics for this model are as follows: $R^2 = 0,905$; $R_{adj}^2 = 0,862$; $RMSE=5,05^\circ\text{C}$.

The LOOCV validation results are as follows: $RMSE_{LOOCV} = 9,43^\circ\text{C}$, $Q^2 = 0,668$.

4. Discussion

4.1. Physical interpretation of the observed thermal behaviour

The experimental investigations conducted under the operating conditions of the Muruntau open-pit mine demonstrated that the thermal condition of ultra-large mining tires is governed by the combined effects of haul distance, operating speed, longitudinal road grade, and ambient temperature. In all experimental regimes, an increase in operating severity resulted in a

corresponding increase in the internal tire temperature. This behaviour can be explained by the accumulation of hysteresis heat generated during cyclic tire deformation at a rate exceeding its dissipation to the surrounding environment.

An increase in haul distance prolongs the period during which the tire operates under load, promoting heat accumulation within the internal tire structure. Likewise, higher operating speeds increase the frequency of cyclic deformation, thereby intensifying hysteresis losses. In addition, steeper longitudinal road grades require greater tractive effort and wheel torque, resulting in increased cyclic deformation and, consequently, higher thermal loading of the tire. These relationships are further supported by the regression models developed from the experimental data.

The results also showed that the rear-axle tires consistently operated at higher temperatures than the front-axle tires under all investigated operating conditions. This behaviour is primarily attributed to the higher vertical loads acting on the rear axle and the restricted airflow between dual rear tires, which reduces heat dissipation. Furthermore, the temperature profiles obtained from the nine measurement locations across the tread revealed a non-uniform thermal distribution, with the highest temperatures occurring in the shoulder regions and the lowest temperatures at the tread centre.

Overall, the findings indicate that the thermal condition of ultra-large mining tires should not be evaluated on the basis of individual operating parameters alone but rather by considering their combined influence. Such an integrated approach provides a scientific basis for predicting excessive tire heating, extending tire service life, and improving the operational efficiency of haul trucks operating under severe open-pit mining conditions.

4.2. Comparison with previous studies

The thermal trends observed in this field study are consistent with the established thermomechanical behaviour of ultra-large off-the-road (OTR) tires. Using the OTRTire-T numerical model, Ma et al. [2] demonstrated that tire temperature is governed by the combined effects of vertical load, operating speed, ambient temperature, structural characteristics, and heat dissipation. Their study covered vertical loads of approximately 0.34–1.04 MN, speeds of 5–30 km/h, and a wide range of ambient temperatures. The Muruntau field measurements confirm these relationships under full-scale operating conditions, showing that internal tire temperature increased with haul distance, average operating speed, longitudinal road grade, and ambient temperature.

The physical mechanism underlying these trends is supported by the rubber-compound experiments of Ma et al. [3]. Cyclic tensile tests conducted at strain amplitudes of 10–100%, strain rates of 10–500% s⁻¹, and temperatures from –30 to 100°C showed that hysteresis loss increased substantially with both strain amplitude and strain rate. The sidewall compound also exhibited greater hysteresis loss and stronger strain-rate sensitivity than the tread compound. Therefore, higher loading, speed, and road grade increase deformation magnitude and frequency, converting a larger proportion of mechanical energy into heat within the tread, belt, and sidewall structures.

The observed influence of ambient temperature agrees with the numerical findings of Li et al. [8], who showed that surrounding temperature affects tire deformation, stress, and the resulting thermal field. In the Muruntau tests, an increase in mean ambient temperature from 3°C to 38°C raised the average internal temperature from 42.1°C to 100.3°C in the front tires and from 45.7°C to 112.9°C in the rear tires. This pronounced increase reflects both the additional external thermal exposure and the reduced temperature gradient between the tire and the surrounding air, which limits heat dissipation under hot summer conditions.

The relationship between haul distance and internal temperature is also compatible with the tonne-kilometre-per-hour (TKPH) concept used for OTR tire selection. Bridgestone defines operating TKPH as the product of mean tire load and average work-shift speed and notes that sustained operation under heavy loads, high speeds, and long haul cycles causes progressive heat accumulation. Operation above the rated TKPH may therefore accelerate tire deterioration because OTR tires have a limited capacity to withstand accumulated heat [28]. The manufacturer's method uses 38°C as the reference maximum ambient temperature, requires temperature-based correction when actual conditions differ, and generally applies to one-way haul distances of up to 16 km.

The Muruntau results provide a site-specific experimental complement to this industrial framework. Under summer conditions with an ambient temperature of approximately 33–36°C, a mean speed of about 15 km/h, and an average longitudinal grade of approximately 4%, each additional kilometre of one-way haul distance increased the measured internal temperature by approximately 2.79°C. The fitted relationship reached the locally adopted screening temperature of 105°C at an estimated one-way haul distance of 5.8 km. This value should not be interpreted as a universal manufacturer limit or a general tire-failure distance. It is a site-specific screening threshold applicable to the investigated 50/80R57 Bridgestone MasterCore VREM E1A tires, payload range, routes, climate, and operating regime.

The measured speed effect is consistent with previous experimental and coupled thermomechanical studies [4], [16]–[21], which have shown that vehicle speed influences deformation frequency, hysteretic heat generation, thermal accumulation, and the time required to reach thermal equilibrium. At Muruntau, increasing the average speed from approximately 14.3 to 18.1 km/h raised the mean internal temperature of the front tires from 93.4°C to 107.9°C and that of the rear tires from 94.1°C to 110.0°C. The corresponding front- and rear-axle regression coefficients were approximately 2.64 and 2.38°C per 1 km/h, respectively. However, these coefficients remain site-specific because speed was not completely independent of truck assignment, route geometry, road grade, and cycle characteristics.

Longitudinal road grade produced a similarly distinct thermal response. A steeper loaded-haul segment requires greater tractive force and wheel torque, increasing tangential forces in the tire–road contact area and cyclic deformation of the tread, belt, and sidewall regions [2], [3], [7]. When the mean longitudinal grade increased from 4.12% to 7.24%, the front-tire temperature range rose from 91–97°C to 105–110°C, while the rear-tire range increased from 96–100°C to 109–114°C. These field results demonstrate that road grade should be considered together with load, speed, haul distance, and ambient temperature when assessing the thermal exposure of OTR tires.

The systematically higher temperature of the rear tires is physically attributable to their operating conditions. The rear axle carries the principal share of the payload, causing greater tire deflection and cyclic strain, while the dual-tire arrangement restricts

airflow around the inner sidewalls and adjacent shoulder regions. Studies of earthmover and heavy-vehicle tires [2], [9], [16]–[18], [25]–[27] have similarly shown that internal temperature fields are spatially non-uniform because heat generation and dissipation vary between the tread, belt, shoulder, sidewall, and bead regions. Under Muruntau conditions, the rear tires were generally 5–8°C hotter than the front tires, and the shoulder regions were commonly hotter than the tread centre.

The measured transverse profiles also support numerical findings that the maximum temperature does not necessarily occur on the visible tire surface. Marais and Venter [9] and other coupled thermomechanical studies [16]–[18] demonstrated that internal temperature depends on local deformation, material properties, structural geometry, and heat-transfer paths. Consequently, cavity-air and tread-surface temperatures cannot be assumed to represent the local temperature near the tread–breaker interface.

Infrared thermography remains useful for rapid non-contact screening, as demonstrated by Li et al. [24] in tire-sidewall monitoring. Nevertheless, infrared readings represent accessible surface temperatures and are affected by emissivity, measurement angle, environmental conditions, and post-stop cooling. TPMS and KODA systems provide valuable continuous information on inflation pressure and cavity-air temperature but monitor a different thermal location. Therefore, the differences observed between thermocouple, infrared, and cavity-air measurements primarily reflect actual spatial temperature gradients rather than measurement error alone.

A principal contribution of the present study is the direct measurement of rubber temperature near the tread–breaker interface at nine positions across the tire profile. Previous OTR tire research has provided finite-element simulations, laboratory analyses of rubber hysteresis, cavity-air monitoring, surface thermography, and TKPH-based operational assessments [1–4], [8], [9], [11], [13], [16–24]. The Muruntau investigation integrates needle-thermocouple measurements with GPS, route, speed, grade, ambient-temperature, infrared, and KODA data collected during actual production operation. Direct measurement does not replace numerical analysis or continuous monitoring; rather, it provides a local reference for calibrating thermal models, warning levels, and non-invasive monitoring systems.

The findings also support the route-oriented tire-selection approach proposed by Pascual et al. [12] according to which tire specifications should correspond to the thermal and mechanical demands of individual haul routes. Bridgestone similarly classifies compounds according to their balance of heat and cut resistance and identifies E3A as a heat-resistant option in the MasterCore product range. For Muruntau, E1A tires may remain suitable under moderate thermal exposure, whereas longer, faster, steeper, and hotter routes require intensified monitoring, operational mitigation, or consideration of a more heat-resistant compound. Any change in tire specification should nevertheless be verified against manufacturer approval, payload, inflation pressure, road condition, and the site-specific TKPH calculation.

Overall, the Muruntau results experimentally confirm the established effects of hysteresis, load-related deformation, speed, haul duration, road geometry, and ambient temperature on OTR tire heating. Their main contribution is the quantitative evidence obtained for individual wheel positions and tread-profile locations under actual production conditions. These measurements enable general thermomechanical principles and manufacturer TKPH guidance to be translated into site-specific warning distances, monitoring priorities, operating restrictions, and tire-selection decisions.

4.3. Study limitations and further work

The present study provides direct experimental evidence on the thermal behaviour of ultra-large OTR tires operating under real production conditions at the Muruntau open-pit mine. Unlike previous studies based mainly on numerical simulations, cavity-air monitoring, infrared thermography, or TKPH analysis [1–4], [8], [9], [14], [15] this investigation measured the internal rubber temperature directly at the tread–breaker interface using needle thermocouples.

A major contribution of the study is the integration of direct temperature measurements with synchronized operational parameters, including haul distance, vehicle speed, longitudinal road grade, ambient temperature, infrared thermography, and KODA monitoring. This approach enabled evaluation of both the magnitude and spatial distribution of internal tire temperature under actual mining conditions.

Site-specific regression models developed for the front and rear tires demonstrated that internal temperature increased systematically with haul distance, operating speed, road grade, and ambient temperature. Rear tires consistently operated at higher temperatures than front tires because of greater loading and reduced cooling, while the shoulder regions exhibited the highest thermal levels across the tread profile.

From a practical perspective, the proposed methodology provides a basis for site-specific thermal assessment of OTR tires. Under the investigated operating conditions, the haul-distance model predicted that the site-adopted screening temperature of 105°C would be reached at an estimated one-way haul distance of approximately 5.8 km. This value represents a local operational criterion for the investigated tire type and operating conditions rather than a universal thermal limit.

Overall, the proposed methodology offers a practical framework for calibrating thermal monitoring systems, improving tire selection and haul-route management, and reducing the risk of premature tire failures caused by excessive heat accumulation.

5. Conclusions

Direct This study investigated the thermal behaviour of ultra-large 50/80R57 OTR tires operating under actual production conditions at the Muruntau open-pit mine using direct internal temperature measurements. Unlike conventional monitoring methods based on surface or cavity-air temperatures, the proposed approach measured the temperature directly near the tread–breaker interface, providing reliable information on the thermal state of the most critical structural region.

The high ambient temperatures, increasing haul distances, and greater longitudinal road grades at the Muruntau open-pit mine were found to intensify the thermal loading of haul-truck tires. Consequently, these operating conditions were classified as severe with respect to tire thermal performance.

Direct measurement of the internal tire temperature at the breaker–carcass interface using a needle-type thermocouple was confirmed to be the most reliable measurement method. Temperature was distributed non-uniformly across the tread width, with the shoulder zones operating at temperatures 3–7°C higher than the central tread region.

Multiple regression models incorporating a quadratic ambient-temperature term were developed to estimate the internal temperatures of the front- and rear-axle tires. The models explained 97.6% of the variation in front-tire temperature and 90.5% of the variation in rear-tire temperature.

According to the single-factor regression analysis, each additional kilometre of haul distance increased the maximum internal tire temperature by an average of 2.79°C. The calculated haul distance corresponding to the critical internal temperature of 105°C was approximately 5.8 km.

The regression models were statistically validated within the following experimental ranges:

$$\begin{aligned} 3,53 \leq L \leq 8,94 \text{ km} \\ 14,62 \leq V \leq 17,86 \text{ km/soat} \\ 3,30 \leq i \leq 7,24\% \\ 3 \leq T_a \leq 38^{\circ}\text{C} \end{aligned}$$

Calculations outside these limits should be regarded as extrapolative predictions.

Under the tested conditions, with haul distances of up to 5 km and payloads of 225–230 t, the internal temperature of Bridgestone MasterCore VREM E1A tires did not exceed the critical limit. When the haul distance exceeds 5.8 km, enhanced thermal monitoring is required. On hot routes of 7 km or longer, the use of tires with greater heat resistance, such as E3A tires, is recommended.

Under the operating conditions of the Muruntau mine, ambient temperatures of up to 25°C were considered optimal, while the range of 25–33°C was assessed as conditionally safe. When the ambient temperature exceeds 33°C, continuous monitoring and restrictions on operating speed, haul distance, and payload should be introduced.

To ensure safe tire operation, KODA monitoring data should be cross-validated periodically against thermocouple measurements. Continuous inflation-pressure monitoring, control of longitudinal road grades and curve radii, and reductions in payload and operating speed during the hot season are also recommended. Operational restrictions should be established according to the thermal condition of the rear tires, as they are subjected to the highest operating temperatures.

Based on the research findings, recommendations were developed for the safe operation of OTR tyres under sharply continental climatic conditions.

Table 2. Recommendations for the safe operation of OTR tyres considering ambient temperature.

№	Ambient temperature	Assessment	Recommendation
1	$T_a \leq 20^{\circ}\text{C}$	Most favourable thermal conditions	Normal operation
2	$20 < T_a \leq 25^{\circ}\text{C}$	Optimal operating range	Standard monitoring
3	$25 < T_a \leq 30^{\circ}\text{C}$	Conditionally safe zone	Monitor tyre pressure and temperature
4	$30 < T_a \leq 33^{\circ}\text{C}$	Approaching the critical threshold	Reduce operating speed and haul distance
5	$33 < T_a \leq 38^{\circ}\text{C}$	Thermally hazardous zone	Implement continuous monitoring and tyre-cooling measures
6	$T_a > 38^{\circ}\text{C}$	Very high thermal risk	Review the haul route and loading regime

By the end of the second quarter of 2026, the average service life of the 50/80R57 Bridgestone MASTERCORE tires installed on KOMATSU 860E-1K haul trucks reached 49,804 km, representing an increase of approximately 5.4% compared with the average tire service life recorded in 2025 (47,250 km). This improvement indicates the effectiveness of haul-route optimization and demonstrates the practical performance benefits of the MASTERCORE VREM technology under actual operating conditions.

The implementation of the developed organisational and technical recommendations for improving tire utilisation at the Muruntau mine reduced operating costs by UZS 1013 per kilometre. Based on the estimated annual operating volume, the resulting annual economic benefit amounted to UZS 607.8 million per haul truck.

Acknowledgments

The authors acknowledge the Central Mining Administration of Navoiy Mining and Metallurgical Company and the technical specialists of Bridgestone for their valuable support during the field measurements conducted at the Muruntau open-pit mine. This paper is part of the PhD research by Quvondiq Urinboev.

Author contributions

Umiddbek Yusupov: supervision, resources. Gayrat Ubaydullaev: spelling and grammar checking as well as virtual validation. Barno Kenjayeva: writing-original draft preparation. Quvondiq Urinboev: conceptualization, methodology, data curation, investigation, analysis, validation, writing-reviewing and editing.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate

Not applicable.

Consent for publication

Informed consent to publish was obtained from all participants involved in the study.

Competing interests

The authors declare no competing interests.

References

- [1] S. Ma, C. Fan, and W. V. Liu, "Effects of site operating conditions on real site TKPH (tonne-kilometer-per-hour) of ultra-large off-the-road tires," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 8, pp. 2227–2239, 2024, doi: 10.1177/09544070231166166.
- [2] S. Ma, L. Wu, and W. V. Liu, "Numerical investigation of temperatures in ultra-large off-the-road tires under operating conditions at mine sites," *Journal of Thermal Science and Engineering Applications*, vol. 15, no. 2, Art. no. 021010, 2023, doi: 10.1115/1.4056086.
- [3] S. Ma, G. Huang, K. Obaia, S. W. Moon, and W. V. Liu, "Hysteresis loss of ultra-large off-the-road tire rubber compounds based on operating conditions at mine sites," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 236, nos. 2–3, pp. 439–450, 2022, doi: 10.1177/09544070211015525.
- [4] J. Hyttinen, M. Ussner, R. Österlöf, J. Jerrelind, and L. Drugge, "Truck tyre transient rolling resistance and temperature at varying vehicle velocities—Measurements and simulations," *Polymer Testing*, vol. 122, Art. no. 108004, 2023, doi: 10.1016/j.polymertesting.2023.108004.
- [5] A. Mujdeci, V. M. Rodriguez, H. Maqbool, A. Amadeo, and M. Grasso, "Advances in numerical modelling of tyre fatigue performance: A review," *Journal of Materials Science: Materials in Engineering*, vol. 20, Art. no. 105, 2025, doi: 10.1186/s40712-025-00315-7.
- [6] A. Shakenov, A. Śladowski, and I. Stolpovskikh, "Haul road condition impact on tire life of mining dump truck," *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 6, pp. 25–29, 2022, doi: 10.33271/nvngu/2022-6/025.
- [7] H. Fathi, Z. El-Sayegh, J. Ren, and M. El-Gindy, "Analysis of tire–road interaction: A literature review," *Machines*, vol. 12, no. 11, Art. no. 812, 2024, doi: 10.3390/machines12110812.
- [8] Y. Li, W. Y. Liu, and S. Frimpong, "Effect of ambient temperature on stress, deformation and temperature of dump truck tire," *Engineering Failure Analysis*, vol. 23, pp. 55–62, 2012, doi: 10.1016/j.engfailanal.2012.02.004.
- [9] J. Marais and G. Venter, "Numerical modelling of the temperature distribution in the cross-section of an earthmover tyre," *Applied Mathematical Modelling*, vol. 57, pp. 360–375, 2018, doi: 10.1016/j.apm.2018.01.018.
- [10] W. Nyaaba, S. Frimpong, and A. Anani, "Fatigue damage investigation of ultra-large tire components," *International Journal of Fatigue*, vol. 119, pp. 247–260, 2019, doi: 10.1016/j.ijfatigue.2018.07.009.
- [11] U. Yusupov and X. Shavkatov, "Development of a standard mileage for large-sized tires under moderately severe quarry conditions," *BIO Web of Conferences*, 2024, doi: 10.1051/bioconf/202414104034.
- [12] U. Kuvondik, R. Zilola, and I. Mashrab, "Improvement of the classification of causes for the decommissioning of large-size tires," *Vibroengineering Procedia*, 2025, doi: 10.21595/vp.2025.24964.
- [13] M. Israilov and U. Yusupov, "Determining the weight of factors affecting the TKPH of large-sized tires," *E3S Web of Conferences*, 2025, doi: 10.1051/e3sconf/202562705010.
- [14] S. Ma, G. Huang, K. Obaia, S. W. Moon, and W. V. Liu, "A novel phenomenological model for predicting hysteresis loss of rubber compounds obtained from ultra-large off-the-road tires," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 237, no. 1, 2023, doi: 10.1177/09544070211072494.
- [15] M. G. Lipsett and R. Vaghar Anzabi, "Seasonal effects on haul truck tyre life," *International Journal of Strategic Engineering Asset Management*, vol. 1, no. 3, pp. 316–327, 2013, doi: 10.1504/IJSEAM.2013.056327.
- [16] J. R. Cho, H. W. Lee, W. B. Jeong, K. M. Jeong, and K. W. Kim, "Numerical estimation of rolling resistance and temperature distribution of 3-D periodic patterned tire," *International Journal of Solids and Structures*, vol. 50, no. 1, pp. 86–96, 2013, doi: 10.1016/j.ijsolstr.2012.09.004.
- [17] R. Behnke and M. Kaliske, "Thermo-mechanically coupled investigation of steady state rolling tires by numerical simulation and experiment," *International Journal of Non-Linear Mechanics*, vol. 68, pp. 101–131, 2015, doi: 10.1016/j.ijnonlinmec.2014.06.014.
- [18] T. Tang, D. H. Johnson, R. E. Smith, and S. D. Felicelli, "Numerical evaluation of the temperature field of steady-state rolling tires," *Applied Mathematical Modelling*, vol. 38, no. 5–6, pp. 1622–1637, 2014, doi: 10.1016/j.apm.2013.08.033.
- [19] J. Hyttinen, R. Österlöf, J. Jerrelind, and L. Drugge, "A semi-physical thermodynamic transient rolling resistance model with nonlinear viscoelasticity," *Mechanics of Time-Dependent Materials*, vol. 28, no. 3, pp. 895–916, 2024, doi: 10.1007/s11043-023-09650-8.
- [20] J. Hyttinen, R. Österlöf, L. Drugge, and J. Jerrelind, "Constitutive rubber model suitable for rolling resistance simulations of truck tyres," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 237, no. 1, pp. 174–192, 2023, doi: 10.1177/09544070221074108.
- [21] T. C. Nguyen, T. M. H. Le, and H. H. Nguyen, "Rolling tires on the flat road: Thermo-investigation with changing conditions through numerical simulation," *Applied Sciences*, vol. 13, no. 8, Art. no. 4834, 2023, doi: 10.3390/app13084834.
- [22] F. Farroni and A. Sakhnevych, "Tire multiphysical modeling for the analysis of thermal and wear sensitivity on vehicle objective dynamics and racing performances," *Simulation Modelling Practice and Theory*, vol. 117, Art. no. 102517, 2022, doi: 10.1016/j.simpat.2022.102517.
- [23] K. Xing, P. Cheng, Q. Wang, and H. Li, "Optimal design of radial tire section layout based on thermal fatigue life improving," *Heliyon*, vol. 10, Art. no. e22864, 2024, doi: 10.1016/j.heliyon.2023.e22864.
- [24] X. Li, J. Han, X. Dai, Z. Zheng, and Y. Niu, "Monitoring overloaded trucks with infrared thermal imaging of tire sidewall," *Heliyon*, vol. 10, no. 14, Art. no. e34358, 2024, doi: 10.1016/j.heliyon.2024.e34358.
- [25] M. Greiner, H. J. Unrau, and F. Gauterin, "A model for prediction of the transient rolling resistance of tyres based on inner-liner temperatures," *Vehicle System Dynamics*, vol. 56, no. 1, pp. 78–94, 2018, doi: 10.1080/00423114.2017.1343955.
- [26] J. Ejsmont, G. Ronowski, W. Owczarzak, and S. Sommer, "Temperature influence on tire rolling resistance measurements quality," *International Journal of Automotive Technology*, vol. 23, no. 1, pp. 109–123, 2022, doi: 10.1007/s12239-022-0009-y.
- [27] H. S. Aldhufairi and O. A. Olatunbosun, "Developments in tyre design for lower rolling resistance: A state of the art review," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 232, no. 14, pp. 1865–1882, 2018, doi: 10.1177/0954407017727195.

- [28] V. Boykov, and M. Israilov, "Optimizing TKPH for Large-Sized Tires in Quarry Conditions," *Lecture Notes in Networks and Systems*, 2025, doi: 10.1007/978-3-031-95649-2_33.
- [29] A. Mukhitdinov, S. Tukhtamishov, and Q. Urinbayev, "Results of the study of the influence of an average longitudinal slope of routes on the life of tires in the quarry," *AIP Conference Proceedings*, 2024, doi: 10.1063/5.0197301.
- [30] Off-the-Road Tire Data Book. Tokyo, Japan: Bridgestone Corporation, 2024.



Umidbek Yusupov is a Doctor of Technical Sciences and Professor specializing in *Wheeled and tracked vehicles and their operation*. His research focuses primarily on the operation of mining haul trucks, improving the reliability and service life of large off-the-road (OTR) tires, developing methodologies for predicting tire life under open-pit mining conditions, and enhancing the efficiency of haulage operations. His scientific work includes the assessment of tire thermal behavior, the investigation of the effects of operational factors on tire service life, and the development of mathematical and regression models for evaluating and predicting tire performance.



Gayrat Ubaydullaev holds a Candidate of Technical Sciences degree and conducts research in the field of *Manufacturing engineering technology*. His scientific work is primarily focused on improving manufacturing and repair technologies, advancing quality control methods for the assembly of repaired products, and enhancing the efficiency and reliability of technological processes in manufacturing enterprises. He is actively engaged in research on the optimization of manufacturing and repair processes for machinery and equipment, the implementation of modern diagnostic and quality control methods, the assessment of the reliability of technological systems, and the investigation of factors affecting product quality.



Barno Kenjayeve is a Senior Lecturer specializing in transport logistics and management. Her research activity is primarily focused on the development of a strategic management mechanism for urban public transport, aiming to enhance the efficiency, quality, and sustainability of passenger transportation in modern urban systems. She is actively engaged in research related to public transport optimization, strategic transit planning, route network management, and the implementation of digital technologies into transport governance. Her scientific interests include urban mobility, transport economics, sustainable infrastructure development, and the integration of intelligent transport management systems.



Quvondiq Urinboev is a PhD researcher whose scientific work focuses primarily on the operation of mining haul trucks, improving the reliability and service life of large off-the-road (OTR) tires, and enhancing the efficiency of haulage operations in open-pit mines. His research is centered on evaluating the thermal behavior of OTR tires, investigating the influence of operational factors on tire service life, and developing mathematical and regression models for predicting and assessing tire performance under mining conditions.