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Influence of climate changes on railway superstructure

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Subject review

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Weather conditions significantly impact transportation systems, particularly in terms of safety, mobility, accessibility, economic efficiency, and infrastructure resilience. Currently, approximately 27 % of the world's road and rail infrastructure is exposed to at least one type of damaging weather condition. The extent to which rail infrastructure is affected by climate change largely depends on its geographic location. Climate change poses a serious risk to rail transport, with the potential to disrupt operations or bring them to a complete standstill. This paper examines the effects of extreme weather conditions, including high and low temperatures, strong wind gusts, snow and ice, as well as flooding, on the superstructure of ballasted tracks. It also highlights measures that can mitigate the adverse impacts of climate change on railway infrastructure. Furthermore, it emphasizes the importance of regular track inspections, the adoption of advanced railway monitoring methods, and thorough track condition assessments following extreme weather events.

Key words:
railway infrastructure, ballasted track, climate change, high temperatures, flooding, track monitoring

Pregledni rad

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Utjecaj klimatskih promjena na elemente gornjeg ustroja kolosiječne konstrukcije

Vremenski uvjeti imaju velik utjecaj na prometne sustave, pogotovo na sigurnost, mobilnost, pristupačnost, ekonomsku učinkovitost te infrastrukturu. Trenutačno je oko 27 % cestovne i željezničke infrastrukture na cijelome svijetu izloženo opasnosti od barem jedne vremenske nepogode. To kojim će klimatskim promjenama željeznička pruga biti izložena ovisi ponajprije o njezinoj lokaciji. Klimatske promjene mogu ugroziti tijek željezničkog prometa ili ga u cijelosti prekinuti. U ovome je radu analiziran utjecaj niskih i visokih temperatura, olujnih naleta vjetra, snijega i leda te poplava na elemente gornjeg ustroja kolosiječne konstrukcije sa zastornom prizmom i na kontaktnu mrežu elektrificiranih pruga. U radu su također navedene neke od mjera kojima se može djelovati na smanjenje štetnih posljedica koje će klimatske promjene uzrokovati na kolosijeku te je objašnjena važnost redovitog monitoringa kolosijeka, primjene novih metoda monitoringa te kontrole stanja kolosijeka nakon ekstremnih vremenskih uvjeta.

Ključne riječi:
željeznička infrastruktura, kolosijek sa zastornom prizmom, klimatske promjene, visoke temperature, poplave, monitoring kolosijeka

1. Introduction

Since 1850, the average global temperature has increased by 0.76 °C, while the average temperature in Europe has increased by almost 1 °C [1]. Existing climate change models show that the average annual temperature over Europe will increase between 1 °C and 5.5 °C during the 21st century and that extreme heat waves will occur with increasing frequency [2, 3]. Furthermore, it is assumed that the annual amount of precipitation will increase in the north and decrease in the south of Europe, while the intensity of daily precipitation and the probability of extreme precipitation will increase in all European regions [3]. It is expected that the mean wind speed will increase in the northern parts of Europe, and it will decrease in the Mediterranean, while extreme wind speeds will be higher in Western and Central Europe and near the North Sea [3]. An increased amount of precipitation during longer periods will mostly lead to fluvial (river) floods, while shorter and more intense precipitation will cause pluvial floods, i.e., flooding of urban areas, the main cause of which is extreme rainfall. River floods are a common natural disaster in Europe and, together with storms, have resulted in numerous victims and caused huge economic losses in the last three decades [4, 5]. Climate change is being increasingly observed within the territory of the Republic of Croatia, where trends of temperature increase are recorded, with the highest daily temperatures above 35 °C becoming more frequent. In most parts of Croatia, a significant decrease in the total amount of precipitation have been noticed. The exception are the eastern parts of Croatia, where the total amount of precipitation in the mentioned 50-year period has increased, primarily due to an increase in the frequency of very intense precipitation during autumn [6]. The intensity and duration of dry periods is increasing significantly, and previous analyses show an increase in atmospheric instability, due to which the frequency of extremely strong winds, the frequency of short-term large amounts of precipitation in certain locations, as well as the frequency of extreme thunderstorms and hail are increasing [6].

Weather conditions have a major influence on transport systems, especially on safety, mobility, accessibility, economic efficiency, but also on the infrastructure itself, which is why it is necessary to take care of their sustainability [7, 8]. According to [9], nowadays around 27 % of the road and railway infrastructure in the whole world is exposed to the danger of at least one weather hazard. Globally expected annual maintenance costs due to direct weather-related damage to road and rail transport systems range from 3.1 to 22 billion US dollars, of which about 73 % is caused by surface water and river flooding [9]. In the paper [10], maintenance costs caused by extreme weather conditions in several European countries (United Kingdom, Austria, Czech Republic, Germany, Italy and Switzerland) were analyzed. Three main impacts were analyzed: ice and snow, floods and rain, and storms. It was found that of the total annual costs, 80 % of the costs were caused by damage to the road infrastructure, while only 2.7 % are the costs of the railway infrastructure. The remaining 17.3 % of the costs are incurred in other forms of transport. These costs will be different in different parts of Europe as not all countries are exposed to the same weather hazards. The costs of maintaining road and railway infrastructure due to damage caused by high temperatures are analyzed in detail in the paper [11]. It was established that when it comes to the effect of high temperatures, the road infrastructure is exposed to greater risk due to the harmful effect of high temperatures on the asphalt. According to the projections, it was established that the annual costs of maintaining road and railway infrastructure in the European Union and the United Kingdom will increase by 0.9 billion euros with a global warming of 1.5 °C and up to 4.8 billion euros with a temperature increase of 4 °C. Of the stated amount, road infrastructure causes the majority of these costs: 0.8 billion euros for 1.5 °C, while for an increase of 4 °C this amount would be 3.3 billion euros [11]. On the other hand, railway infrastructure recorded a lower increase in costs: 0.1 billion euros for 1.5 °C, and 1.5 billion euros for 4 °C. However, although when designing the railway infrastructure, its resistance to high temperatures must be ensured, extreme temperature values such as those present in recent years exponentially increase the probability of the track buckles, which increases the need for maintenance [11].

Although currently the costs caused by extreme weather conditions are lower in rail transport than in road transport, it is extremely important to take into account the harmful effects of climate change when talking about rail transport, given that

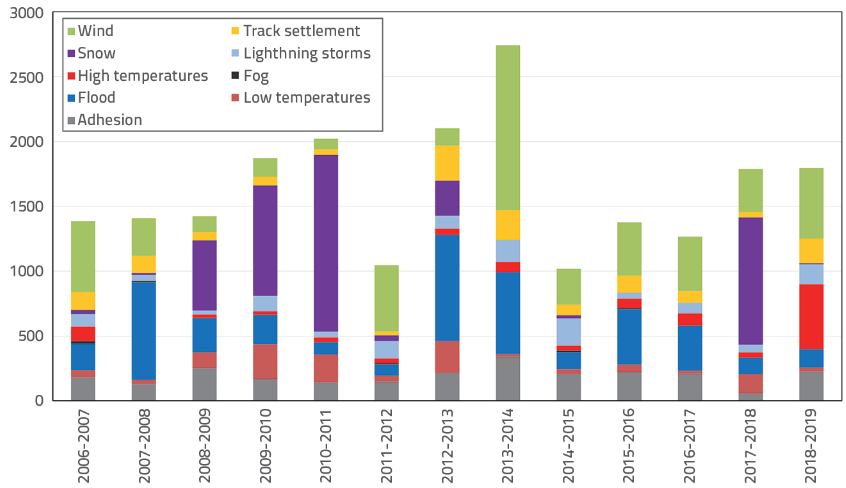

Figure 1. The number of train delays recorded in various periods, the reason for the delay being different adverse weather conditions [16]

it is becoming an increasingly important form of transport worldwide. Especially after the electrified railway has been recognized as convincingly the least polluting of all types of public transport. The development and use of railway transport will be increasingly encouraged in order to ensure environmental protection, which was confirmed by the fact that the European Parliament declared 2021 the European Year of Rail [12]. The electrified railway is also a key factor in achieving the goals of the European Green Deal, a guideline of the European Commission for a sustainable economy whose goal is to reduce the emission of harmful gases by up to 90 % by 2050 [13].

Weather conditions have a negative impact on the railway infrastructure, and the most harmful effect on the elements of track superstructure have high temperatures that can cause rail buckling, while large amounts of precipitation can have a harmful effect on drainage systems [14, 15]. Strong wind gusts have a negative effect on the contact network of the track structure, but also on high-speed passenger trains, as well as on empty freight wagons. Extreme weather conditions cause traffic problems, train delays, and in extreme cases can result in service disruption. Figure 1 shows the number of train delays recorded in the period from 2006 to 2019, caused by different weather conditions.

The negative effects of climate change have also been reported on the railway infrastructure in Croatia, where track buckling have occurred due to very high temperatures (Figure 2). Also, there was a case of a forest fire caused by brake sparks. The large amounts of precipitation in 2014 that caused the embankment of the Sava River to break and floods in the area of Slavonia, resulted in major damage to the superstructure and the substructure, where the torrent of water carried away parts of the ballast bed and embankment material, and in some places damage of the entire superstructure was also reported (Figure 3) [17].

For these reasons, when designing new railway lines, climate changes to which the railway will be exposed to must also be considered, especially the effects of increasing temperatures, windstorms, as well as extreme amounts of precipitation resulting in floods [19]. Regarding the existing railways, it is important to pay attention to adapting the railway to climate change. Most of the current railways were built several decades ago to cater to society's need for mobility and to facilitate quicker freight transport. Nonetheless, the current railway infrastructure is subject to rising traffic loads due to the escalating demands of passengers and freight transport. This, when combined with extreme climate conditions, is resulting in heightened degradation [20, 21].

The railway infrastructure in the Republic of Croatia was constructed during the 19th and early 20th centuries, necessitating modernization. This modernization is currently a strategic goal of the Croatian government to enhance safety, traffic speed, and transport and throughput capacity [18]. During this modernization, it is vital to factor in climate change and to explore methods for adapting the railway to the new climatic conditions it will face.

The research presented in paper [20] found that many railways infrastructure operators have acknowledged climate change as a factor contributing to track structure degradation. They are increasingly aware of the detrimental effects climate change may have on railway operations and are considering measures to avert or lessen these effects.

To highlight the threats posed by climate change to railway infrastructure, this paper analyzes the impact of weather hazards on the components of the ballasted railway superstructure. In addition, several protective measures have been defined to minimize the adverse effects of climate change on the railway. Chapter 4 highlights the importance of regular track monitoring to maintain good track characteristics and the importance of urgent track

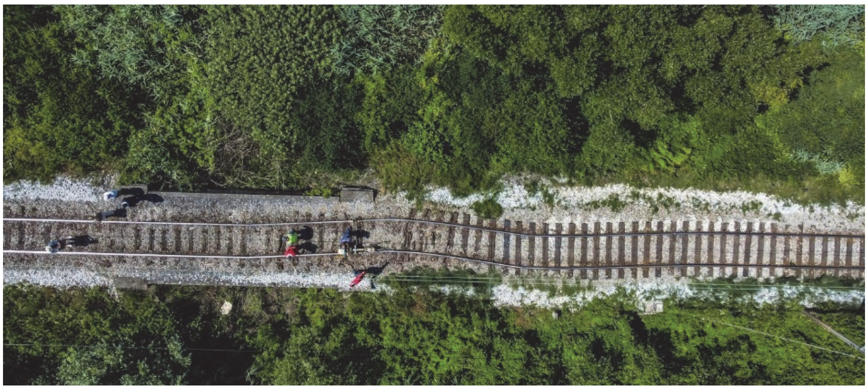
Figure 2. The condition of the M103 Dugo Selo - Novska railway section following the effects of high temperatures [18]


Figure 3. The state of the railway superstructure after the flood on the R105 Vinkovci – Drenovci – state border railway sectiona [17]

inspection following extreme weather conditions to detect potential damage to the railway.

2. Influence of climate changes on railway superstructure

Railway infrastructure is sensitive to extreme weather conditions such as high and low temperatures, heavy precipitation and floods, rising sea levels, strong winds [22]. Extreme winds and snowstorms can cause snowdrifts on rail infrastructure during winter and disrupt train services. On the other hand, heat waves can lead to rail and track buckling, thus causing disruption of service and in extreme cases resulting in derailment. Figure 4 illustrates the probability of damage to railway structure due to different weather conditions, showing that snow and ice cause the most damage to railway turnouts, while storms can cause damage to the track overhead contact lines and to signaling system [23].

The paper [23] analyzed the probability of an adverse event occurring on the track or a specific track component at various degrees of low and high temperatures and snowfall. It was established that the adverse event will almost certainly occur if the air temperature exceeds 35 °C or falls below -12 °C, and if the snowfall exceeds the value of 50 mm/d (Table 1).

Due to climate change, the costs of maintaining the railway structure will increase. Published paper [24] looked at track maintenance costs under normal weather conditions as well as under conditions when the track is exposed to flooding and high temperatures, considering only direct costs and not indirect costs such as delays and interruptions to train services. The effects of flooding were found to increase maintenance costs by 22 % and the effects of high temperatures by 15 %.

2.1. The effects of extremely high temperatures

2.1.1. Rails

Although railway structures are designed to withstand large temperature differences, very high temperatures can cause rail buckling due to the creation of large compressive forces resulting from the expansion of the steel, which is especially pronounced in the case of continuously welded rails (CWR) [25-27]. Using CWR on railway structures has proven beneficial in various ways, including reduced expenses for track and vehicle maintenance, reduced excessive noise and vibration levels, and enhanced driving comfort. However, CWR can also lead to negative outcomes, with the most significant being rail buckling-primarily occurring horizontally-when rail temperatures surpass established limits [28]. Rail buckling will rarely occur spontaneously but is the result of internal and external forces in the track. Internal forces are caused by temperature, and external forces are caused by traffic load [29]. Rail buckling occurs very frequently during the summer months and is caused by forces acting on the tracks that are greater than the lateral track resistance, the value of which depends largely on the condition of the railway track. Figure 5 illustrates the correlation between the number of reported traffic accidents in the EU between 2008 and 2018 associated with rail buckling and other track irregularities and the recorded global temperature. It can be determined that the reported cases of rail buckling rise with increasing air temperature.

Because the rails heat up quickly, the temperature in the rail is always higher than the air temperature, and based on the rule used in practice, the relationship between the air temperature and the rail can be expressed as [31]:

$$T_{air} \approx (2/3) \cdot T_{rail} \tag{1}$$

where:

T_{air} – air temperature [°C]

T_{rail} – rail temperature [°C].

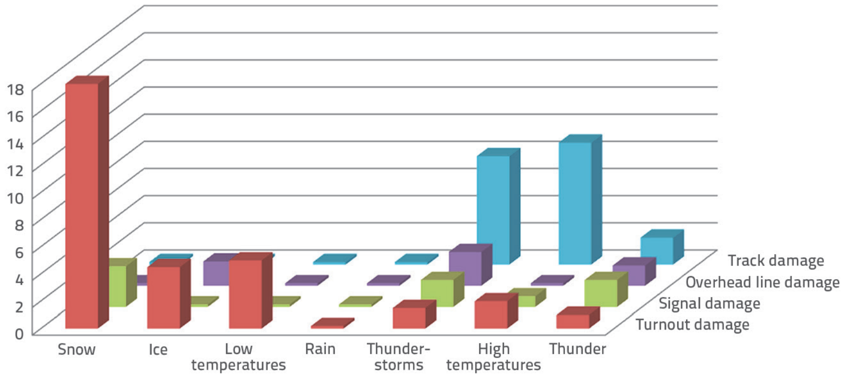

Figure 4. The frequency of the occurrence of an adverse event with regard to the weather [23]

Table 1. Limit values for the occurrence of an adverse event on the track due to different weather conditions [23]

Weather conditions	Probability of an adverse event				Compromised component
	< 33 %	33 – 66 %	66 – 99 %	99 %	
High temperatures [°C]	T ≤ 28	28 < T ≤ 33	33 < T ≤ 35	T > 35	Track
Low temperatures [°C]	T > - 4.5	-9 < T ≤ -4.5	-12 < T ≤ -9	T < -12	Turnouts
Snow [mm/d]	s ≤ 10	10 < s ≤ 22	22 < s ≤ 50	s > 50	Turnouts

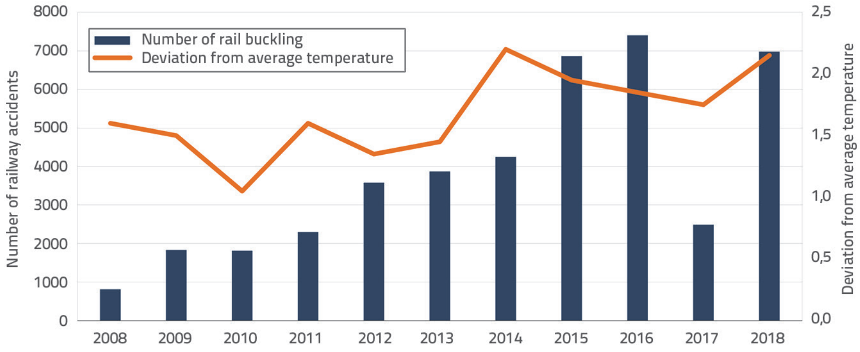

Figure 5. Reported number of railway accidents caused by rail buckling and other track irregularities, and indication of global temperature in the EU in between 2008 and 2018 [30]

The rail temperature is also affected by the location of the track – when exposed directly to the sun, the rails heat up much faster than when the rails are in the shade, in a cut, a tunnel, etc. [32].

To minimize the risk of rail buckling, the rails are fastened to the sleepers at a neutral temperature, i.e. at a stress-free temperature (*SFT*) [29]. Compressive forces in the rails develop from stresses induced by temperatures above the rail's SFT, as well as mechanical factors like braking, wheel friction during travel, and wheel-rail contact during train passing through curves. The SFT should be set to balance the risk of buckling at high temperatures and rail breaks at low temperatures [31]. In practical track maintenance, the issue of significant heat load is addressed by securing the rails at a SFT of 35 °C to 43 °C (with corresponding air temperature ranging from 23 °C to 29 °C). This high SFT range prevents the occurrence of excessive buckling forces even when the rail temperature reaches values between 54 ˚C and 65 ˚C (36 ˚C – 43 ˚C associated air temperature) [10]. Currently, there are no standardized definitions for the SFT in rails, and it varies by country. This variation is illustrated in Table 2, which presents the defined SFT in various European countries.

Table 2. Defined values of neutral rail temperature (SFT) in different countries of Europe [10]

Country	**Neutral temperature (SFT)** [°C]
Germany	23
Spain	27
France	25
Ireland	23
The Netherlands	25
United Kingdom	27

When new rails are installed on the Croatian Railway network, they are placed on fastening points and secured with a specific tensile force. The track is then adjusted for alignment and height, and the rails are welded into continuously welded rail. Welding should not occur at temperatures below 5 °C or above 35 °C [33]. After welding, the fastening systems are loosened to eliminate internal stress from continuously welded rails. After reaching the required temperature in the rails, they are returned to their fastening points, and the fastening system is fully tightened. The temperature at which the rails are laid back into the bedding can differ from the required temperature by up to ±3 °C, depending on the climate zone; in continental Croatia, this required temperature is 22.5 °C ±3 °C [33].

According to [27], the likelihood of rail buckling is contingent on the temperature within the rail, where the authors distinguish the following two temperatures in the rails:

- the maximum rail temperature at which there is no risk of buckling $T_{b,min}$
- rail temperature at which some buckling $T_{b,max}$ will occur.

Temperatures between $T_{b,min}$ and $T_{b,max}$ have a certain probability of buckling. Given these two temperatures, it is possible to calculate the temperature $T_{allowable}$, that is, the highest temperature above the neutral temperature (SFT) at which the rails are deemed safe from buckling. This temperature can be calculated using the following expression:

$$T_{allowable} = T_{b,min} + 0{,}25 \cdot (T_{b,max} - T_{b,min}) \qquad (2)$$

The probability of buckling is based on the relationship between buckling energy and temperature. At temperatures close to the value $T_{b,max}$, the additional energy required for buckling decreases exponentially.

On the other hand, at temperature $T_{b,min,}$ the maximum additional energy is required for rail buckling to occur. The dependence of the probability of rail buckling and rail temperature is shown in Figure 6.

The formation of differential settlements along the track can disrupt the rail's neutral temperature, resulting in voltage fluctuations that are localized. This is most often expressed in places where the track structure is changed – for example from a ballasted track to a slab track, which is the case when transitioning from an embankment to a viaduct or bridge. Based on the events observed, different settlements lead to the elongation of rails and the generation of stresses within them [32].

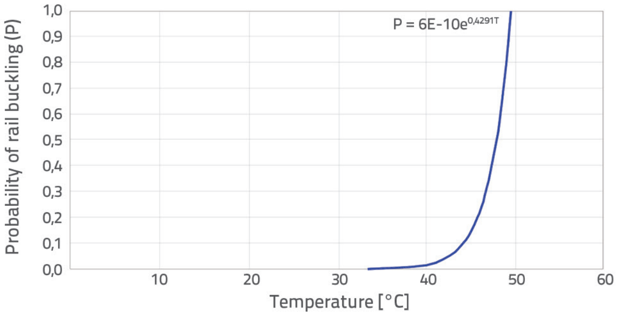

Figure 6. Probability of rail buckling in relation to temperature [27]

In addition to differential track settlements that will cause problems in the vertical geometry of the track, buckling will be additionally affected by irregularities in the horizontal geometry, given that they will affect additional lateral forces that, in combination with high temperatures, can initiate buckling.

2.1.2. Turnouts

Out of all weather conditions, extremely high and low temperatures have the most damaging effect on the railway turnouts. High temperatures elongate the rails, which can lead to a change in the position of the points. Railway turnouts are very sensitive to changes in the track geometry, so small rail elongations can result in problems with the operation of the turnout. In addition, the elongation of rails in the turnout zone can cause the train to jump out when passing through the turnout [34]. The paper [35] analyzed several detected train derailments at turnouts, with the largest number of derailments observed in the summer and winter months (Figure 7).

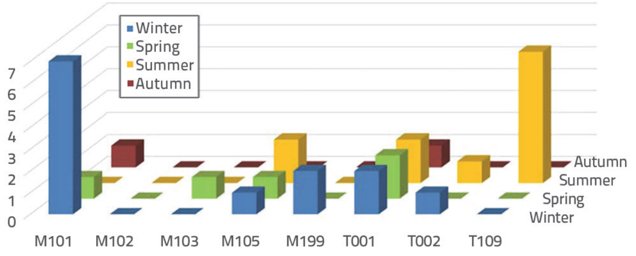

Figure 7. Number of train derailments at turnouts recorded according to the seasons [35]

2.1.3. Overhead line and signaling

On electrified railways, vehicles are most often supplied with the power required to start up via the overhead line. The overhead line is located above the railway, and is mainly exposed to weather conditions, such as high temperatures, wind, snow and ice [36]. Since a pantograph provides power to the vehicle, it is crucial to maintain effective contact between the pantograph and the overhead line, which is why the tension of the line is important. Temperature changes result in changes in the geometric position of the overhead line – at high temperatures the overhead line expands, at low temperatures it contracts, resulting in high tensile stresses [36, 37].

The paper [37] analyzed the influence of temperature change on the spatial position and tensile stresses in the overhead line using a mathematical model. The simulations revealed that while the temperature variation significantly influences the longitudinal position of the overhead line, it does not have a notable effect on the vertical and lateral spatial positions of the line. As illustrated in Figure 8, the overhead line is positioned at a design temperature of 20 °C and 50 °C, where the difference in the height of the lines is visible as a result of material elongation due to high temperatures.

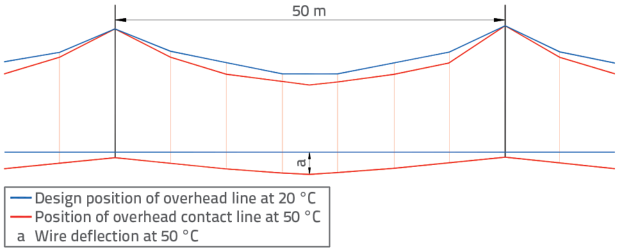

Figure 8. The position of the overhead contact line at a temperature of 20 °C and 50 °C [37]

It was also found that the string tension of the contact line changes with the external temperature variations. By reducing the temperature, the string tension increases significantly. A temperature change from 20 °C to -60 °C was found to increase the string tension by 0.177 kN, which corresponds to an increase of 0.66 %. However, a change in temperature from 20 °C to 60 °C reduces the tension by 0.088 kN, equivalent to a decrease of 0.33 % [37]. Changing the position of the overhead lines may affect the contact force between the pantograph and the overhead lines, and this force must be within safe limits to ensure the vehicle's power supply [38]. According to [39], the value of mean contact force for the 25 kV 50 Hz power supply system must be greater than 60 N and less than $0.00047 \cdot V^2 + 90$, where V is the operating speed of the train in km/h. Paper [38] analyzed the change in contact force at different temperatures ranging from -60 °C to 80 °C, with the temperature at which the superstructure was set up being 20 °C (reference temperature). It was found that the maximum force difference between the lowest and the highest temperatures is 8 N, with the minimum and maximum contact forces measured at various temperatures presented in Table 3.

As can be seen from Table 3, the minimum contact force decreased with each deviation from the reference temperature. On the other hand, the maximum contact force increases continuously with decreasing temperature, while the force decreases with increasing temperature [38].

Table 3. Values of the minimum and maximum contact force between the pantograph and the overhead line at different temperatures [38]

Temperature [°C]	**Minimum recorded contact force**		**Maximum recorded contact force**	
	Force [N]	**Percentage of change** [%]	**Force** [N]	**Percentage of change** [%]
-60	101.81	-4.80	379.09	1.59
-40	102.85	-3.82	377.73	1.23
-20	104.29	-2.48	376.17	0.81
0	105.99	-0.89	374.39	0.33
20*	106.94	0	373.15	0
40	106.69	-0.23	372.52	-0.17
60	105.99	-0.89	372.33	-0.24
80	105.99	-0.89	372.10	-0.28

**Temperature at which the overhead line is set up. reference temperature*

2.2. Snow, ice and extremely low temperatures

Low temperatures cause freezing of the railway track, and the depth of freezing depends on the temperature level and the duration of such low temperatures. Irrespective of the layer thickness of the railway track, however, the freezing depth must not reach the planum [40]. In regions with cold climates, the snow cover on the ballast bed positively influences the thermodynamic processes of the railway superstructure's layers, as a sufficiently thick layer of snow can diminish freezing depth [40]. Problems that can be caused by snow, ice and low temperatures on the railway include [41]:

- ice formation on the overhead contact line and the third rail,
- malfunction of turnouts due to accumulation of snow and ice,
- ice formation on the rails,
- rail fracture,
- tcracks on reinforced sleepers,
- freezing in the tunnel, especially at the tunnel entrance,
- freezing of platforms at railway stations,
- swelling and crushing of the ballast material.

2.2.1. Rails and turnouts

Because of the low temperatures, significant tensile stresses build up in the rails, potentially leading to rail breakages [28]. Extremely low temperatures can cause wheel tire materials to lose plasticity, leading to brittleness and a deterioration of mechanical properties. Ice formation on the rails decreases the friction between the wheels and rails, extending the vehicle's braking distance while also lowering the locomotive's tractive power. It is therefore necessary to limit the travel speed under such extreme conditions. In winter, the low temperatures cause ice to form on the turnouts and block the turnouts. This prevents the turnouts from changing position correctly and causes them to stick to the adjacent main rails [23, 42].

As noted in [43], extremely low temperatures, especially below -10 °C, can alter the mechanical properties of elastomer under-rail washers, resulting in high noise levels and vibrations from passing trains.

2.2.2. Overhead line

Snow weighs down the overhead line with its weight and can cause a change in its position [44]. Due to the winter months, ice remains on the contact line, and the formation of ice can be classified as icing, the formation of granular rime ice, crystalline rime ice, wet snow and mixed rime ice. The formation of ice depends on the geometry of the line and atmospheric parameters, such as air humidity, atmospheric temperature, wind speed [41, 45].

The formation of ice on the overhead line also causes an electric arc between the pantograph and the lines, since the layer of ice affects the current flow from the overhead line to the pantograph, which results in accelerated wear of the wires [36].

2.3. Stormy gusts of wind and thunderstorms

Strong winds can uproot trees and hurl them onto the track, damaging the overhead lines, which results in costly repairs and disruption to railway operations. On open railway lines, atmospheric wind plays a significant role. This wind can blow from different directions relative to the train's movement and is called crosswind. Crosswinds travelling at speeds above 120 km/h may, under certain circumstances, cause a train to overturn, which is mostly seen in empty freight wagons and passenger trains where speed increases and mass decreases. With high-speed trains being introduced into transport, more and more emphasis is being placed on safety when crossing bridges, as a bridge built in an area exposed to strong gusts of wind can experience significant deformation. Moreover, low-frequency vibrations generated by the wind can impact not only the bridge but also pose a risk to the safety of trains passing

Table 4. Analysis of the impact of different wind speeds on railway infrastructure [47]

Limit value	Impact	Repercussions
$W_G \geq 17$ m/s	▪ Trees falling onto tracks and overhead lines	▪ Local problems in rail operations
$W_G \geq 25$ m/s	▪ A large number of trees down on the track ▪ Reduced visibility in low temperatures and snow due to snowdrifts	▪ Power outage ▪ Train delays and cancellations
$W_G \geq 32$ m/s	▪ A very large amount of downed trees ▪ Major breakdowns in the railway infrastructure ▪ Damage to signaling installations, reduced visibility	▪ Delays and disruption to railway operations for up to several days due to major breakdowns

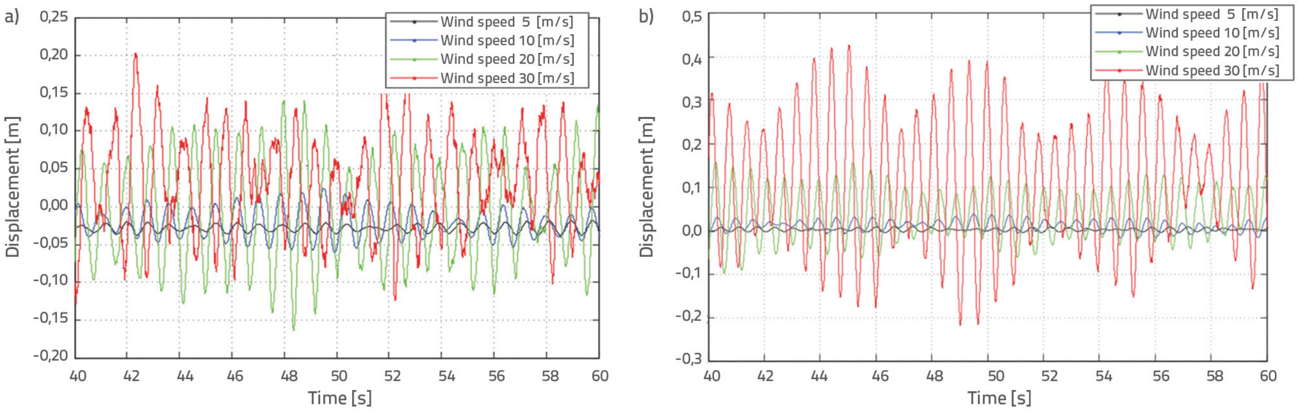

Figure 9. Displacements recorded in the middle of the observed contact line segment at different wind speeds: a) vertical displacement, b) lateral displacement [50]

over it. Wind can make the train vibrate, and at high speeds, it may even lead to overturning or derailment [46].

Thunderstorms with strong winds can scatter large amounts of leaves onto the tracks. When a train passes, the pressure from the wheels forces leaves to stick to the rails, forming a layer that reduces adhesion between the wheels and the rail, which in turn increases the train's breaking distance and reduces the traction force, thereby increasing energy consumption. The extent of wind damage to the track primarily depends on wind speed. Table 4 outlines the effects of various wind speeds on the track and their resulting repercussions.

Along with the information presented in Table 4, it is important to highlight that strong winds adversely affect the vehicles involved, namely, high-speed passenger trains and empty freight cars, as they are at risk of toppling due to lateral gusts.

Wind load in the environment can be categorized based on whether it is of constant or variable speed. Under some extreme conditions, a frozen transmission line placed in a uniform airflow is subject to aerodynamic forces due to the non-circular cross-section of the transmission line. Such oscillations of large amplitudes and low frequencies are called galloping [48]. A similar phenomenon can occur on a railway overhead line, where galloping oscillations can only cause crosswinds when the overhead line is worn [49, 50].

The dynamic properties at the contact of the pantograph with the overhead line are important to ensure that the vehicle is supplied with energy for starting, especially at very high traffic speeds. Earlier studies on the contact between pantographs and lines only considered the vibrations of the lines, but very rarely the effects of the environment, which is important to ensure continuous and consistent contact between pantographs and overhead lines with optimal contact force and thus minimized contact line wear [48]. The research revealed that wind speeds exceeding 130 km/h can induce vibrations of the contact line, create issues with the connection between the pantograph and the lines, and result in interruptions of this connection [15, 51]. Given the complexity of the overhead line structure and the stochastic effect of the surrounding wind, wind-induced oscillations of the overhead line with high amplitude can lead to problems with the electrical power supply of high-speed vehicles.

Different wind speeds produce different values of vertical and lateral displacements on the contact line, which is analyzed in more detail in [50], with the findings illustrated in Figure 9. The results show that the vertical and lateral displacements recorded increase rapidly as wind speed rises.

In addition, the study [50] examined how wind speed and direction influenced the contact force between the pantograph and the overhead line. The results showed that an increase in wind speed leads to a significant increase in the fluctuation of the contact force (Figure 10.a). The angle of the wind gust also affects the force between the pantograph and the contact line (Figure 10.b).

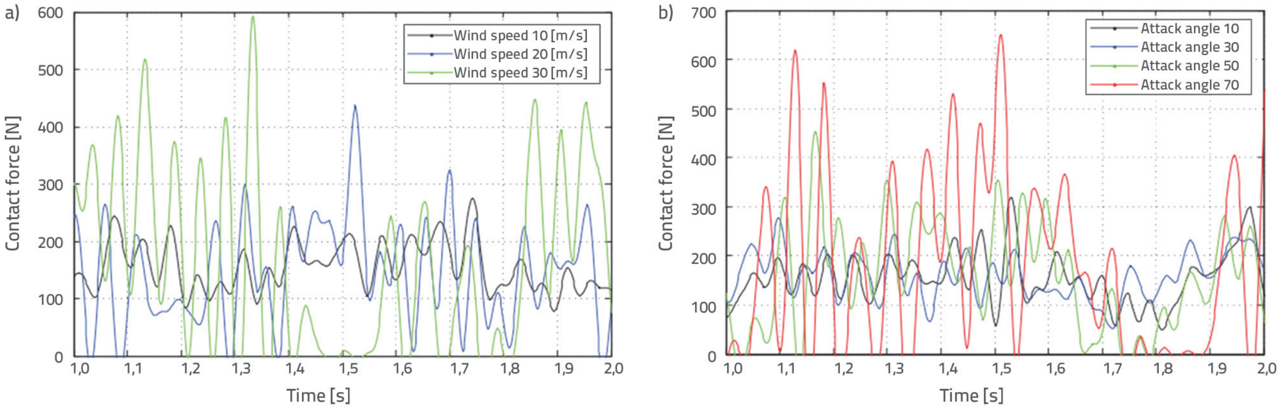

Figure 10. The force between the pantograph and the contact line at: a) different wind speeds; b) wind gust angle; train passing speed 325 km/h [50]

In addition to the adverse effects of wind, thunderstorms can also lead to damage to the railway infrastructure, as there is a risk of lightning striking it. This can have a particularly significant adverse impact on signaling devices that are sensitive to electromagnetic interference and magnetic fields [20].

The adverse effect of storms with high winds manifests in open coastal regions, where massive sea waves can inflict further harm on the track structure [52].

2.4. Floods and torrents

Heavy rainfalls, which are becoming more frequent in Europe, have a particularly significant adverse impact on embankment and cuts, but also on other track elements. Rain increases the risk of landslides, whilst the collapse of embankment and cuts most often results in damage to the superstructure of the railway – rails, sleepers, ballasts, and can also cause train derailment [21, 53]. Floods also have a detrimental effect on railway geometry [54]. Heavy rainfall within a short period of time can cause major flooding, while longer periods of rain can lead to groundwater flooding. Railway infrastructures located near the coast are at risk from rising sea levels, which can result in flooding [52]. The paper [55] analyzed the impact of flooding on damage to the railway network in Europe using the RAIL software to assess the damage caused by flooding to the cross-section of the railway structure and the cost of reconstruction. The results revealed that the estimated annual costs for the renovation of the railway structure because of flooding amount to around 581 million euros. In addition to damage to the railway structure, flooding can also trigger a short circuit in electrical installations and interrupt the power supply.

In the study [56], the flooding risk of the track was evaluated at various water levels in relation to the top edge of the rail, considering only the stationary state of the water and excluding torrents. It was determined that at a water level of -2.5 m from top edge of the rail, the stability of the railway line is not compromised, and traffic can continue. When the water level is between -0.45 m and -2.5 m, it may adversely affect the railway substructure, but railway traffic can persist under these conditions. The water level of 0 to -0.45 m will affect the elements of the superstructure of the track that are most sensitive to floods, and in this case, there is a moderate risk of damage to the track structure. In addition, when the water level on the track ranges from 0 to 0.5 m, there is a considerable risk of damage to the track, making it essential to halt railway

Table 5. Risk levels at different water levels at the track structure [56]

Flood type	Water level	Water level relative to the height of the top edge of the rail	Track damage	Level of risk
I.	It does not reach the substructure	Less than 2.5 m	-	-
II.	It does not exceed the height of the substructure	From - 2.5 m to -0.45 m	Bedding	Low
III.	At the level of the superstructure or above rail height	From -0.45 m to 0 m	Smaller parts of the ballast bed	Medium
IV.	It exceeds the height of the rails	From 0 m to 0.5 m	Most of the ballast bed and smaller parts of the substructure	Tall
V.	It exceeds the height of the rails	Greater than 0.5 m	The substructure and most of the ballast bed	Very high

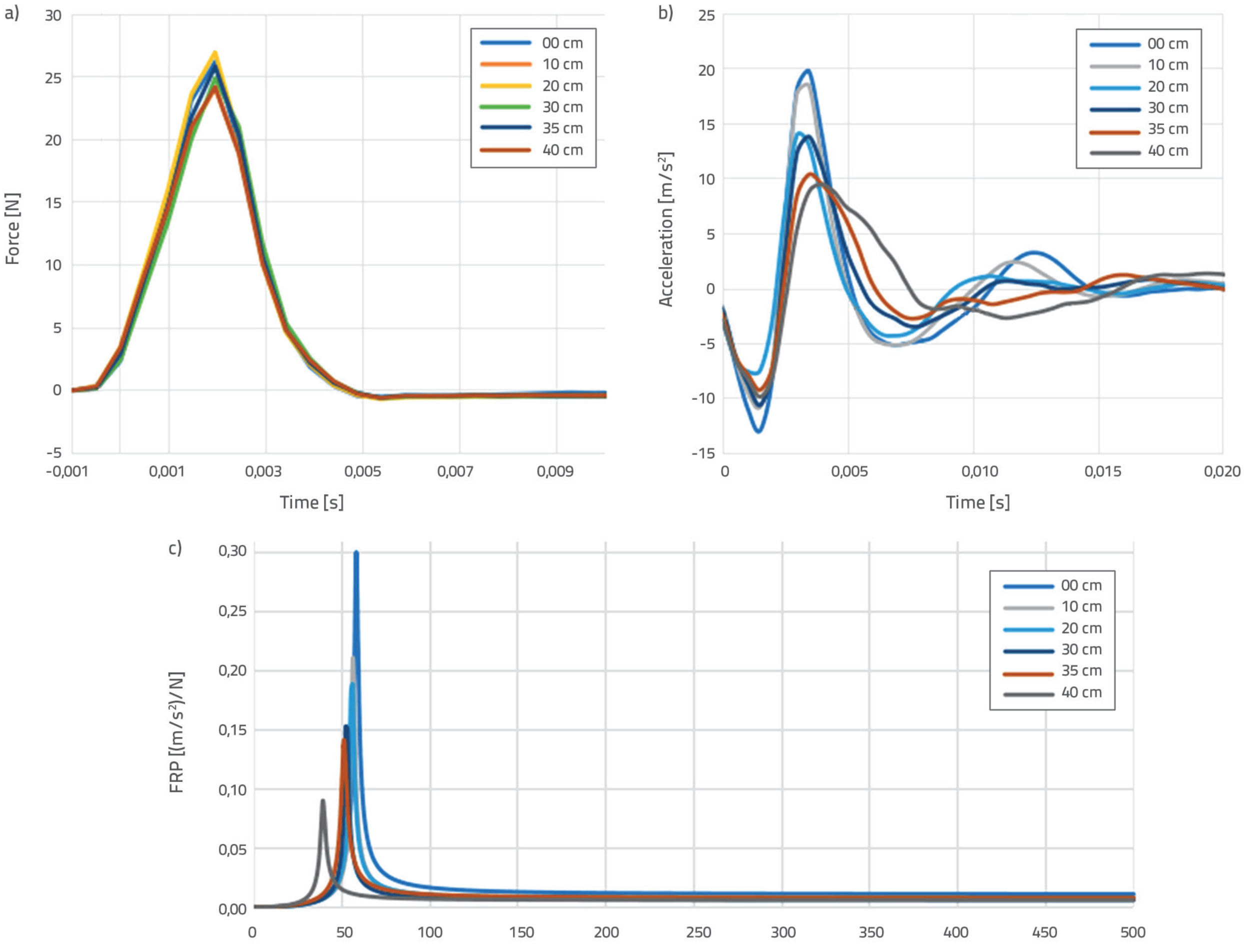

Figure 11. Results obtained from laboratory testing of a track sample with varying water levels simulating a flood: a) force variation over time, b) acceleration variation over time, c) variation in the frequency response function – FRF [57]

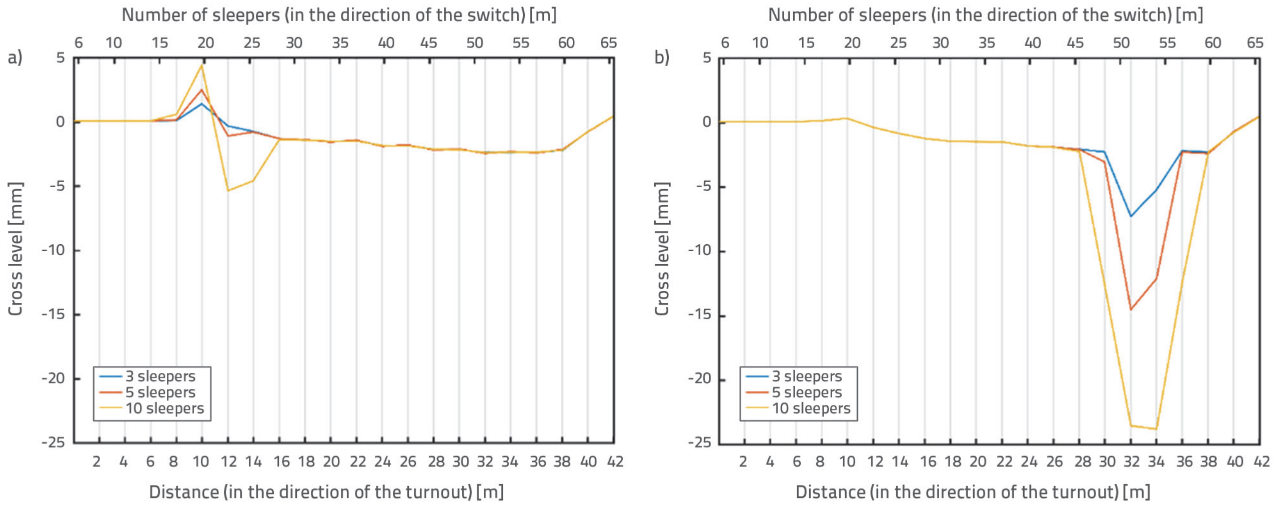

Figure 12. The recorded height ratio of the rails along the turnout when the load is located on a) the transfer device, b) the turnout point [58]

operations. With a water level of +0.5 m, all railway components are at significant risk, and the flooding damages the railway along with its substructure and superstructure. The results of this research are summarized in Table 5.

The paper [57] analyzed the effect of different water levels on the distance with a ballast bed, whereby the water level was increased from 0 to 40 cm every 10 cm. A mold measuring 1.85 x 0.9 x 0.5 m was used for the laboratory sample, into which the ballast bed material with a thickness of 35 cm was inserted, and half of the reinforced concrete sleeper was placed on top. For testing, a non-destructive testing method was used, which is based on the excitation of the track with a hammer and the measurement of the vibration response of the track. The received vibration signal was converted into a frequency response function using Fourier transformation. It was determined from the tests carried out that the pulses were damped within 0.005 seconds and that the highest force value occurred at approximately the same time, regardless of the water level in the samples (Figure 11a). Furthermore, it was observed that accelerations diminish as the water level rises (see Figure 11b), suggesting that flooding significantly enhances track damping. Furthermore, it was observed that the frequency response function generally decreases as the water level rises (see Figure 11c). Once the water level reached its peak, a notable change in the natural frequency of the ballast bed material occurred, leading to a reduction in the overall dynamic stiffness of the track.

The study reported in [58] employed a finite element model to examine how turnouts behave both under dry conditions and when the railway superstructure is flooded, leading to ballast bed erosion and settling of the track. Figure 12 presents an analysis of how washing the ballast bed below 3, 5, and 10 sleepers affects the crosslevel (difference in height between two top surfaces of the rails) near the conductor device and turnout point. It was found that the number of sleepers below which the ballast bed was washed out has a direct influence on the crosslevel of the rails. Since rails are highly responsive to alterations in track geometry, modifications in crosslevel that result in ballast bed erosion can lead to trains derailment when passing through turnouts [59].

3. Methods of restoration and protection of the railway track from climate change

3.1. Rail protection measures against buckling

As buckling usually happens from the passage of a train, it is customary to lower the speed of travel and reduce the traffic load during high-temperature periods [27]. This method reduces stress on the rails and lowers the likelihood of vehicle derailing. In the United Kingdom, as shown in Table 6, speed reduction measures are implemented when the air temperature goes beyond 36 °C.

Reducing the speed of the train will cause delays. Therefore, to prevent the occurrence of buckling on existing tracks, it is necessary to [60]:

- Prevent the occurrence of large compressive forces in the rails during high temperatures,
- Increase the lateral and longitudinal track stability.

It is also possible to prevent large compressive forces in the rails by selecting an appropriate neutral temperature. As previously mentioned, *SFT* or the neutral temperature of the rails is the temperature of the rail at the time of its fastening. To minimize the chances of rail buckling during high summer temperatures, rails are fastened to sleepers at a neutral temperature of 35°C to 43°C (with relative air temperature ranging from 23°C to 29°C). This high neutral temperature range prevents the occurrence of excessive buckling forces (compressive forces in the rails) even when the temperature of the rails reaches values of 54°C - 65°C (36°C - 43°C corresponding air temperature) [10]. If the rails are fastened at a lower neutral temperature than required, this leads to increased compressive forces at high temperatures and increases the likelihood of buckling.

3.1.1. Preventing the occurrence of large compressive forces in the rails

The paper [61] involved an analysis of using potassium aluminosilicate to apply a coating on the rails to reduce maximum temperatures. This coating creates a highly reflective surface in white color and at the same time guarantees high abrasion resistance and self-cleaning properties. The article describes

Table 6. Travel speed limit in the United Kingdom with respect to track conditions at high temperatures [44]

Railway condition	In a precautionary state	Travel speed limit	
		30/60 mph (48/96 km/h)	20 mph (32 km/h)
Good condition	SFT + 32	SFT + 37	SFT + 42
Insufficient quality of the ballast bed	SFT + 10	SFT + 13	SFT + 15
SFT - neutralna temperatura tračnica, mph - milja na sat (1 mph = 1,6093 km/h)			

the measurement of the temperature of an unprotected rail sample and a rail sample protected with the coating. The analysis showed that the temperature drops by up to 10.5 °C. The results of the research are shown in Figure 13.

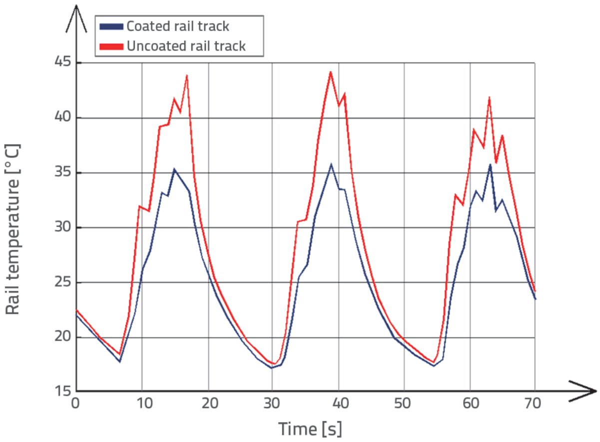

Figure 13. Measured temperature in the rail with coating and the rail without applied coating [61]

3.1.2. Increasing lateral and longitudinal track stability

By improving the track's lateral stability, we can also prevent rail buckling in addition to lowering the compressive stresses in the rails. The level of lateral track stability is largely influenced by the interaction with the ballast bed and sleepers [32]. Since the sleepers serve as the link between the rails and the ballast bed, they are crucial to the track's buckling resistance. When buckling occurs, the compressive force produced by the rails' thermal expansion is transmitted to the ballast bed and the lower track structure through the fastening system and sleepers. The lateral buckling resistance of the track depends on the following factors [60, 62]:

- Type of sleepers and distance between the sleepers;
- Interaction between the ballast bed and the sleepers;
- Applied fastening system;
- Shape and dimensions of the ballast bed.

In general, concrete sleepers are thought to be more buckling-resistant than steel and wood sleepers. This is due to the concrete sleepers' increased weight, size, and shape, which creates a more robust railway track with more resistance to rail buckling [63]. The smaller the distance between the sleepers, the greater the lateral stability of the track. The interaction between the ballast bed and the sleepers refers to the frictional forces between the bottom surface of the sleeper and the ballast material, the friction between the side faces of the sleepers and crib ballast, and the resistance of the ballast shoulders. All three components depend on the type of sleeper, the type of ballast material, and its density [64].

The lateral resistance of sleepers is an important characteristic in defining the lateral stability of the track structure. In the paper [65], laboratory testing was conducted on a track sample where the sleeper is situated on a ballast bed to determine the lateral resistance of track with installed B70 concrete sleepers and with installed winged sleepers. A rail is supported and fastened to the sleeper. During the test, a force was applied to the sleepers and the lateral displacement measured. It was found that with a measured displacement of 2 mm, the lateral resistance of the winged sleeper was 101 % greater than that of the B70 sleeper (Figure 14).

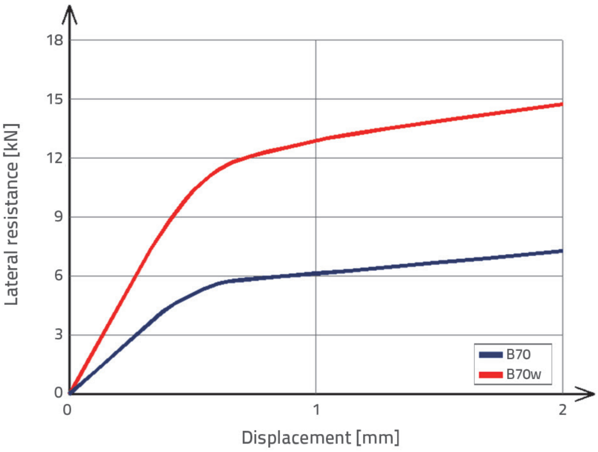

Figure 14. Diagram of displacement and applied force during laboratory testing of sleepers [65]

The lateral resistance of six different types of concrete sleepers was evaluated in [66] using the pull-out test (Figure 15). It was found that the lateral resistance depends on the friction of the ballast bed on the sleeper ends and on the friction between sleeper and ballast bed and not on the weight of the sleeper. The test also showed that the width of the wings has a considerable influence on the lateral resistance, while the shape of the cross-section of the winged sleeper has only a minor influence. Figure 16 shows the resulting diagrams of the relationship between the recorded horizontal displacement and the horizontal applied force.

Frictional sleepers can be used to increase the frictional force and interaction between the ballast material and the sleepers. These sleepers resemble B70 reinforced concrete sleepers in shape, with the exception that they have additional serrations on the bottom to increase the coefficient of friction between the sleeper and the ballast bed [67, 68]. According to the results, the track with these sleepers has a lateral resistance that is almost 67 % greater than that of the track with regular concrete sleepers [67]. In the case of steel sleepers, the lateral resistance can be increased by using sleepers with vertical stiffeners on the underside [69]. This increases the interaction between the sleepers and the ballast material, leading to larger resistance. Lateral resistance can be further increased by using devices to increase the lateral track resistance [62]. These devices, which can increase lateral resistance by up to 50 %, were initially used only for wooden sleepers. Today, these devices can also be fitted to concrete sleepers in the middle and at the ends of the sleepers [62].

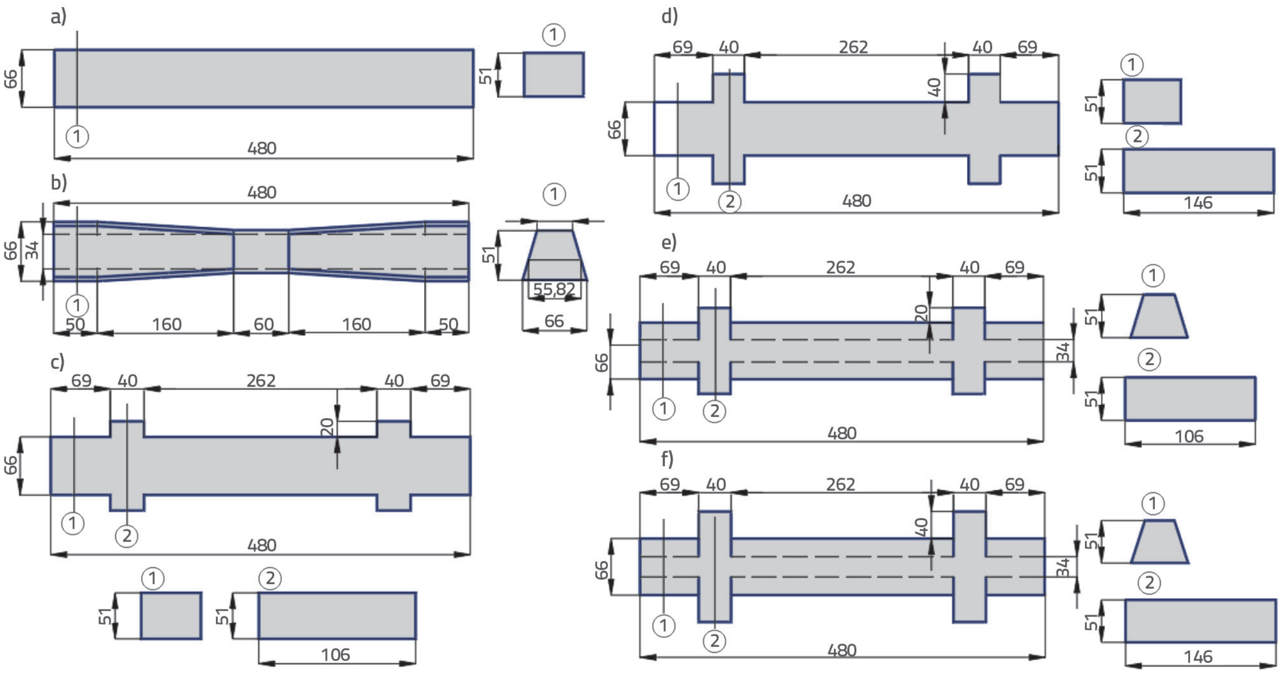

Figure 15. Types of sleepers tested: a) Rectangular parallelepiped sleeper; b) 3H sleeper; c) sleeper with 20 mm long wings and rectangular ends; d) sleeper with 40 mm long wings and rectangular ends; e) sleeper with 20 mm long wings and trapezoidal ends; f) sleeper with 40 mm long wings and trapezoidal ends [66]

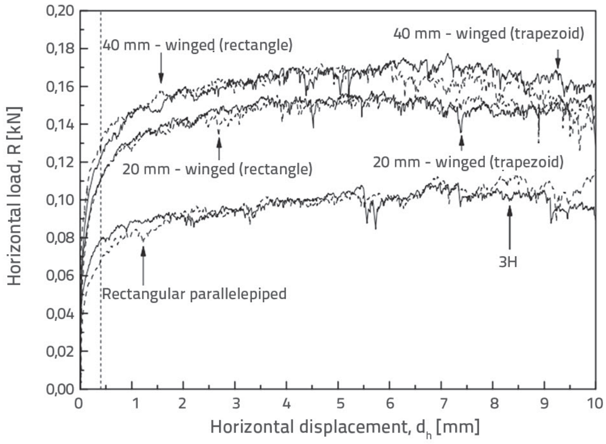

Figure 16. The relationship between the observed horizontal displacement and the applied horizontal force for the various sleeper types under test [66]

Apart from the effects on the interaction between sleepers and ballast bed, the type of rail fastening also influences the lateral resistance of the track. The rail has a low lateral bending stiffness, but if the rails are connected to sleepers, the lateral stiffness of the track increases. This depends on the type of fastening system used; it was found that elastic fastening systems have a higher torsional resistance than rigid fastening systems. The result is a higher strength of the track grid and a higher buckling resistance [60, 70]. In paper [71], the torsional resistance of fastening systems on wooden and concrete sleepers was investigated. The torsional resistance of the fastening system on the concrete sleeper is about 40–70 % of the value determined for the wooden sleeper, which indicates that the fastening system of the wooden sleeper works significantly better than that of the concrete sleeper. Additionally, the resistance to rail rotation relative to the sleeper contributes approximately 15 to 30 % of the total lateral resistance.

The lateral resistance of the track is also significantly influenced by the size and form of the ballast bed. In the paper [63], it was discovered that the lateral resistance of the ballast bed reduces with increasing thickness. For this reason, the ideal thickness should be 30 cm.

The lateral resistance of the track is mainly influenced by the ballast shoulder, the ballast crib and the ballast under the sleeper. According to [70] the resistance produced by the ballast bed is a combination of the resistance at the point where the sleeper's lower side and the ballast bed come into contact (resulting in 26 – 35 % of the total resistance), the resistance that will occur at the point where the sleeper's side and the ballast shoulder come into contact (resulting in 37 – 50 % of the total resistance), and the resistance that will arise at the point where the front and rear sides of the sleeper come into contact with ballast crib (resulting in 15 – 37 % of the total resistance). The ballast material not only increases friction but also makes the track panel more stable [63]. According to [72] under sleeper pads have a major impact on the track's lateral resistance. The lateral resistance increases with the hardness of the pad, but it's recommended that the hardness shouldn't be greater than 7.5 x 107 Nm-1.

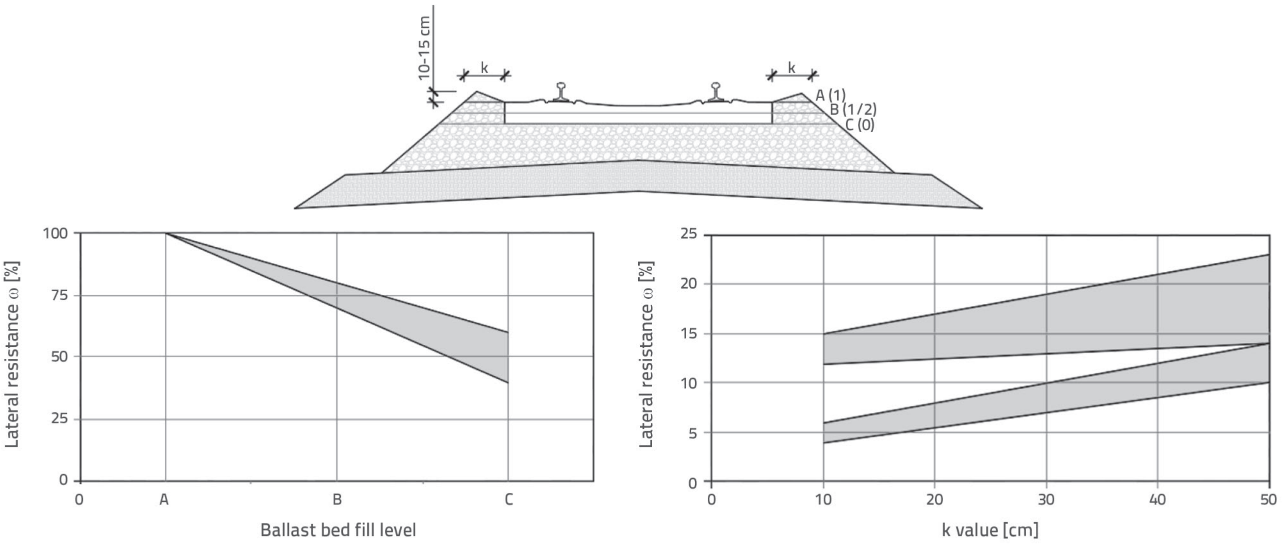

Figure 17. Reliance of lateral resistance on the shape of the ballast bed [73]

The lateral stability of the track is positively influenced by the increase in width and height, as the weight of the ballast prevents the rails from buckling. Therefore, some operators recommend that the ballast shoulder should have a minimum width of 350 mm in curves and on straights. Figure 17 shows how the lateral resistance varies with the shape of the ballast bed.

3.2. Railway protection from gusts of wind

For high-speed lines in Europe, the Technical Specification for Interoperability (TSI) and the EN14067-6 standard require an assessment of the safety of trains regarding the effects of strong crosswinds [74]. Wind barriers installed along the rail structure are most used to reduce the wind speed that could affect the train [75]. In the study [76], a numerical model was used to analyze the slip coefficient of a train running at a speed of 300 km/h and a wind speed of 260 km/h with and without wind barriers. The barriers were of different heights - 2, 4 and 6 meters. It was found that the aerodynamic coefficient of the train was significantly altered by the wind barriers. The local airflow pattern was drastically changed by the ends of the barriers, which was reflected in the fluctuations of the aerodynamic coefficient and led to an abrupt shift in lateral resistance as the train entered and exited the barrier area. In addition, the slip coefficient continued to decrease as the height of the wind barriers increased. It was found that a 2 m high barrier has no discernible effect on protecting the train from wind-induced hazards, while a 4 m high barrier has a significant effect, and a 6 m high barrier was considered too high.

3.3. Railway protection against floods and storms

In response to storms, rail infrastructure operators introduce speed restrictions, which vary in severity and can lead to traffic problems [77]. If the infrastructure is located on the coast, sensors can detect rising sea levels and warn operators of possible traffic restrictions to avoid negative effects [77].

Flooding often occurs along the tracks, causing damage to the embankment and ballast bed. The measure that can prevent such damage is the installation of rock armour. This is a reliable method of protecting the ballast bed during floods and extreme weather conditions. Large stone blocks are placed on the slope of the ballast bed along the track and prevent the screening material from being washed away by reducing the velocity of the water and restricting its flow [78].

According to [65], to protect infrastructure from flooding, it is crucial to carry out continuous weather monitoring, react to potential flooding in good time and equip endangered areas with the necessary flood defense facilities. This includes the installation of flood protection measures such as water-filled inflatable barriers.

Drainage systems need to be regularly maintained and cleared of leaves, branches, and other debris to ensure effective water drainage during periods of high precipitation [65]. The installation of pumping stations at strategic locations can allow water to be pumped out quickly during repeated flooding [65].

The paper [79] examined the use of a GIS system to identify key areas of the railway network that are at risk from various flood types. Heavy rainfall, rising subsurface water levels, and surface flooding were identified as the primary causes of floods. In addition to estimating flood intensities and likelihood of occurrence, the GIS model also identified high-risk zones and infrastructure vulnerability. After applying the model to 380 km of railway line, the findings indicated that locations susceptible to flooding can be identified very successfully. Priority locations for more thorough investigation and protective measure installation might also be determined. The model also facilitates track maintenance planning. The flood early warning system was applied to the railway infrastructure in Austria in the places where the railway runs along the river courses, and the results are presented in the paper [80]. The method predicts potentially susceptible infrastructure by combining existing flood data with additional hydrological and hydraulic analyses. Key flood events in Austria were analyzed, including floods that caused rail disruptions. The methodology included identifying critical points, simulating water flow using hydraulic models and using river flow prediction systems. According to the findings, warnings can be given using this technology two to four hours before a possible flood.

3.4. Railway protection from snow and ice

3.4.1. Turnouts heaters

Snow and ice can make it difficult to properly adjust the turnouts' positions and prevent them from adhering to the main neighboring rails during the winter, which prevents trains from switching tracks. Turnouts are fitted with heaters to avoid snow and ice from obstructing them [81]. With the help of temperature sensors that respond to variations in air temperature, more recent heating systems will begin heating the rails until they reach a predetermined temperature, typically 7 °C, if a low temperature is reached. This temperature is measured by a temperature sensor that is mounted on the train rails of the hearth [82].

3.4.2. Clearing of snow and ice from rails and the overhead line

Clearing snow from the rails is a common practice during winter months. The kind of equipment and technique used to remove the snow depends on the location, accessibility, and quantity of snow. To enable their mobility, conventional trains should be equipped with standard, tiny plows when the snow cover is between 20 and 30 cm high. Special, larger plows installed on locomotives can be used to clear the snow from the rails under severe weather conditions when the snow cover is more than 45 cm [47].

There are several ways to keep overhead line wires from freezing. These methods generally require an external supply of thermal heating energy to act on the melting of the formed ice or mechanical energy to break the ice on the overhead lines [83, 84].

These days, pantographs which utilize a felt roller to apply an antifreeze combination to the contact line that is kept in a separate tank within the vehicle replace the traditional carbon contact strip [85]. To prevent freezing, the overhead lines are additionally treated using a variety of techniques. On certain railways, vibro-pantographs are utilized, which produce extra vibrations to shatter the ice that has accumulated on the overhead lines [85]. Additionally, if a vehicle is powered by the third rail, it is important to make sure that it is not covered in snow or ice during the winter months. This is because it prevents the supply of electricity that the train needs to start. To avoid this issue, the following actions can be taken [86]:

- Placing the heating strips on the third rail to melt the ice and snow
- Use specialized rail trucks to remove ice from the tracks. These trucks have heaters that blast hot air to melt the ice, or they can spray hot deicing solutions to clear the tracks of ice.

4. Monitoring the conditions of rails as a preventive measure for track maintenance and prevention of the adverse effects of climate change

In addition to the measures already mentioned to protect the track from extreme weather events, new monitoring techniques should be implemented to the railway infrastructure to continuously monitor and maintain the track's condition, given the growing detrimental effects of climate change on the railway track. Visual inspections and measurements of different track characteristics utilizing measuring carts and small handheld instruments are the mainstays of traditional track condition analysis techniques. The main drawback of these measurements is that they need a lot of time to implement, and hand-held equipment can only be used for spot measurements. Additionally, it is exceedingly challenging to do routine track condition monitoring with such sensors on big infrastructure networks because of the lengthy measurement duration [87]. There are two types of monitoring techniques used on railway infrastructure: contact and contactless. When using contact methods, it can occasionally be required to halt traffic to conduct the measurements and training the professionals who will perform them is a very ambitious process [88]. Because of this, contact methods are becoming undesirable, and contactless methods are increasingly being used. One such technique is the use of computer vision to identify the track condition using normal thermal or laser cameras mounted on regular railway carriages. This prevents traffic interruptions and allows for extremely low-cost track condition monitoring [88].

The increasing development of railway infrastructure requires the use of modern methods to monitor the track structure and determine its condition. These days, it's common practice to monitor utilizing ordinary vehicles or measurement trains that are outfitted with various kinds of sensors. Accelerometers are the most often used sensors because they can record vibrations from passing vehicles. Based on this data, it is possible to analyze driving comfort and track geometry. But in addition to track geometry, it's critical to keep an eye on the condition of every component of the track structure, which is done in a variety of methods nowadays. So, for example - by using different sensors, it is possible to detect defects on the track, such as a broken rail or degradation of the ballast bed [89]. The condition of the ballast bed, as well as the lower structure of the track, including mud and moisture content, can be monitored using GPR (*ground penetration radar*) [90]. In the paper [91], an analysis of the detection of the state of the fastening system was conducted, including the deterioration of the rail pad and the loosening of the anchor bolts using the vehicle vibration data. Visual inspections are the primary method used to assess the condition of the fasteners, but they only identify the elements that are visually accessible. The research analyzes track condition data that is continuously collected with technologies such fiber optic cables [92]. By analyzing the backscattered light along such cables, it is possible to determine vibrations, sound waves, and voltage changes with very high precision. The wire becomes a continuous network of sensors in this manner, allowing for continuous monitoring along its whole length. The wire can pick up sound signals produced by the wheels' contact with the rail as the train moves along the track. The condition of the ballast bed and the existence of anomalies on the track, such as temperature fluctuations that suggest overheating or shifts in stress that indicate rail deformations, can also be determined using this technique [92].

Nowadays, infrared thermography is increasingly being used to analyze the condition of track construction elements. It can monitor the temperature in these parts, which is crucial for rails because of high temperatures [93].

Due to the increasing frequency of extreme weather events, rail infrastructure operators need to be prepared to carry out routine track inspections as well as quick and efficient infrastructure inspections after an adverse event to assess whether rail traffic can continue or need to be stopped. The functionality index of the track is drastically reduced by weather-induced deterioration of the track structure. Under these circumstances, appropriate intervention measures must be taken to restore the intended functionality of its structure. It is possible to restore the structure so that it has a significantly higher resistance to future extreme events (curve C in Figure 18). However, it is also possible that after the measures have been implemented, the structure will no longer have the same properties as before the extreme weather event (curve A in Figure 18). Due to the numerous extreme weather conditions to which railway infrastructure is exposed, track condition monitoring is a useful tool for tracking the functionality index and very beneficial for predictive maintenance [94].

According to [95] wireless sensor networks are often used for railway infrastructure condition monitoring. These sensors are most frequently used to monitor bridges, tracks, and track equipment, but they can also be used to monitor the condition of trains and their many components, including axles, wheels, wagons, etc. The sensors can detect any significant changes on the track before or after extreme weather conditions. Moreover, unmanned aerial vehicles with a variety of sensors have shown excellent qualities due to their speed and efficiency, particularly while examining tracks following a harsh weather event [96]. Some of the most important new track condition monitoring techniques that can lessen the negative effects of climate change on tracks or more rapidly and effectively identify track damage brought on by extreme weather conditions will be discussed later in this article.

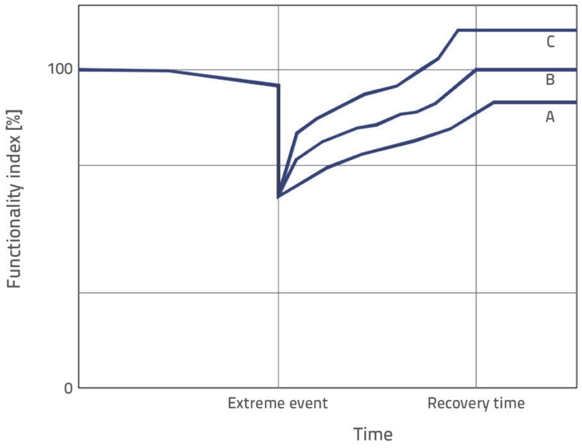

Figure 18. The curve of the functional index of the structure during extreme weather conditions [94]

4.1. Wireless sensor networks for assessing the condition of railway structures

Wireless sensor networks consist of a large number of spatially distributed sensors that ensure the monitoring of infrastructures, structures and vehicles. This type of system, comprising a sensor, a base station and a server, ensures real-time monitoring (Figure 19) [94, 97]. In such a system, each sensor node independently collects continuous data in real

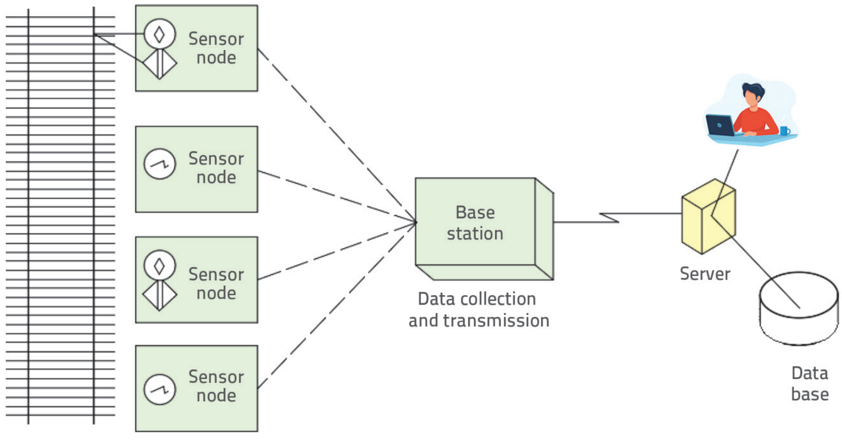

Figure 19. Schematic representation of ongoing monitoring of railway condition [95]

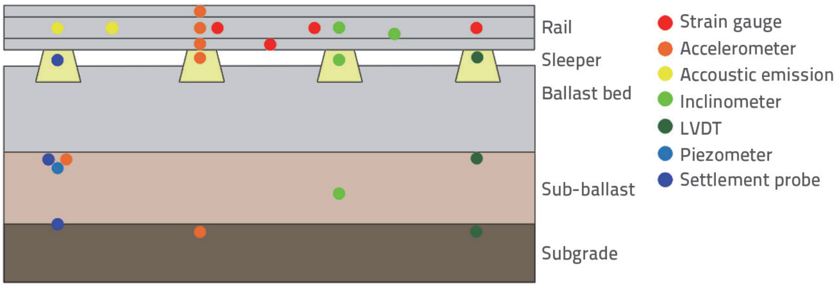

Figure 20. Schematic representation of locations on the track where a particular type of sensor is installed for monitoring the condition of the track [94]

time, which is continuously monitored using several predefined classifications for damage detection or prediction [95]. Considering the increasing axle loads and speeds of train traffic, as well as the more frequent weather disasters to which railway infrastructure is exposed, the need for this type of monitoring is becoming more and more evident. Monitoring makes it possible to detect cracks and rail buckling, settlement of the railway structure, etc. In addition, various sensors are used to detect ground changes such as changes in pressure, tension and displacement [98].

Different levels of detail can be used for construction monitoring, depending on how sophisticated the system is. The paper [99] defines several levels of monitoring detail, with the first level covering only damage detection, level 4 including damage detection, location, frequency of occurrence analysis, and consequences of damage, and level 5 including recommendations for the removal of specific damage in addition to all of the above. Consequently, it is evident that a more sophisticated monitoring system is needed at a higher level.

Numerous types of sensors, including accelerometers, displacement sensors, temperature-detecting optical sensors, strain gauges, gyroscopes, tilt sensors, piezometers, magnetic-electric sensors, ultrasound, and the like, are employed to create a continuous monitoring system [95]. Figure 20 shows the locations where these sensors are installed.

The main disadvantage of this kind of monitoring is that it requires a source of electricity at the locations where the sensors are mounted, necessitating the use of extra batteries. It also requires a significant volume of data to be processed.

4.2. Utilizing infrared thermography (ICT) to assess the condition of railway structures

Infrared thermography can be used to determine the condition of individual track elements. This is based on the fact that, for example, the newly installed material of the ballast bed has different thermal properties than the muddy ballast, as a higher proportion of small particles in the ballast bed leads to a longer retention of water and thus to lower temperatures. Figure 21 shows the surface temperature of a clean and a muddy ballast bed in relation to the temperature of the underlying structure. Since the condition of the ballast bed affects the lateral resistance of the track, this type of monitoring is of great importance at high temperatures, that can cause the rails to buckle. As the surface of the observed object depends on the environment, thermographic surveys are best carried out in stable weather. The properties of the material, including its heat capacity, convection, thermal conductivity and variations in infrared radiation, are also crucial.

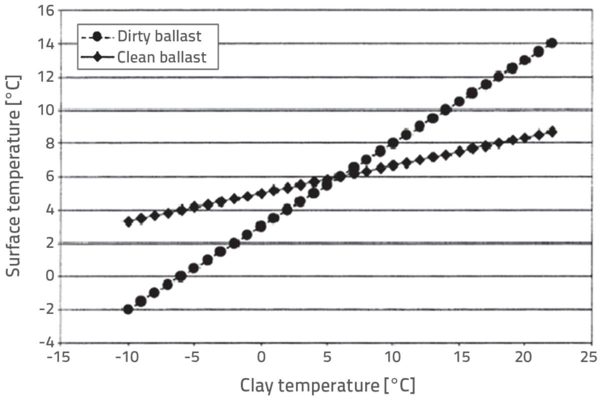

Figure 21. The temperature of the ballast surface in relation to the temperature of the underlying structure and the atmospheric temperatureu [100]

Infrared thermography was used in paper [93] to detect both internal and external deterioration on the tracks on a solid surface. At ambient temperatures over 20°C, the study

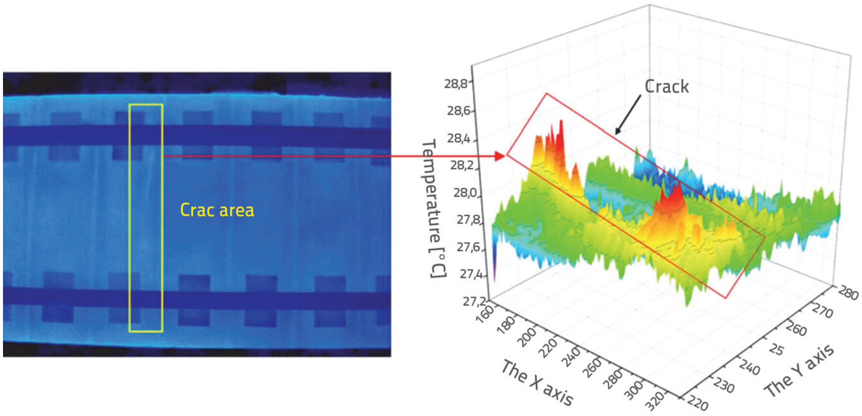

Figure 22. ICT damage testing of the railway concrete slab [93]

demonstrated that this technique may successfully identify cracks on the surface of a plate measuring 0.14 mm in width (Figure 22). According to research [101], the behavior and accuracy of the heaters on the turnouts can be examined by using the ICT technique (Figure 23).

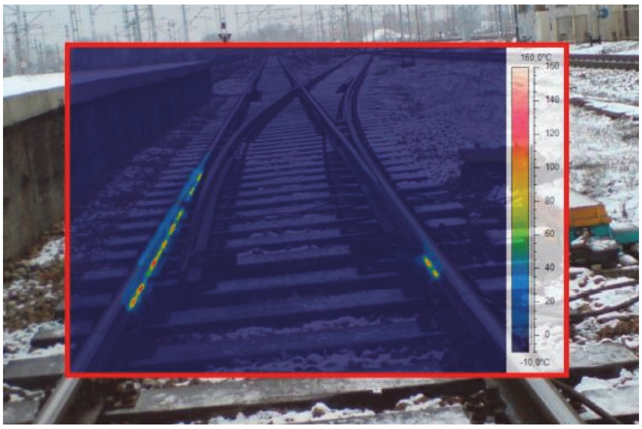

Figure 23. ICT snapshot of the control panel showing the heating temperatures [101]

4.3. Use of unmanned aerial vehicles to detect the condition of railway track

Implementing control and monitoring is extremely difficult due to the vast lengths of infrastructure facilities. For this reason, automated, easier, and more effective solutions are being sought after more and more these days, with the usage of unmanned aerial vehicles showing excellent results [96]. Aircraft or aerial vehicles without a crew that can be operated remotely or that can fly on their own with a pre-programmed flight plan are known as unmanned aerial vehicles, or UAVs [102]. Originally created for military applications, these aircraft are now often employed in economic and scientific domains. Based on their characteristics such as size, weight, flight time, distance and flight height, the following three categories are defined: tactical, strategic and special purpose aircraft [103].

According to [103] unmanned aerial vehicles must fulfill the following fundamental requirements to be used for recording: the ability to carry recording and navigational equipment, the ability to execute a pre-planned flight, flight autonomy, and the capacity to absorb vibrations and other outside influences while in flight.

Unmanned aerial vehicle use has been more widespread recently on various road and rail facilities in Europe and around the world. They are most frequently used to evaluate the state of infrastructure facilities [104], track, turnouts, and contact line conditions [105], monitor landslides on embankments [106], and analyze damage to infrastructure facilities from natural disasters like earthquakes, floods, and fires [107]. Drones can be fitted with a variety of sensors during control, including thermal or infrared cameras, laser rangefinders, and ultrasonic sensors, which can provide information about the environment and condition of the observed object, vegetation near the object [108-110]. Unmanned aerial vehicles can be used to create a three-dimensional (3D) model of the terrain or item; however, this requires taking a lot of pictures of the area under study that overlap in both the longitudinal and transverse directions. Using computer programs, these photos are connected into a single whole, creating a cloud of points, that is, a set of points in a coordinate system [103].

The use of unmanned aerial vehicles for monitoring the railway infrastructure reduces the costs and time required for track control, given that they cover a wide area in a short time [111, 112]. Drones offer a superior option to conventional techniques for collecting data on track conditions because they may be used to study and record vast and challenging-to-reach locations, as well as to make various adjustments to meet user needs. By utilizing them, data collection is quicker and less expensive because fewer samples need to be taken from the field, and the pilot's life is not in danger in the case of an aircraft malfunction or crash. Safety is further increased by the fact that filming may be done without halting traffic and that no personnel are required close to the track. Their limitations include limited battery capacity, the inability to operate in all weather conditions, the expense of building and maintaining the aircraft, and the potential of falling [103, 112].

In [113], the use of unmanned aerial vehicles equipped with infrared cameras to assess the condition of the track ballast bed is investigated. In the initial phase of the test, the ballast bed samples were recorded with a permanently installed camera to show that temperature fluctuations for different ballast bed situations can be identified with an infrared camera. The temperature fluctuations of four different ballast bed samples – a clean sample, a wet sample and samples with 25 % and 50 % fouling - were examined with a camera positioned at a height of 2.4 meters. Following this test phase, a test was carried out on a moving structure to determine whether drones could be used for thermographic imaging and to define the ability to distinguish temperature during camera movement.

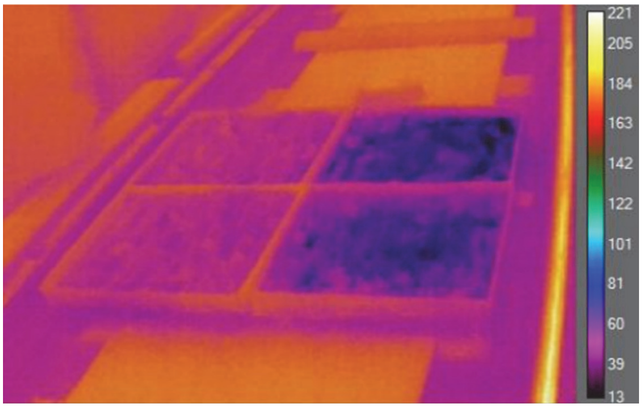

Figure 24. Thermogram of samples at a camera movement speed of 1 m/s [113]

Figure 25. The use of drones and thermography to control the correctness of heaters on turnouts [114]

During the test, various samples of the ballast bed were placed in shallow wooden containers and the camera was positioned on the device at a height of 1.7 meters (Figure 24). During the test, the device moved at different speeds and the ambient temperature did not change. The measurement showed that the condition of the ballast bed in relation to fouling can be determined from the recorded temperature differences. The Dutch railway company ProRail often uses unmanned aerial vehicles with infrared sensors to monitor the operation of the heating system on turnouts (Figure 25).

5. Discussion

5.1. Impact of climate change on railway tracks

Climate change can cause major damage to railway lines, leading to interruptions in rail traffic and high repair costs. In the event of severe storms, it is important to carry out track inspections as quickly as possible to determine whether rail traffic can continue or whether it must be stopped. Extreme

Table 7. A summary of the impact of climate change on the railway structure elements

Climate factor	Impact on railway infrastructure	Standard methods for protection
High temperature	▪ Rail buckling	▪ Increase in the lateral resistance of the track ▪ Rail coating
	▪ Malfunctioning of turnouts	
	▪ Wire elongation of the overhead line	
Snow, ice and extremely low temperatures	▪ Ice formation on the wires of the overhead line and the third rail	▪ Coating the contact line with an antifreeze compound ▪ Application of a vibration pantograph ▪ Installing the heater on the third rail
	▪ Malfunction of turnouts due to accumulation of snow and ice	▪ Placing heaters on turnouts
	▪ Ice formation on rails	▪ Use of special railway vehicles to remove ice from the tracks
	▪ Rail cracks, cracks on reinforced concrete sleepers	
	▪ Freezing in the tunnel	
	▪ Freezing of platforms at railway terminals	▪ Implementation of more frequent maintenance measures
Stormy gusts of wind and thunderstorms	▪ Falling trees on tracks and overhead lines ▪ Wire rupture of the overhead line ▪ Damage to signaling devices	▪ Regular maintenance of the vegetation of track-side
	Overturning of high-speed passenger trains and empty freight cars	▪ Construction of windshields against bora
Floods	▪ Changes in track geometry due to the settlement of railway embankments	▪ Ongoing weather monitoring and providing the required equipment (installation of a flood defense system) to vulnerable areas when floods are predicted ▪ Regular maintenance of the drainage system ▪ Installation of pumping stations in critical locations
	▪ Rinsing of the ballast bed	
	▪ Malfunctions in signaling devices	

weather conditions that can have a negative effect on rail infrastructure are listed in Table 7. It is important to identify and repair damage to the rails caused by severe weather as quickly as possible so that rail traffic can continue unhindered.

In addition to the track elements, climatic changes, especially high temperatures and heavy rainfall, also have a negative impact on the implementation of regular track maintenance measures. High temperatures make it difficult to keep track of height and direction. If the track is tamped in extremely hot weather, for example, track buckling can occur, and in very cold weather there is a risk of the rails breaking [115]. As the tamper lifts the track during tamping, the lateral resistance of the track is immediately removed, which means that in this case high rail temperatures lead to buckling of the track. Considering this, it can be said that a longer period between extremely high temperatures shortens the amount of time the track can be controlled in height and direction. This can lead to a deterioration of track geometry, the development of more dynamic forces in the track and faster wear of the track components. The direction and height of the tracks on the Croatian Railways network are mechanically controlled at temperatures that can deviate by up to ±15 °C from the required temperature, which is 22.5 ± 3 °C in the continental part of Croatia [33]. At higher temperatures, track tamping with dynamic tampers can be used, but even in this case care must be taken to ensure that temperatures do not reach the extreme values of the summer months. In view of the rising temperatures in Europe throughout the year, it can be assumed that such temperatures will lead to the mandatory use of track tampers with dynamic stabilizers, which is not yet the case today and will certainly lead to an increase in the cost of track tamping.

During heavy rainfall, it is important that the ballast bed remains in good condition, i.e. with a low proportion of small particles, to ensure effective drainage. In the event of excessive rainfall, effective drainage cannot be guaranteed and water retention in the track leads to redistribution of the ballast bed material, which can lead to settlement [116]. Such settlements will require more frequent implementation of regular track maintenance measures. Additionally, when the ballast bed is crushed by traffic load, tiny particles are produced that, when combined with regular precipitation, can reduce its elasticity. For these reasons, screening or replacing the ballast bed is more frequently required.

5.2. Suggestions for mitigating the adverse effects of climate change on current railway tracks

To maintain the positive characteristics of the track, more regular maintenance measures are required due to the increased exposure of the railway infrastructure to unfavorable weather conditions. To prevent the track from buckling due to high stresses in the rails caused by high temperatures, it is essential to maintain a high value of lateral resistance while taking regular measures to maintain the track superstructure. In addition, by maintaining the vegetation of the railway line, it is possible to avoid trees falling onto the contact line and track during storms. Regular maintenance is important to ensure adequate drainage of the tracks and regular cleaning is necessary to prevent the accumulation of leaves and other debris as rainfall becomes heavier. It is essential to determine how to handle traffic when the water level rises and at what water level to stop the traffic. Once the flood has subsided, it's essential to establish protocols for the immediate inspection and restoration of the tracks.

As Table 7 shows, there are some weather conditions that cannot be remedied by preventive measures; in these cases, track refurbishment is required. The use of new track monitoring systems is a good option to quickly detect the condition of the track and possible weather-related damage after severe weather [81]. Some of the latest track monitoring methods that are increasingly being used on railway infrastructure. One of these techniques is the use of unmanned aerial vehicles. Initial studies on the use of unmanned aerial vehicles equipped with infrared cameras to detect track problems have been carried out on part of the Croatian railroad network. The aim of these studies was to determine the condition of the ballast bed by monitoring its recorded temperature values. The results showed that this monitoring can be used to determine the condition of the ballast bed.

5.3. Adaptation of new railway tracks to climate change

As extreme weather conditions become more frequent, studies must be carried out to determine the weather conditions that the track structure will be exposed during its lifetime and to determine the highest level of weather extremes that can be expected during the operation of the track. This is necessary for the planning of new and the maintenance of existing track systems. Historical data and climate models can be used to predict the future development of climatic conditions. Based on this prediction, measures to prevent track damage due to unfavorable weather conditions can be anticipated.

Research needs to be carried out into how wind affects vehicles such as empty freight wagons and high-speed trains, as well as track structures, viaducts and bridges, to reduce its harmful effects. During planning, wind protection devices or wind barriers must be provided at the points most susceptible to strong gusts of wind.

In addition, the risk of rail buckling can be reduced by choosing the correct neutral temperature of the rails and by using techniques to lower the rail temperature in direct sunlight (e.g. by adding different coatings). The neutral temperature of the rail must be determined taking into account the current outdoor temperature data and the expected temperatures during the lifetime of the track. To prevent buckling of the track, the best type and shape of sleepers and the installation of devices to improve lateral resistance must also be provided. The lateral resistance of the track can also be improved by changing the proportions and shape of the ballast bed.

For newly planned railway infrastructure, thorough protection measures must be developed and implemented at the planning stage if there is a risk of flooding in the area due to heavy rainfall. This can be ensured by ensuring that the level is above the expected flood level, that the drainage system is carefully planned and that culverts with a higher flow capacity ensure the outflow of flood water.

Current infrastructure monitoring systems are able to anticipate any problems associated with climate change. To monitor changes in the track structure, such systems can be anticipated at the design stage and include the installation of sensors on the track (e.g. near the rails) that record temperature, displacements, vibrations or other parameters in real time. The installation of this type of remote monitoring technology makes it possible to intervene immediately in the event of anomalies or possible damage.

6. Conclusion

Track infrastructure must be adapted to the significant problems caused by climate change, which is characterized by rising average annual temperatures, more frequent extreme weather events and heavier rainfall. To raise awareness of the negative consequences of unfavorable weather conditions and encourage swift action, this article describes how climate change affects certain components of the ballasted track superstructure. The most widely used strategies to mitigate climate change, including improving the drainage system, using new technologies and techniques to protect individual track elements and applying contemporary monitoring techniques, are discussed along with the analysis of the adverse effects.

Given the increasing importance of rail transportation as an environmentally friendly mode of transport, resilience to climate change must be considered in the construction and reconstruction of railway lines. Regular track inspections, especially after extreme weather events, are key to ensuring safety. The use of technologies such as drones and sensors that monitor the condition of tracks in real time makes it possible to quickly detect damage after an extreme event and make informed decisions about continuing or stopping traffic.

By adapting to climate change, railway infrastructure reduces the risk of financial loss, traffic congestion and expensive remedial measures. It can be argued that a combination of modern monitoring technology, preventative maintenance practices and the anticipation of rapid remediation in the event of track damage is required to ensure the long-term resilience of the railway line to climate change. Ignoring the above challenges would not only jeopardize the financial sustainability of the system, but also its ability to meet the growing demand for fast, safe and reliable transport. To adapt rail transportation to increasingly challenging weather-related conditions, new monitoring and maintenance techniques must be employed as train speeds and frequencies increase.

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