Investigation of Mechanical Performance for Railway Tracks Elastic Components in Extreme weather Conditions: A Literature Review

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Abstract

Extreme weather conditions present unique challenges to the mechanical behavior of elastic materials under railway dynamic loading. For designers, operators, and maintenance teams in railway projects, understanding how temperature variations impact material performance is crucial throughout a project's lifecycle. Deviations from specified temperature limits can compromise system integrity, potentially leading to failures and catastrophic events like rail vehicle derailments or track shutdowns. This issue has become increasingly relevant due to climate change, which exposes railway tracks to temperature variations beyond their original design specifications. In this literature review, we explore the behavior of elastic track components, focusing on materials such as polyurethane on extreme weather conditions. Our goal is to examine how the unique properties of these materials affect the overall track structure and propose strategies to mitigate issues arising from unusual temperatures like extreme cold conditions. Our findings show that changing of the material composition can enhance safety margins, ensuring that railway track systems maintain performance and reliability even in the harshest environments.

Introduction

Discussions about global warming and climate change are prevalent in the media, among the public, and in scientific literature. It can be said that these topics are headline news worldwide. In Canada, the average temperature increased by 1.7°C from 1948 to 2016[1], which is more than twice the global average increase of 0.8°C for the same period[2]. It is important to note that this change has not been smooth over the years, with winters warming more significantly than summers. During this period, the average temperature increased by 3.3°C in winter, 1.7°C in spring, 1.5°C in summer, and 1.7°C in autumn (Figure 1). The greatest annual increase occurred in the northwest, where temperatures rose by 3°C, while northern Canada saw an increase of about 2.3°C. Additionally, reduced snow cover and earlier snowmelt are further indicators of warming in Canada[3].

Figure 1. Seasonal temperature change across Canada from 1948 to 2016 [1]

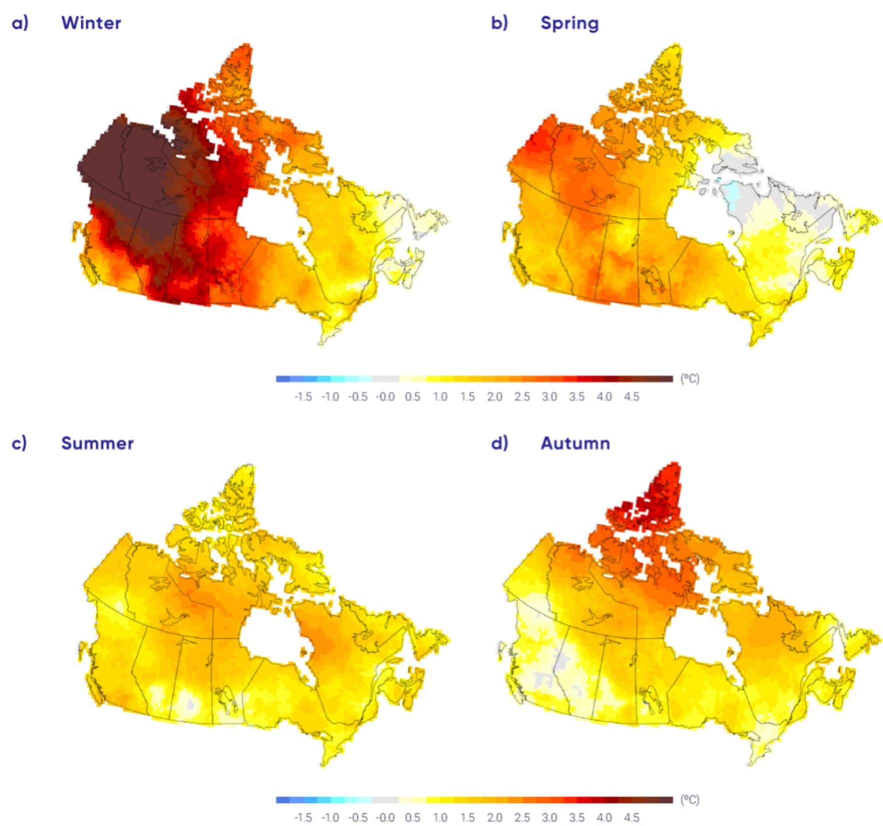


Table 1. Changes in annual and seasonal mean temperature from 1948 to 2016 for six regions and for all Canadian land [3]

Region	Change In Temperature,˚C				
	Annual	Winter	Spring	Summer	Autumn
British Columbia	1.9	3.7	1.9	1.4	0.7
Prairies	1.9	3.1	2.0	1.8	1.1
Ontario	1.3	2.0	1.5	1.1	1.0
Quebec	1.1	1.4	0.7	1.5	1.5
Atlantic	0.7	0.5	0.8	1.3	1.1
Northern Canada	2.3	4.3	2.0	1.6	2.3
Canada	1.7	3.3	1.7	1.5	1.7

On the other hand, a common misconception is that global warming only leads to higher temperatures and heatwaves. However, evidence shows that disruptions in the stratospheric polar vortex (SPV) are making extreme cold waves more frequent in North America and parts of Asia. The February 2021 Texas cold wave was one of the severe examples of this phenomenon.[4]

The definition of extreme cold varies by region. In southern Ontario, extreme cold is considered when the temperature or wind chill is forecasted to reach -30°C for at least two hours. In Southeastern Ontario, Southern Interior and Coastal B.C., and Atlantic Canada (excluding Labrador), the threshold is -35°C. For Central Interior B.C., Northern Ontario, and the Prairies (Alberta, Southern Saskatchewan, Southern Manitoba), the limit is around -40°C. In Northern Ontario, Northern Saskatchewan, Northern Manitoba, Northern B.C., and Labrador, it is considered -45°C. In Quebec, the threshold is -38°C for Western, Central, and Eastern areas, while it is -48°C for Northern Quebec.[5] It should be noted that these values are typically used to restrict human activities to temperatures below these thresholds. However, in many instances, extremely cold temperatures can affect the performance of systems such as railway transportation.

Climate Change on Railway Transportation

There are numerous studies and discussions on how climate change will impact railway transportation. Most of these focus on events like floods, heatwaves, storms, tornadoes, and even permafrost. These issues are specific to the regions where railroads pass through, and the primary approach is to develop countermeasures to mitigate their negative effects on infrastructure and operations. For example, in the case of extreme winds or flooding, the only option for a rail operator is to halt operations until conditions return to normal. Similarly, a sun kink, which often occurs during heat waves, can cause injuries, fatalities, and property damage, leading to operational delays.[6]

While the impact of extreme weather on track components remains uncertain, numerous studies have examined track buckling and track stability during extreme heat[7]. Conversely, there are studies on rail fractures during cold snaps or extreme cold conditions. In North America, rail fractures are most prevalent at the onset of winter when the tensile stress is approximately half of the rail's yield stress.[8]

While there is extensive information available on rails, other track components have not been given the same consideration. This study aims to provide an overview of the impact of extreme weather conditions on the resilient and elastic components of railway tracks, which are often overlooked. The goal is to identify the adverse effects of climate change on these components, enabling railway authorities to upgrade or replace them with more durable materials.

Typical Track Cross Sections in North America and Elastic Components

In North America, numerous rail operators and authorities are involved in the railway industry, each developing their own standards and requirements for their regions. The most prominent ones are AREMA[9] in the US, and CN[10] and GTS[11] in Canada, which serve as primary references for other standards.
Based on these standards, there are two types of ballasted tracks in their railway networks: wood-tie and concrete tie ballasted track. Most railway tracks are constructed with wooden ties. However, due to environmental considerations and sustainable design requirements, many authorities have decided to use concrete ties for new and renewed tracks. Despite this shift, many railways still use wooden ties, and some authorities, like CN, continue to prefer them. However, they developed required standards for concrete ties too.

Concrete ties are heavier and can provide much more track stability and are more durable than wood ties, but less elastic than wood ties and it needs to add another element to provide more elasticity to avoid of concrete damage from impact loads which is usually rail pads[12]. Thus, in GTS[13], AREMA[14] and CN, using rail tie pad for concrete ties is necessary (Figure 2 to Figure 4). Given that Polyurethane is the approved material type for rail tie pads in Canada [13] (Figure 5), this study will primarily focus on Polyurethane as the dominant material.

Figure 2. Ballasted track section with concrete tie as per GTS[15] and CN[16]

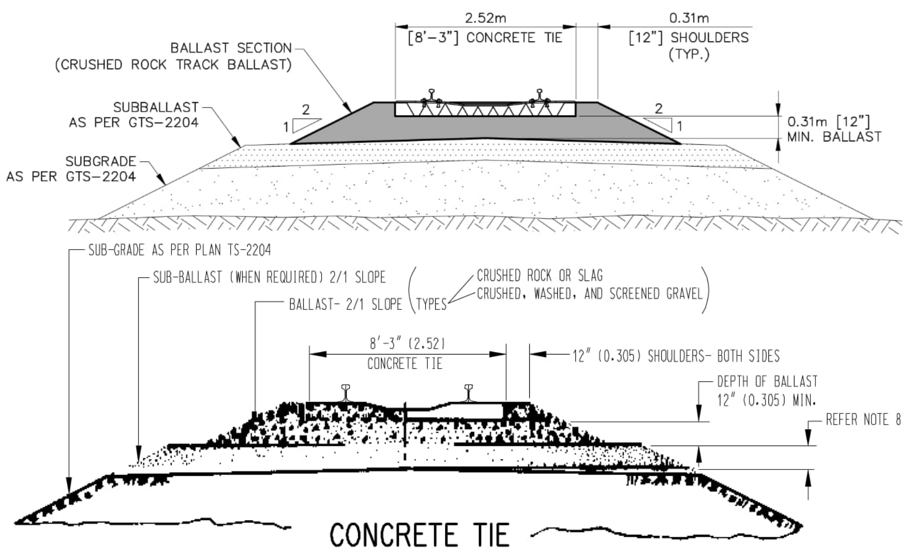


Figure 3. concrete tie Specification as per GTS[17]

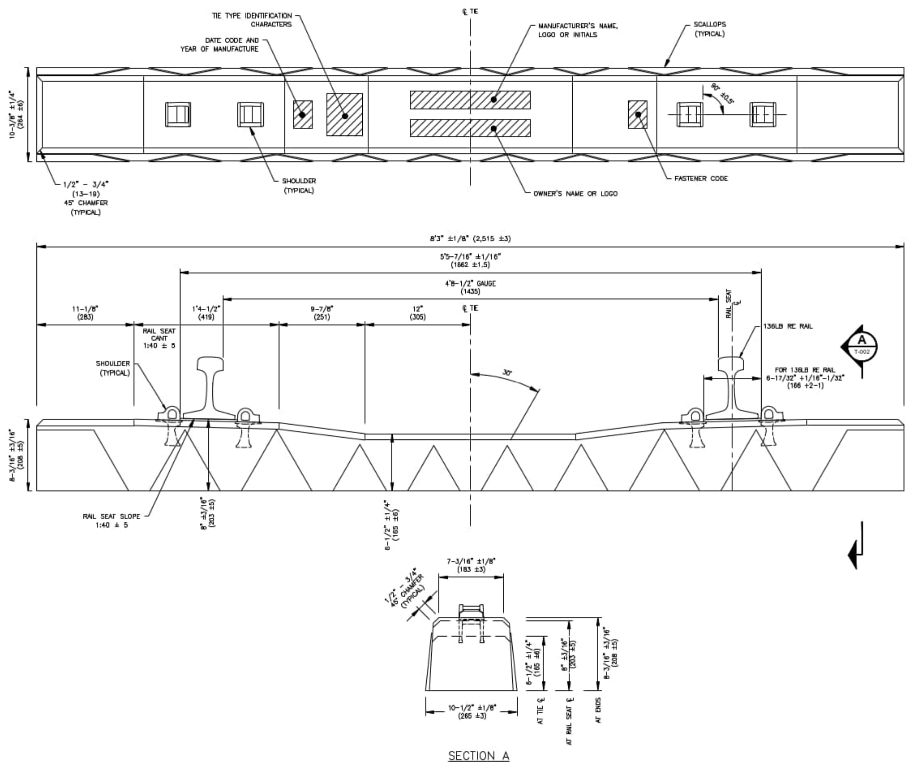


Figure 4. Concrete tie Specification as per CN[18]

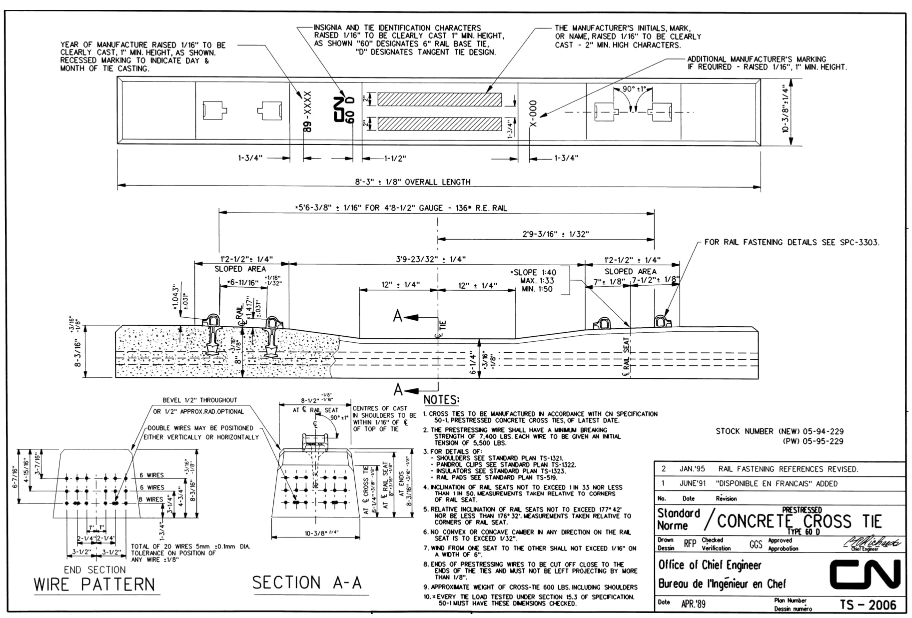
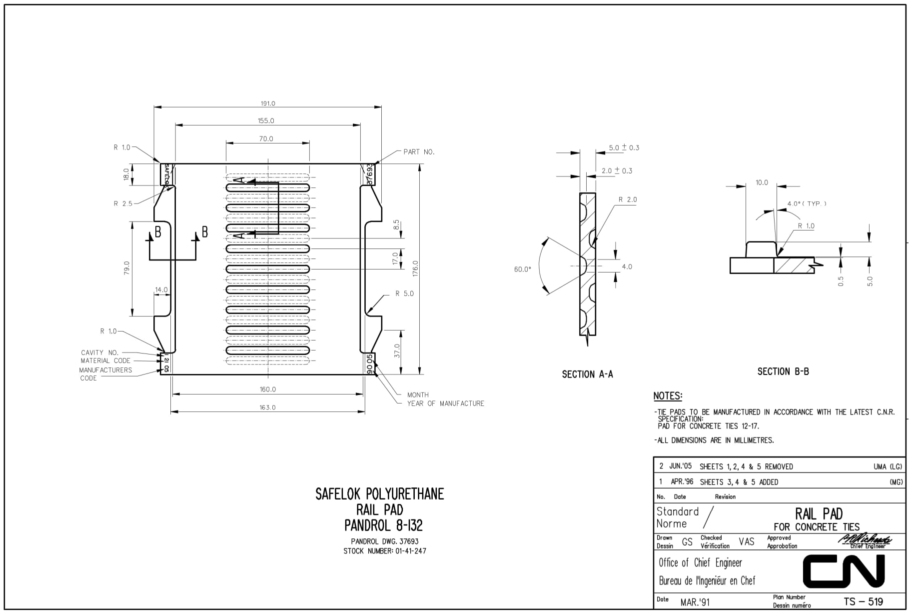


Figure 5. Concrete Tie Pad Specification as per GTS[19] and CN[20]



The other resilient materials used in railway track structure is under-ballast mat and under-tie pads. According to the Metrolinx General Guidelines for Design of Railway Bridges and Structures[21], most bridges should be equipped with ballast mats. This includes all new bridges, rehabilitated bridge decks where the ballast will be removed, and the top face of roof slabs of pedestrian tunnels or concrete culverts with less than 1.0m of fill between the underside of the tie and the top of the structure. Consequently, over time, ballast mats should be installed on all railway bridges in this area. However, some standards, such as those from CN, do not mandate the use of ballast mats. AREMA provides specifications for resilient track components[22], which are primarily used in transition zones.

In summary, the spread of concrete ties in North America suggests that rail pads will become dominant in track structures. The use of under sleeper pads will be limited to special areas with specific requirements, while under ballast mats are expected to be used for all bridges in the near future and could be an option for transition zones.

In this study, given the significance of rail tie pads and ballast mats in the North American rail industry, we will examine these materials and their behavior in extreme weather conditions.

Materials used in rail tie pads and ballast mats

In railway industry the wide range of the material are used for rail tie pads, regarding the requirements and available materials. The most employed materials around the world are Ethylene Vinyl Acetate (EVA), High-Density Polyethylene (HDPE), Polyurethane, and Natural Rubber (NR) or rubber composites and recycled materials.[23]
In north America, Polyurethane pads in conjunction with nylon 6/6 are mostly used because of its abrasion resistance and impact attenuation for rail pads.[24]
In Canada, one of the approved materials for under ballast mats is closed-cell polyurethane, commonly referred to as PU foam [21].

Review of Previous Studies

Numerous studies have examined the behaviour of under tie pads under railway loading, but most have overlooked the impact of temperature on their mechanical properties. In some research, it is merely noted that temperature affects the mechanical behaviour of rail tie pads [24].

Chang Su Woo et al conducted tests on rubber pads to determine the effect of temperature on their behavior, revealing significant changes in properties such as stiffness. However, the temperatures considered in the study were all above zero, excluding extreme cold or freezing conditions.[25]

Shurpali et al investigated the mechanics of rail seat deterioration and proposed methods to improve the abrasion resistance of concrete sleeper rail seats, focusing on polyurethane pads and their behavior over time and aging. While considering temperature effects, only the rail temperature was measured during the tests.[26]

Zhihao Zhai et al developed a meshed-type rail pad and investigated its response in extremely cold environments. Their work utilized a nonlinear model that considered temperature effects as a significant factor.[27]

Xiaogang Gao et al investigated the effects of temperatures ranging from −70°C to 50°C and various frequencies, discovering that the stiffness of elastic pads in fastener systems is particularly sensitive to low temperatures and high frequencies.[28]

Kai Wei et al conducted a series of tests on the WJ-8 fastening system at temperatures ranging from −60°C to 20°C and compared the results with the FDKV (fractional derivative Kelvin–Voigt) model. Similar to Xiaogang Gao's findings, they discovered that the storage stiffness and loss factor of the tested rail pad are sensitive to low temperatures.[29]

Jing Guoqing et al discovered in their studies on polyurethane-reinforced ballasted tracks that polyurethane foam can lose up to 70% of its retention rate of tensile strength and elongation at break when exposed to low temperatures, specifically at -20°C.[30]

Impact of Extreme Cold Weather on Polyurethane Pads and Mats

Despite the widespread use of polyurethane pads and mats in railway tracks, their performance can be significantly impacted by extreme cold weather, primarily due to the glass transition temperature (T_g) of the material. The glass transition temperature is a critical thermal property of polymers, including polyurethanes, representing the temperature range below which the polyurethanes are glassy materials, losing their elastomeric properties result higher mechanical strength (Figure 6) like higher modulus, stiffness and lower attenuation. It should be noted that high cross-linked polyurethane has the minimum sensitivity to temperature changes.[31]

This parameter is challenging to address theoretically due to its nonunique nature. It is totally dependent on the Polyurethane composition. For polyurethanes, this transition is influenced by the polymer's composition[32]. Additionally, the glass transition is not defined by a single temperature but rather by a temperature region, which can have a finite and sometimes substantial breadth.

Figure 6. General Variation of Modulus 3G for Different Polyurethanes Across Various Temperatures [31].

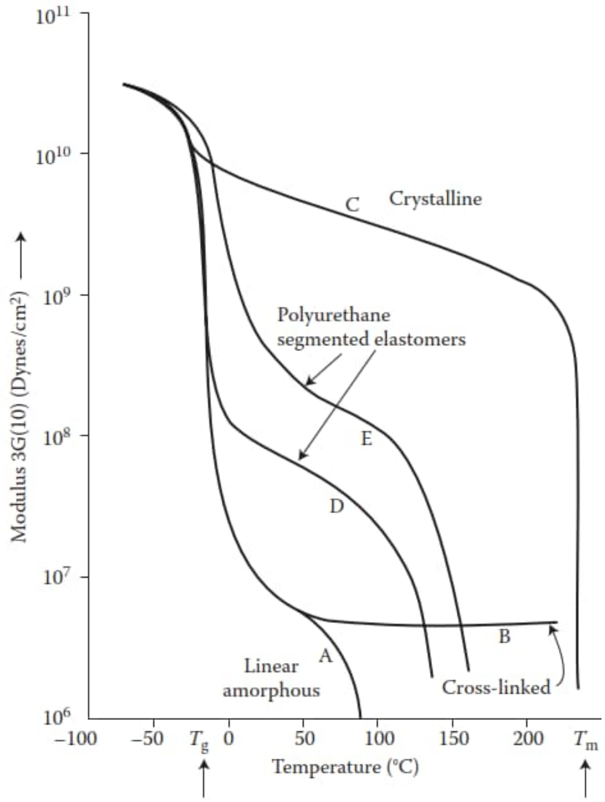
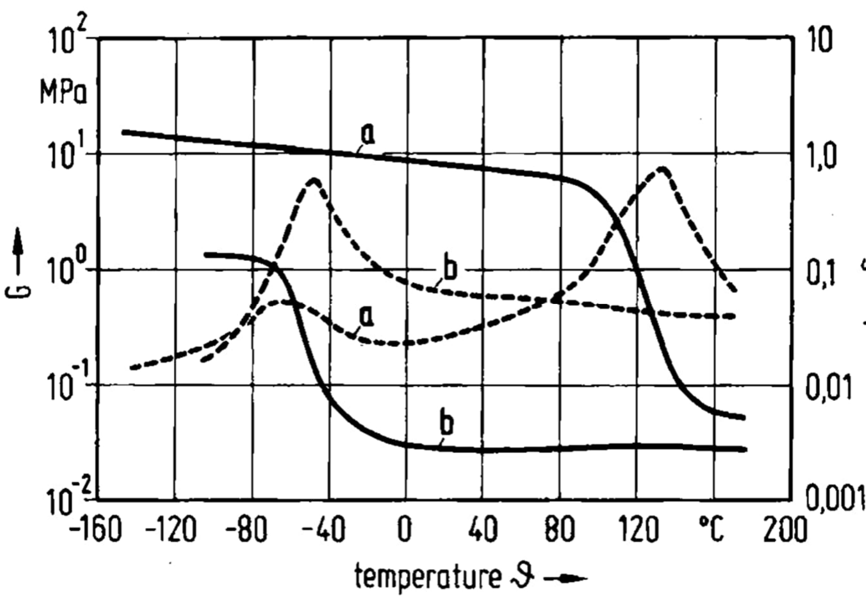


Table 2. Effect of Polyurethane composition on Glass Transition Temperature [32]

Composition (Percent)	T_g (˚K) (expt.)	T_g (˚K) (calc.)	T_g (˚K) (av.)
100% PU	209	-	-
75% PU / 25% PA	246	234	249
50% PU / 50% PA	274	267	288
25% PU / 75% PA	321	317	327
100% PA	367	-	-

This statement also applies to polyurethane foams. However, the glass transition region for polyurethane foams is broader compared to the rigid polyurethane used in rail tie pads. In this temperature range, the material exhibits rubber-like elasticity. It becomes softer compared to its glassy state and is capable of undergoing reversible elastic deformation.[33]

Figure 7. Example of shear modulus(G)/damping(δ) – temperature curve. a = rigid polyurethane foam, b = flexible polyurethane foam [33].

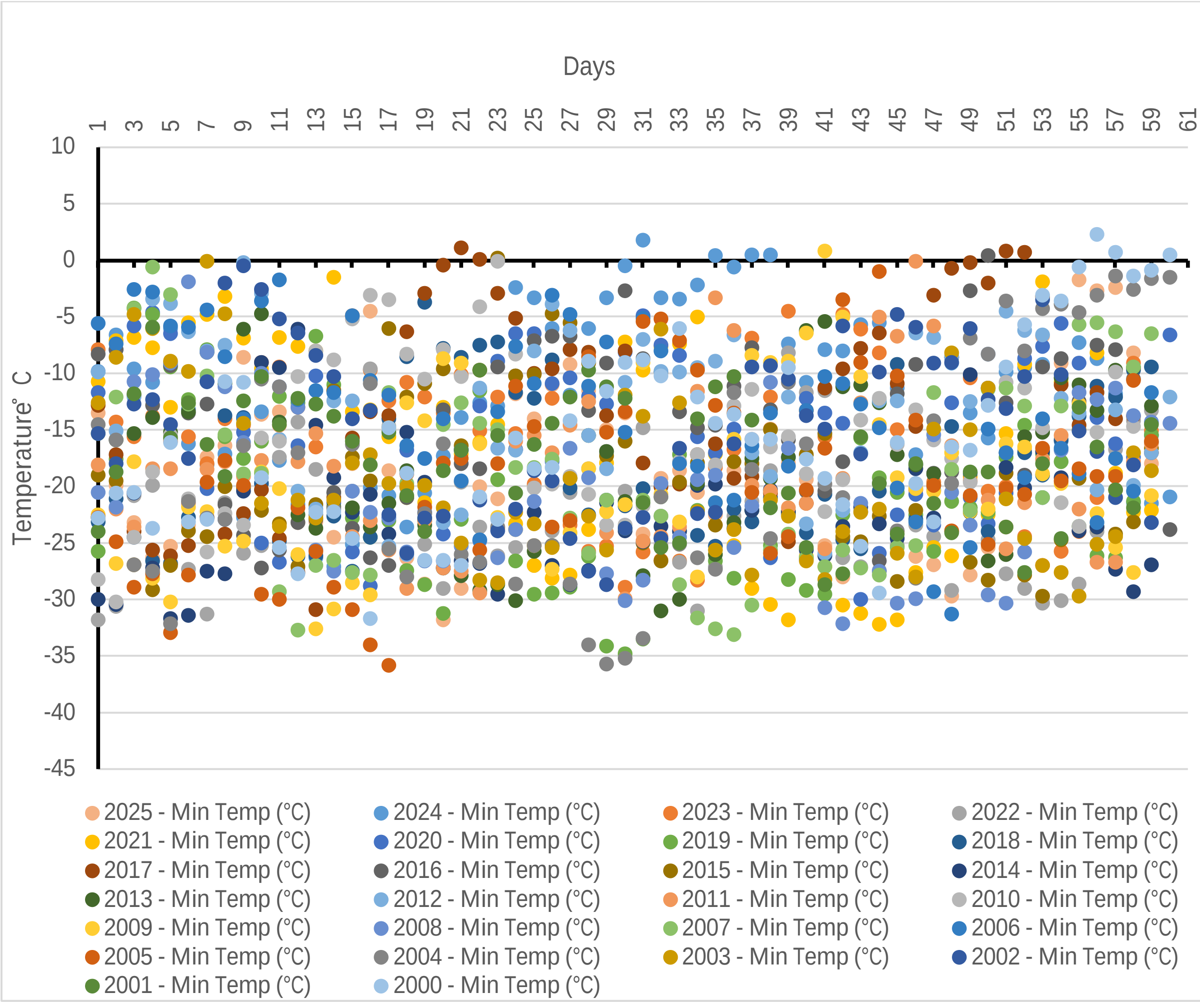


Impact of Extreme Cold Weather on Track Behavior in North America and Canada

Numerous polyurethane rail tie pads have been installed across various railway tracks in Canada and North America, and the same applies to polyurethane under ballast mats. In many regions across North America, railway tracks endure extreme cold weather annually. For instance, Winnipeg, a city in Canada's cold region with railway connections spanning the entire country, has recorded temperatures at Forks Weather Station from January and February each year from 2000 to 2025, as shown in Figure 8[34].

These records pertain to Winnipeg, demonstrating that temperatures of -30°C are common in the city. It is important to note that temperatures in remote and outdoor areas are likely to be much lower than those recorded within the city, due to factors such as wind and the absence of human activities in these locations.

Figure 8. Minimum Temperature record from January and February each year from 2000 to 2025 [34]



Track mechanical behavior can be affected by temperature variations. As discussed in previous sections, low temperatures can alter the mechanical properties of the track by increasing the stiffness and/or attenuation of rail tie pads. This may lead to load redistribution within the track structure or a higher likelihood of rail seat deterioration in concrete ties [26].

The modulus of elasticity of rail support defined within the "beam on elastic foundation" theory. Track Modulus is the force required to depress 1 inch of a continuous rail length through a distance of 1 inch. Track Modulus is generally stated in units of "lb/in/in."[35]

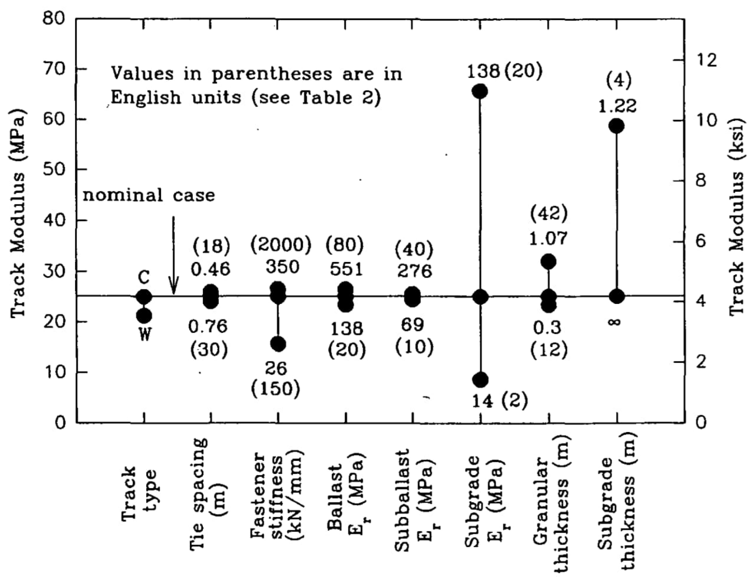
Typical track modulus values for some tie configurations in main-line track are given below[36]:

- Wood-tie track, after tamping k = 1,000 lb/in^2
- Wood-tie track, compacted by traffic k = 3,000 lb/in^2
- Plastic composite-tie track, compacted by traffic k = 3,000 lb/in^2
- Concrete-tie track, compacted by traffic k = 6,000 lb/in^2
- Wood-tie track, frozen ballast and subgrade k = 9,000 lb/in^2

It is noteworthy that, according to AREMA, there is a significant difference between the track modulus of concrete-tie tracks under normal conditions and wood-tie tracks in extreme cold weather. Consequently, a concrete-tie track in frozen conditions may exhibit a much higher track modulus.

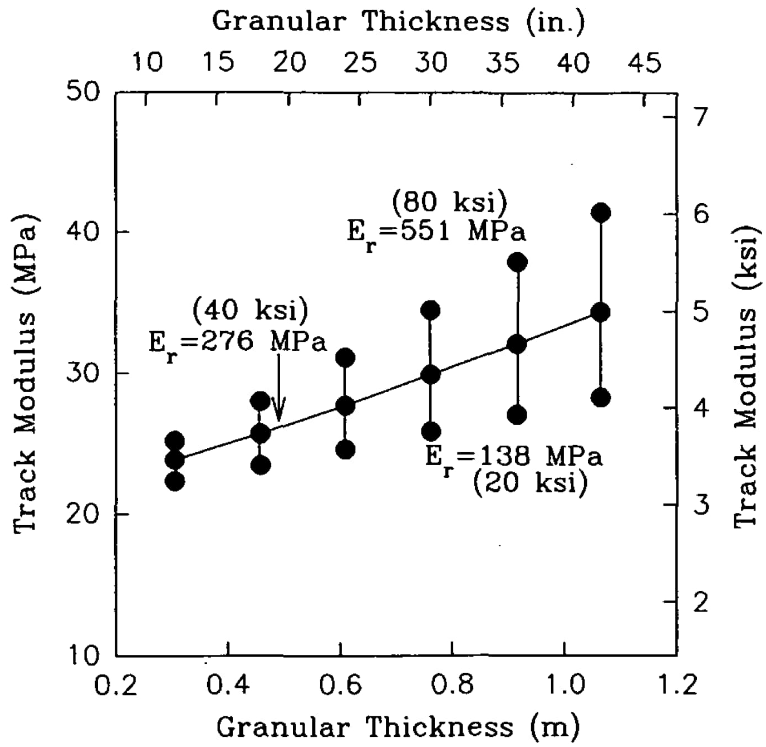
Considering the similar conditions of frozen ballast and subgrade for both concrete-tie and wood-tie tracks, the primary components influencing track behavior are the rail tie pads[37] or under ballast mats. Figure 9 illustrates the influence of each component of the track structure on the overall track modulus. According to this diagram, the track modulus increases significantly with the rise in fastener stiffness. In other words, after subgrade specifications, the next most important factor influencing track modulus is the stiffness of the fasteners, which is provided by the rail tie pads. [37].

Figure 9 -Impact of track component on track modulus [37]



The same principle applies to the under-ballast mat. Integrating the modulus of the under-ballast mat with the ballast modulus, as a granular material, can alter the track modulus. Figure 10 demonstrates how variations in the thickness or modulus of granular materials can impact the overall track modulus.

Figure 10 – Effects of granular layer thickness and modules on track modulus [37]



This implies that using an under-ballast mat in areas with extreme cold conditions can alter the track modulus, potentially negatively impacting track behavior and railway structures, particularly for under-ballast mats on bridges.

Increasing the track modulus can lead to several serious problems in both the short and long term. These issues include rail seat deterioration [37], an increased incidence of rail cracking[38], concrete tie cracking, as well as accelerated fatigue of rail fasteners and degradation of rail pads. Moreover, in transition zones - such as approaches to bridges or tunnels - a sudden increase in track modulus can disrupt the smooth stiffness transition. This discontinuity in modulus can introduce additional dynamic loads and stresses into both the track structure and the bridge, thereby exacerbating track degradation and increasing maintenance demands [37]. Each of these issues can pose operational or maintenance risks to the railway system, potentially resulting in revenue loss or compromising safety.

Conclusion

In this study, the current condition of railway tracks across North America and Canada has been reviewed. It has been observed that the impacts of climate change, particularly the occurrence of extreme cold conditions, can significantly affect track structure behavior, leading to increased maintenance costs and heightened safety risks. As climate change progresses, such challenges are expected to become more frequent. Therefore, it is essential for railway authorities to implement a comprehensive strategy to address these issues, which may include:

- Revising the temperature performance range for pads and mats: The current temperature testing range specified by AREMA is from -20°C to 70°C [14], whereas GTS[39] specifies a range from -40°C to 70°C. As a result, pads approved under AREMA standards may not be suitable for use in cold regions in certain cases across Canada.

- Developing performance testing procedures for fastening assemblies under cold region conditions to better evaluate their behavior and reliability in environments that replicate actual field conditions.
- Developing new materials for rail tie pads and under-ballast mats that maintain consistent mechanical properties under extreme cold conditions.

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