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Designing the Target Neutral Temperature for Continuous Welded Rail via CUTHI-IDW Spatial Interpolation of Climatological Data

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Abstract

A methodology is proposed to design target neutral temperature of continuous welded rail when direct rail-temperature measurements are unavailable. The approach relies exclusively on historical ambient-temperature records from Mexican climatological stations and a linear relationship between rail and ambient temperatures. Extreme ambient temperatures are spatially interpolated along the railway alignment using the Clusters Unifying Through Hiding Interpolation method. The resulting continuous surface of target neutral temperature is then discretised into uniform segments suitable for construction planning. The methodology is applied to a 100.6 km railway alignment in north-eastern Mexico, using records from 15 climatological stations within a 25 km buffer. Results show that the target neutral temperature varies between 33.4 and 35.0 °C along the alignment. A discretisation interval of 0.5 °C yields five segments with four distinct values, offering a practical balance between thermal resolution and construction feasibility. A comparison between classic Inverse Distance Weighting and the Clusters Unifying Through Hiding Interpolation variant confirms that differences are below 0.5 °C, validating the robustness of the interpolation. The proposed

desk-based methodology provides a practical and reproducible tool for the early design stages of railway projects where field instrumentation is not yet available.

Keywords: continuous welded rail, stress-free temperature, neutral temperature, target neutral temperature, spatial interpolation, inverse distance weighting, clusters unifying through hiding interpolation, climatological data, geospatial analysis

1 Introduction

Continuous welded rail (CWR) is the standard track configuration for modern railway lines. Since rail joints are eliminated by welding, the continuous rail strings are constrained from expanding or contracting freely. Consequently, significant longitudinal thermal stresses develop as the rail temperature deviates from the temperature at which it was initially fixed in position. In this context, it is important to distinguish three key concepts:

- Fixation temperature (T_{fix}): the actual temperature at which the rail is fastened into position.
- Stress-free temperature, or neutral temperature (T_{sf}): the temperature at which the rail experiences zero longitudinal thermal stress. It fundamentally depends on the actual fixation temperature, T_{fix}.
- Target neutral temperature (T_N): the designed temperature at which the rail should be fixed in position to ensure zero longitudinal stress. Ideally, it should equal the stress-free temperature, but in practice, exact equivalence is difficult to achieve. To account for this, standards such as ADIF NAV 7-1-4.1 [1] impose a constructive tolerance (e.g., $|T_N - T_{sf}| \leq 3$ °C). Its definition depends on the extreme temperatures of the region under analysis.

When the rail temperature exceeds T_{sf} the rail is in compression and, if the compressive force is large enough, lateral track buckling may occur. Conversely, when the rail temperature falls well below T_{sf}, tensile stresses may cause rail fracture [2, 3].

The correct determination of T_N is therefore a fundamental task in the design and maintenance of CWR track. According to the Spanish railway infrastructure standard ADIF NAV 7-1-4.1 [1], the target neutral temperature is calculated as:

$$T_N = \frac{T_{r,\max} + T_{r,\min}}{2} + 5\,^{\circ}\mathrm{C} \tag{1}$$

where $T_{r,\max}$ and $T_{r,\min}$ are the maximum and minimum rail temperatures expected over the service life of the track, corresponding to the hottest summer and coldest winter on record, respectively.

In practice, obtaining $T_{r,\max}$ and $T_{r,\min}$ requires long-term field measurements of rail temperature at representative locations along the alignment. Such measurements are seldom available during the early design stages of new railway projects, particularly in countries where dedicated rail-temperature monitoring networks have not been established. This situation creates a practical gap: the target neutral temperature must be specified for construction, yet the data needed to compute it rigorously are not available.

The relationship between ambient (air) temperature and rail temperature has been studied extensively. Chapman et al. [4] showed that rail temperature depends on air temperature, solar radiation, wind speed, humidity and cloud cover. Hunt [5] proposed a simple empirical model for estimating elevated rail temperatures from air temperature. More sophisticated approaches based on heat-transfer physics have been developed by Zhang and Lee [6] and the US Federal Railroad Administration [7] and Frigeri [8]. Data-driven models using machine learning [9] and a methodology for long-term continuos monitoring of welded rail in cold areas [10] have also been proposed. However, all these methods require either concurrent measurements of rail and ambient temperatures for calibration, or detailed meteorological variables beyond simple air temperature.

This paper proposes a desk-based methodology for designing target neutral temperature along a railway alignment when field measurements of rail temperature are not yet available. The approach combines: (i) a simplified linear relationship between rail and ambient temperatures; (ii) historical ambient-temperature records from national climatological networks; and (iii) a cluster-aware spatial interpolation technique to produce a continuous spatial value of T_N along the alignment. The methodology is demonstrated through a case study on a 100.6 km alignment in north-eastern Mexico.

2 Methodology

The proposed methodology calculates T_N at every point along a railway alignment using only historical ambient-temperature records. It consists of four stages: (1) establishing the rail–ambient temperature relationship; (2) obtaining extreme ambient temperatures from climatological stations; (3) spatially interpolating extreme temperatures along the alignment; and (4) discretising the continuous T_N surface into uniform construction segments.

2.1 Rail–ambient temperature relationship

The starting point is the assumption that average rail temperature can be related to ambient temperature through a simplified linear model, based in the experimental findings of Aldolex [11] that reported a strong linear correlation between rail temperatures and its difference to ambient temperature. This assumption takes into consideration that Equation (1) only needs average of $T_{r,\max}$ and $T_{r,\min}$, then it is proposed that in average rail temperature is expressed as:

$$T_{r,average} \approx T_a + 10\,^{\circ}\mathrm{C} \tag{2}$$

where $T_{r,average}$ is the rail temperature and T_a is the ambient temperature at the same location and time. Although the actual relationship is nonlinear and influenced by multiple environmental factors [4], Equation (2) provides a reasonable first-order approximation, particularly for the purpose of estimating average extreme values rather than instantaneous predictions.

Substituting the extreme values into Equation (1):

$$T_{r,\max} = T_{a,\max} + 10\,^{\circ}\mathrm{C}, \qquad T_{r,\min} = T_{a,\min} + 10\,^{\circ}\mathrm{C} \tag{3}$$

and taking into account that the constant offsets are averaged:

$$T_N = \frac{(T_{a,\max} + 10\,^{\circ}\mathrm{C}) + (T_{a,\min} + 10\,^{\circ}\mathrm{C})}{2} + 5\,^{\circ}\mathrm{C} = \frac{T_{a,\max} + T_{a,\min}}{2} + 15\,^{\circ}\mathrm{C} \tag{4}$$

Equation (4) expresses the target neutral temperature purely as a function of extreme ambient temperatures, which are widely available from national climatological networks in most countries.

2.2 Extreme ambient temperatures from climatological records

Let there be n climatological stations in the vicinity of the railway alignment. For each station i, let $\{T_{a,\max}^{(i,k)}\}$ and $\{T_{a,\min}^{(i,k)}\}$ denote the historical monthly records of maximum and minimum ambient temperature, where k ranges over all available months.

To obtain a representative extreme value free from outliers caused by instrumental errors or transcription mistakes, the interquartile range (IQR) method is applied independently to each station. For $T_{a,\max}$, the first quartile Q_1 and third quartile Q_3 are computed, and records exceeding $Q_3 + 1.5 \times$ IQR are discarded; the maximum of the remaining values is taken as the representative extreme $\hat{T}_{a,\max}^{(i)}$. An analogous symmetric procedure is applied to $T_{a,\min}$ to obtain $\hat{T}_{a,\min}^{(i)}$.

2.3 Spatial interpolation of extreme temperatures

To estimate extreme temperatures at any point $\mathbf{x}$ along the alignment, a spatial interpolation method is required. The inverse distance weighting (IDW) method [12] is a natural choice, as it assigns greater influence to nearby stations. According to Benmoshe [13], classical IDW can produce biased estimates when stations are unevenly distributed or clustered, because nearby stations in a cluster each contribute a large weight, effectively over-representing the cluster's temperature value.

To address this limitation, the Clusters Unifying Through Hiding Interpolation (CUTHI) variant proposed by Benmoshe [13] is adopted. In this method, the interpolated value at a point $\mathbf{x}$ is:

$$\hat{T}(\mathbf{x}) = \sum_{i=1}^{n} W_i(\mathbf{x})\, \hat{T}^{(i)} \Bigg/ \sum_{i=1}^{n} W_i(\mathbf{x}) \tag{5}$$

where the combined weight W_i incorporates both distance and angular occlusion:

$$W_i(\mathbf{x}) = w_i^{\text{IDW}}(\mathbf{x}) \cdot c_i(\mathbf{x}) \tag{6}$$

The IDW weight is defined as:

$$w_i^{\text{IDW}}(\mathbf{x}) = \frac{1}{d(\mathbf{x}, \mathbf{x}_i)^p} \tag{7}$$

where $d(\mathbf{x}, \mathbf{x}_i)$ is the Euclidean distance between the interpolation point and station i, and p is the distance exponent. The cluster-correction factor is:

$$c_i(\mathbf{x}) = \prod_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{\cos\big(\alpha_{ij}(\mathbf{x})\big) + 1}{2} \right)^{s} \tag{8}$$

where $\alpha_{ij}(\mathbf{x})$ is the angle at station j between the line from $\mathbf{x}$ to j and the line from i to j, and s is the cluster exponent. When a station i is hidden behind another station j as seen from $\mathbf{x}$, the angle approaches zero, driving c_i towards zero and reducing the hidden station's influence.

This interpolation is applied separately to $\hat{T}_{a,\max}$ and $\hat{T}_{a,\min}$ over a regular grid covering a buffer zone around the alignment. The target neutral temperature at each grid cell is then computed using Equation (4).

2.4 Discretisation and segmentation

The continuous surface of T_N is not directly applicable for construction, as the rail must be fixed at a single prescribed temperature within a given track section. Therefore, the continuous T_N values along the alignment are discretised by rounding to the nearest multiple of a chosen interval Δ:

$$T_{N,\text{disc}}(\mathbf{x}) = \Delta \cdot \text{round}\left(\frac{T_N(\mathbf{x})}{\Delta} \right) \tag{9}$$

Consecutive points along the alignment with the same discretised value are grouped into segments. Segment boundaries are refined by linear interpolation between adjacent sampling points where the discretised value changes. The resulting segmentation defines the regions along the alignment where a uniform target neutral temperature should be prescribed.

Several values of Δ may be evaluated to determine the best balance between thermal resolution and the number of construction segments.

3 Case study

The methodology is applied to a railway alignment located in north-eastern Mexico, in the state of Nuevo León. The alignment corresponds to a segment of Mexican Saltillo–Nuevo Laredo railway corridor.

3.1 Alignment description

The horizontal alignment was obtained from a LandXML file exported from AutoCAD Civil 3D. The geometry comprises 147 segments: 38 tangents, 37 circular curves and 72 transition spirals (clothoids). The main characteristics are:

- Initial kilometre post: km 159+349.04.
- Final kilometre post: km 259+912.61.
- Declared length: 100,563.6 m.
- Discretised geometric length: 100,564.5 m (discrepancy: +0.9 m, 0.0009%).

The small discrepancy is attributable to the polyhedral approximation of spiral and circular segments and is negligible for the purposes of the thermal analysis.

3.2 Climatological data source

In Mexico, the National Water Commission (Comisión Nacional del Agua, CONAGUA) manages a comprehensive database comprising over 5,400 climatological stations across the country's 32 federal states, of which approximately 2,800 remain active. Monthly records of temperature extremes (maximum and minimum) are publicly accessible through the National Meteorological Service internet site . The dataset for each station provides essential metadata—such as geographical coordinates, elevation, and municipality—alongside tabulated monthly values detailing historical temperature extremes, mean temperatures, the period of record, and the specific dates of extreme events.

Data acquisition was automated using a Python script to access the state-level catalogs and retrieve the individual station files. A total of 5,512 files were obtained, corresponding to 5,355 unique stations with valid temperature records. This dataset reflects the state of the database as of March 2026.

The records were consolidated into a single dataset containing 247,841 monthly entries across 23 fields. The IQR-based outlier removal procedure described in Section 2.2 was applied independently to each station, yielding representative values of $\hat{T}_{a,\max}$ and $\hat{T}_{a,\min}$ for all 5,355 stations.

3.3 Station selection

A buffer of 25 km was generated around the alignment geometry in the UTM Zone 14N coordinate system (EPSG:32614). Stations were projected to the same coordinate system, and their distance to the nearest point on the alignment was computed. Fifteen stations were found within the search radius, distributed between the states of Nuevo León (13 stations) and Coahuila de Zaragoza (2 stations).

The selected stations span the following ranges:

- Distance to alignment: 1.9 to 24.4 km (mean 13.9 km).
- $\hat{T}_{a,\max}$: 40.0 to 50.0 °C (mean 47.0 °C).
- $\hat{T}_{a,\min}$: -12.0 to -4.0 °C (mean -9.1 °C).

3.4 Interpolation parameters and results

The CUTHI-IDW interpolation was performed on a regular grid with 100 m resolution within a 10 km buffer around the alignment. The grid comprised 410 columns and 1,169 rows, of which 232,233 cells fell within the buffer. The interpolation parameters were set to $p = 2$ (distance exponent) and $s = 0.5$ (cluster exponent), following the recommendation of Benmoshe [13].

For comparison, the classical IDW method of Shepard [12] (without cluster correction) was applied with the same parameters and grid. Table 1 summarises the interpolation results for both methods. CUTHI-IDW produces surfaces with slightly greater local variability (higher standard deviation), which is theoretically more realistic in areas of uneven station distribution.

	$T_{a,\max}$ (°C)		$T_{a,\min}$ (°C)	
	CUTHI-IDW	IDW	CUTHI-IDW	IDW
Min	42.37	43.82	−12.00	−12.00
Mean	46.96	47.04	−9.26	−9.42
Max	48.50	48.50	−5.61	−6.81
Std	1.18	0.81	1.34	0.96

Table 1: Interpolated extreme ambient temperatures over the buffer zone: CUTHI-IDW versus classical IDW.

4 Results and discussion

4.1 Target neutral temperature along the alignment

Using Equation (4), the target neutral temperature T_N was computed at each grid cell from the CUTHI-IDW interpolated surfaces of $\hat{T}_{a,\max}$ and $\hat{T}_{a,\min}$. The differences between the two methods are small: the mean difference is 0.04 °C for T_N, with a maximum of 0.44 °C. Since this maximum difference is smaller than the finest discretisation interval evaluated (0.5 °C), the choice of interpolation method has limited impact on the final practical result unless finer resolution is needed in the future. Figure 1 presents a visualization of both interpolation methods, including climatological stations.

The resulting T_N field along the alignment varies between 33.4 and 35.0 °C, with a mean of 33.9 °C and a standard deviation of 0.58 °C. This relatively narrow range indicates thermally homogeneous conditions along the 100.6 km corridor, which is consistent with the alignment's geographical setting within a semi-arid region at similar elevations.

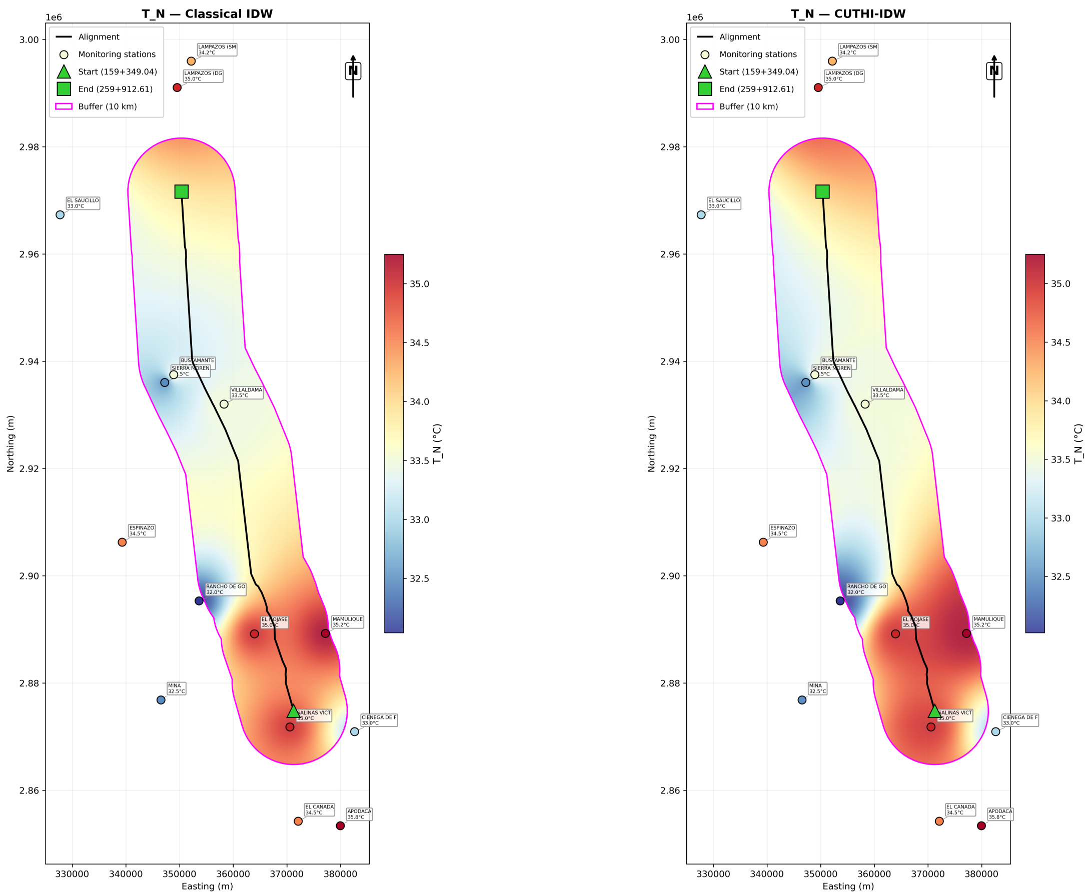

Figure 1: T_N interpolated with traditional IDW and CUTHI-IDW.

4.2 Discretisation scenarios

The continuous T_N profile was sampled at 2,013 points spaced every 50 m along the alignment. Four discretisation intervals were evaluated; the results are summarised in Figure 2 and Table 2.

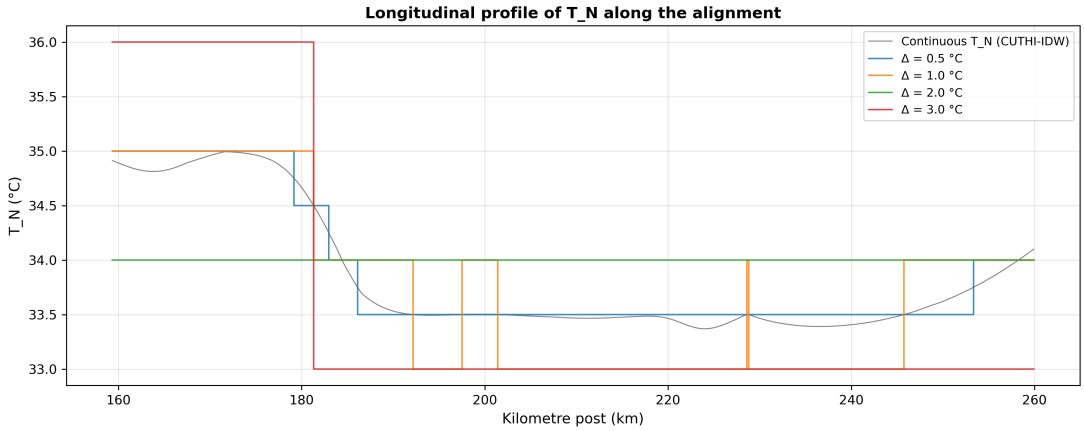

Figure 2: Discretisation scenarios for T_N along the alignment.

Δ (°C)	Regions	Distinct values	Dominant value
0.5	5	4	33.5 °C (66.8%, 67.2 km)
1.0	8	3	33 °C (49.2%, 49.4 km)
2.0	1	1	34 °C (100.0%, 100.6 km)
3.0	2	2	33 °C (78.2%, 78.6 km)

Table 2: Summary of discretisation scenarios for T_N along the alignment.

The $\Delta = 1.0$ °C discretisation produces an excessive number of regions (8), because the continuous T_N profile oscillates around 33.5 °C, which lies exactly at the boundary between two integer values, generating frequent transitions. The coarser discretisations ($\Delta = 2$ °C and 3 °C) oversimplify the thermal variability.

The $\Delta = 0.5$ °C discretisation is recommended: it captures the dominant value of 33.5 °C (which closely matches the continuous mean) and produces only five segments, a manageable number for construction planning. The resulting segmentation is presented in Table 3.

4.3 Discussion

The proposed methodology has several practical advantages. It can be applied at the early design stage, before any field instrumentation has been deployed, using only

Segment	Start kilometre post	End kilometre post	Length (km)	T_N (°C)
1	km 159+349.04	km 179+167.67	19.82	35.0
2	km 179+167.67	km 182+971.29	3.80	34.5
3	km 182+971.29	km 186+108.86	3.14	34.0
4	km 186+108.86	km 253+326.39	67.22	33.5
5	km 253+326.39	km 259+912.61	6.59	34.0

Table 3: Recommended segmentation of the alignment ($\Delta = 0.5\,°\text{C}$).

publicly available ambient-temperature records. The computational pipeline is fully automated and reproducible: data retrieval, outlier filtering, spatial interpolation and segmentation are performed using open-source tools (Python, GeoPandas, Shapely).

The main limitation is the simplified linear relationship between rail and ambient temperatures (Equation 2). This approximation is adequate for estimating extreme values, where the average offset between rail and ambient temperature is relatively stable, but would require calibration if applied in regions with significantly different solar exposure, wind conditions or rail cross-sections. Incorporating field measurements of rail temperature, when available, would allow the methodology to be upgraded to a two-level model with location-specific regression coefficients.

The CUTHI-IDW interpolation method offers a theoretical improvement over classical IDW by reducing the over-representation of clustered stations. In this case study, the practical impact was modest (maximum difference of 0.44 °C), but it could be more significant in regions with highly irregular station distributions.

It is important to note that the results presented herein constitute a desk-based case study. No field measurements of rail temperature were available for this project, so the entire analysis was performed using ambient-temperature data. The values of T_N obtained should be treated as preliminary estimates to be refined once rail-temperature measurements become available during the detailed-design or construction phase.

5 Conclusions

This study proposed a methodology for estimating the target neutral temperature of continuous welded rail using historical ambient-temperature records and spatial interpolation, completely bypassing the need for field measurements of rail temperature. As an initial approximation, the target neutral temperature can be expressed as a direct function of extreme ambient temperatures by assuming a linear relationship, formulated as $T_N = (T_{a,\max} + T_{a,\min})/2 + 15\,°\text{C}$. To apply this across a given route, the CUTHI-IDW interpolation method is utilized, producing spatially continuous estimates of extreme temperatures along the alignment. This approach captures slightly greater local variability than classical IDW at a negligible additional computational cost.

When applied to a 100.6 km railway alignment in north-eastern Mexico using data from 15 climatological stations, the methodology yielded T_N values ranging from 33.4 to 35.0 °C. By implementing a discretisation interval of 0.5 °C, the alignment was effectively divided into five segments featuring four distinct values, with $T_N = 33.5\,°\mathrm{C}$ dominating 66.8% of the total length.

Ultimately, this methodology provides a practical, reproducible, and low-cost tool suitable for the early design stages of railway projects, particularly in regions lacking dedicated rail-temperature monitoring. Future work should aim to incorporate field measurements of rail temperature to calibrate location-specific regression models, replacing the current global offset assumption with empirically determined coefficients.

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