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ORIGINAL RESEARCH

Railway operations in icing conditions: a review of issues and mitigation methods

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Abstract
This article focuses on studying the current literature about railway operations in icing conditions, identifying icing effects on railway infrastructure, rolling stock, and operations, and summarizing the existing solutions for addressing these issues. Even though various studies have been conducted in the past on the impact of winter, climate change, and low temperatures on railway operations, not much work has been done on optimizing railway operations under icing conditions. This study demonstrates that further research is needed to better understand ice accretion and its effects on different parts of railways. It appears that railway infrastructure faces serious problems during icing conditions, and additional research in this field is required to precisely identify the problems and suggest solutions. Therefore, it is important to enhance the knowledge in this area and suitable optimal and cost-effective ice mitigation methods to minimize icing effects on railway operations and safety.

Keywords Railway infrastructure · Icing · Ice mitigation · Snow · Railway operations

1 Introduction

Railways are always in the spotlight because of their advantages and strategic role. Customers mostly choose railway transportation because of its safety and reliability. However, some natural phenomena can affect railway systems and disrupt their operations. Safety, mobility, accessibility, economic efficiency, and infrastructures are different aspects of any transportation system that can be affected by weather conditions. Many countries experience harsh winters and extreme cold resulting in snow and icing conditions. For example, in some railway areas in Norway, Sweden, and Finland, the atmospheric temperature can drop to -20 and -30 ℃. Also, railways

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in Canada, Russia, and the United States experience low temperatures of around -35 ℃ (Rossetti 2003; WeatherSpark 2022). While in areas where snow is widespread, an increasing number of railroads, both Common-Speed Railway (CSR) and High-Speed Railway (HSR), have been built. Some new HSR routes in China and Japan, the Trans-Siberian CSR in Russia, the Helsinki-Tampere HSR in Finland, and the Frankfurt-Cologne HSR in Germany are some examples of such railroads (Gao et al. 2020). Moreover, in some HSR lines in cold areas, there are plans to increase operational speed which means more challenges for railway systems to protect their safety in winter (Luo et al. 2020).

During cold temperatures around -25 or -30 ℃, a reduction in train speed by at least 10–20 miles per hour is necessary. Also, cold weather conditions cause different air pressures along the train, which affects the air brake system. As a result, to keep consistent air pressure throughout the air brake system in temperatures below -25 ℃, trains must be shortened. In addition, infrastructure failures are becoming more common in this situation, resulting in a decrease in the system's overall speed. Furthermore, when an incident occurs, it may take longer to recover the railway system (Seglins 2018).

Along with operational difficulties, snow and ice can seriously damage infrastructures and equipment, posing safety issues and high expenditures. In the Netherlands, snow is the first cause of weather-related infrastructure failures; also, ice is among their most frequent causes (Stipanovic et al. 2013). In Canada, rail operations expenses increased 9% in 2019 due to snow and ice. It also caused a derailment, which claimed three human lives and cost C$69 million in casualty costs (Nair 2019). In 2020, 33 cars of a 144-length freight car derailed in an ice-jacking accident caused by ice and snow buildup beneath a rail. As this train carried crude oil, six homes in the area were evacuated as a precaution (TSB 2020). In Sweden, severe weather conditions account for 5 to 10% of total infrastructure failures and 60% of delays in railway operations (Thaduri et al. 2021); as a case, Sweden experienced 83,000 h of delays and $389 million in costs in 2009/2010 due to extremely cold weather and heavy snowfall (Vitale 2020b). In Sweden, the number of failures causing train delays is up to 41% higher in winter than in summer (Stenström et al. 2012). Also, about 25% of railway infrastructure component failures (switches and related components) are related to ice (Hassankiadeh 2011). In the USA, frozen precipitation causes almost 20% of railway infrastructure damage due to severe weather. Derailment, collision, and obstruction, respectively, with average costs of $10 million, $150,000, and $78,000 are the most reported damages (Rossetti 2007). Ice and snow caused 160 total accidents during the winter months, accounting for 18.5% of all incidents, which means approximately 8% of the total damage costs, around $15 million and $90,000 in average damages per incident (Vitale 2020a).

The significance of ice and snow research in railway operations cannot be overstated. Many studies have been conducted on the impact of climate change or winter issues on railways, but not much work has been done by researchers about icing effects on railway infrastructure and operations. Due to increasing human activities in the high north regions of the world, where icing is an important safety aspect, there is a growing need to improve knowledge about the safe design of railway infrastructure and operations in icing conditions. This study reviews previous research in this subject. Also, it categorizes these studied issues in three parts (infrastructure, rolling stock, and operation), then for each part the mitigation methods are discussed. Finally, the impact flow of ice and snow on railway systems and eventual consequences are presented.

2 Railway infrastructure

Aside from human resources, infrastructure is the most crucial component of any railway system. Infrastructure refers to the elements that are either part of the railway (*for example, ballast, ties, track, bridges, and tunnels*) or adjacent to it (*lineside structures like signs, mileposts, switches,* etc.) (Burns 2022). Railway companies invest heavily in their infrastructure. These expenses are associated to planning, design, construction, and ancillary fees (Attina et al. 2018). According to the European Commission report in 2017, the costs of investing in railway infrastructure are anticipated to be 8.2 million euros per kilometer for new conventional rail lines, 6.1 for upgrading existing lines, and 14.1 and 5.4 for high-speed lines (Attina et al. 2018*)*.

According to previous studies, railway construction in cold regions differs from normal areas. The high cost of infrastructure is one example. In these conditions, conventional methods to railway design and construction are predicted on raising the needed resources, which leads to an increase in their cost (Akkerman et al. 2018). The effects of extreme weather events on railway infrastructure can be significant. So, it is important to integrate the new solutions to combat icing and maintain the safe operations of the railway. For example, the failure of a railway signal switch can lead to fatalities; therefore, suitable ice mitigation systems are required (Palin et al. 2021). Railway infrastructures are vital and must be carefully maintained. At the same time, climate issues complicate the safety of infrastructure. Garmabaki et al. (2021) qualitatively identified and analyzed the impact of climate change on railway infrastructure, as well as the risks and consequences. Using a questionnaire from transportation infrastructure experts, managers, maintenance organizations, and train operators in Sweden, they discovered that even in 2021, there is a low degree of understanding regarding the impact of climate change on many aspects of railway infrastructure. Stenström et al. (2012) worked on the effect of cold climate on railway infrastructure using statistical modeling and maintenance data. They tried to evaluate if seasonal changes affect the failure in infrastructure or not. After comparing work orders and failures at different time intervals and temperatures, it is proved that icing/cold climate can affect the dependability of railway infrastructure, which means capacity and quality of service are affected, and maintenance works should be increased. A correlation between weather conditions and infrastructure failure modes has been established and researchers determined the threshold for the likelihood of occurrence of specific failures. A risk assessment methodology is used in this study, which includes identifying weather-related failures of railway infrastructure, analyzing the failure probability of railway infrastructure due to weather events, determining the vulnerability of railway infrastructure to climate change, and developing adaptation strategies (Stipanovic et al. 2013).

Among winter issues, ice and snow are significant threats for railway infrastructures in cold regions. Snow and ice can cause considerable damage to most of the infrastructure components. According to the literature, the following issues (Table 1) are the most common problems associated with the ice and snow effects on railway infrastructure.

2.1 Signaling system

Icing on railway overhead power lines can jeopardize the network's safety and reliability. As a result of prolonged icing, power outages and tower collapses are possible. Icing on railway contact wires can cause various issues such as overloading, arc formation, mass imbalance, and galloping power lines, which are critical issues for engineers and researchers. This is more challenging for light rail transit systems than it is in conventional rail systems. Studies mentioned the following cases as significant for hazardous wire icing (Er and Çakir 2018; Heyun et al. 2012; Solangi 2018):

- Performance reduction of the contact wire
- Divergence of the contact wire
- Occurrence of electric arcs
- Occurrence of insulator flash-overs
- Occurrence of galloping power lines

According to the appearance on wires, icing can be classified as glaze, granular rime, crystalline rime, wet snow, and mixed rime (Heyun et al. 2012). Their dependency on atmospheric conditions and the growth rate of these ice categories are different from each other (Makkonen 1984). Air temperature, relative humidity, and dew point are significant factors in the probability of ice formation. ProRail reported that distortions in electric signals increase during winter due to ice accumulation (Garcia-Marti et al. 2018).

Studies show that the most common climate failures are caused by the snow and ice in switches and their protection is one of the most promising strategies chosen for railroad adaptations to winter phenomena (Doll et al. 2014). Researchers proved that the failure of switches is almost certain in conditions of -12 °C or the presence of 50 mm of snow per day (Stipanovic et al. 2013), where switches are extremely important in railroads, in terms of capacity and maintenance costs, as well as their role in ensuring the safety of railways (Stenström et al. 2012; Szychta et al. 2012).

Trying to solve the problem of ice on overhead wires has a long-lasting history. Makkonen (1984) worked on modeling ice accretion on wires like overhead power-line conductors. He used a time-dependent numerical model to simulate the amount of accreted ice on wires according to atmospheric conditions. In 2003, an ice-prediction model was developed in order to provide short-period forecasts of ice on the wires. It was a statistical model which provides forecasts of wire surface temperature and state (icy or not) for three hours ahead. Additionally, forecasts included air temperature, dew point, and wind speed. Validation results show slight bias in predicting wire surface temperature, air temperature, dew point, and wind speed (Shao

Table 1 Possible issues due to snow and ice on railway infrastructure (Garcia-Marti et al. 2018; Kostianaia et al. 2021; Nemry and Demirel 2012; Palin et al. 2021; Stenström et al. 2012; Tahvili 2016; Thaduri et al. 2021; Thornes and Davis 2002; Zakeri and Olsson 2018)

Railway infrastructure issues related to icing	Signaling system	Icing on overhead power lines, pantographs, and third rails
		Malfunctioning of switches and turns due to freezing ice
		Trackside equipment like substation traction power
	Track	Snow/ice accumulation on rail tracks
		Cracking rail
		Material failure of sleepers and railway track due to low temperatures
		Rockfall on tracks
		Tunnel icing, particularly at the entrance
	Platforms, stations, and parking spaces	
	More frequent and costly maintenance	

et al. 2003). In 2009 researchers developed an Ice Accretion Forecasting System (IAFS) for power transmission lines using a mesoscale, numerical weather prediction model, a precipitation type classifier, and an ice accretion model. The results confirmed the model's feasibility and approved the performance (Musilek et al. 2009).

2.2 Rail track

Icing conditions can severely affect the rail pavement, and rail tracks can experience contraction forces exposed to ice and snow. Continuous Welded Rail (CWR) is particularly vulnerable to these effects, resulting in track breaks during the winter months. The track stiffness can increase at a low temperature and reduce the strength of the track so that the probability of broken rails increases in the presence of wheel-rail force and higher tensile stress. Rail degradation is another problem which is caused by frost heave. Frost heave happens when freezing water in the ballast results in expansion, moves the track beds, and causes irregularities in track geometry. Differential frost heave can affect track performance and result in speed restrictions due to freeze-thaw cycles (Kostianaia et al. 2021; Silvast et al. 2013; Tahvili 2016); also, ice is the main factor that can influence the properties of frozen ballast layers (Li et al. 2022).

Akagawa et al. (2017) collected ballast and subgrade layer samples from tracks in northern Japan to examine their frost heave susceptibilities and their mineral compositions. They used this experiment with temperature sensors (PT-Resistance Sensor) and X-ray diffraction analysis. They confirmed that the frost heave susceptibility is related to the saturation ratio of the fine materials in its voids, even if the voids of the crushed rock are not saturated with fine materials. In the research of Hodás and Pultznerová (2019), a numerical modeling experiment was presented to find the temperature transition through the individual layers of the track formation during the winter. They explained that frost heave occurs not only in the subgrade but also in the ballast layer. It has been discovered that the ballast layer of a railway track contains frost-susceptible fine materials such as clay minerals and that they heave in winter if the conditions are favorable. Due to frost heaving, the ballast layer might be extended vertically in the winter. So, in this situation, keeping track smoothness at an acceptable level using track maintenance is required; also, it has been shown by experiments that the size of the track formation influences the freezing of its sub-ballast layers. Due to the accumulated heat in the pre-winter period, the depths of freezing will be smaller if the mass in the core of the railway formation is larger (Hodás and Pultznerová 2019).

Furthermore, refreezing snow that has melted can be a bigger issue. It takes longer to melt, can get stuck in switches, harm other infrastructure, and even damage rolling stock (Zakeri and Olsson 2018). Since the typical temperature range for normal maintenance is between -10 ℃ and +30 ℃, after the winter season, a high maintenance & repairing cost can occur (Nemry and Demirel 2012). The formation of ice in rock cracks could result in the collapse of rocks, which might then fall onto the rail track. Ice formation at the entrance of railway tunnels might not only fall onto the track but can also damage the train body (Palin et al. 2021). Researchers studied the possibility of using new materials (Sulfur concrete) for the construction of railway beds in subpolar regions. Using a computer simulation of the “wheel-rail” interaction, laboratory, and field experiments, they showed that the rail geometry stayed constant during all experiments, so it seems that it is a suitable material for use in rail beds in cold regions (Akkerman et al. 2018).

2.3 Ice mitigation methods for railway infrastructure

Anti-icing and de-icing systems are different ways to mitigate the effect of ice and snow. The anti-icing mode prevents ice formation, but in de-icing mode, ice is allowed to accumulate on the surface to a certain level, and then the ice will be removed (Muhammed and Virk 2022). Many ice and snow issues can be reduced or even avoided by taking some precautions during the design phase. It is also possible to control the icing consequences by taking some action before and after the ice accretion. Table 2 highlights some solutions that are used for mitigating the icing on railway infrastructure (Tahvili 2016).

Manual de-icing is the first method for wires, tracks, and switches; despite the fact that it is a time-consuming, inefficient, and dangerous operation, many large domestic railways still use this method to remove ice from infrastructures. Another method is to use contact wire thermal running. If ice thickness reaches the warning level, the control center initiates de-icing operations by allowing electric current to flow through the overhead contact wire. Also, preliminarily operating a heating system in the running rail and guiding rail based on weather projections is a generic technique for anti-icing on railway infrastructures, but it increases the power costs and lowers the lifespan of the concrete running rail resulting in higher maintenance expenses, so a reliable standard for the operation time of the electric pre-heating system is needed. It is also possible to use anti-icing chemicals to lower the freezing point of water and thus prevent icing. However, the environmental pollution caused by chemical scattering is a concern (Er and Çakir 2018; Kim et al. 2014; Zhou et al. 2022). For switches, some railways use gas-fed heaters that run alongside the rails to keep them warm. Manual lighting and constant observation are required for these heaters. Water heating, and geothermal heating are also used in smaller rail facilities (Szychta et al. 2012). Moreover, some heating technologies were developed to stop the growth in CO2 emissions. These systems utilize geothermal energy, so use less electricity and user costs are reduced as a result (Doll et al. 2014).

Ice mitigation strategies can work efficiently when ice accumulation is detected precisely. For this purpose, ice detection systems are required to be used before the mitigation phase. In railway industries, some works have been done to monitor the infrastructure situation. In a study using the Internet of Things (IoT), a high-resolution monitoring of weather impact on infrastructure was proposed. Mitigation actions can be targeted particularly to susceptible infrastructure due to the fact that weather impacts can be forecasted with a great precision (Chapman and Bell 2018). The Tampere University of Technology has also created a monitoring system that

Table 2 Solutions for mitigating ice/snow for railway infrastructure (Er and Çakir 2018; Tahvili 2016)

	Design aspects	Systems and equipment	Instruction and action
Infrastructure	Network location exposed to a minimum of threats	Barrier/fence	Ice and snow clearance
	Design enough space for snow storage	Automatic weather stations	Tunnel insulation
	Increase robustness of infrastructure sub systems	Ballast nets	Vegetation management
	Hoisting track above the ground	Switch heater and protection	Hill-side securing
	Design concrete bed/slab track	Heating systems for current collection component	Inspection and maintenance
	Use modern material for rail alloys	Sprinklers and slush/mixture pumping system	Hydrophobic and high emissivity coatings
	Special catenary surface and line design	Track drain system	
		Avalanche warning systems	
		Avalanche detecting systems	
		Monitoring and measurement systems	

uses analog semiconductor-type temperature sensors, a heave sensor, and dielectric-type moisture sensors to measure the frost depth and frost heave of railway track structures in Finland. They use this device to determine the frost penetration depth, seasonal frost heave, and spring thaw period. The monitoring's ultimate goal is to enable field modeling of frost heave based on material parameters measured in the lab and under field conditions (Pylkkänen et al. 2012). Also, some sensors have been introduced which can monitor switches during ice and low-temperature seasons (Eologix 2019).

3 Railway rolling stocks

In the railroad industry, the term "rolling stock" refers to anything on rail wheels, including locomotives, freight cars, flat cars, and other vehicles that use steel wheels on railroad tracks (EPA 2021). Rolling stocks are railroad capital assets that must be properly maintained. According to their power traction, locomotives can cost between $500,000 to $2 million (Josef 2022). Furthermore, freight cars cost $100,000 to $150,000 depending on their type and design (Blaze 2019). The average annual maintenance costs amount to 3.3% of the vehicle purchase cost (Raczyński 2018). Ice and snow accumulation affects normal operation of rolling stock. It can also affect working reliability of the key components of bogies, passenger comfort, operational quality and the stability of system operation and lead to serious accidents (Gao et al. 2020; Liu et al. 2020). Ice accumulation, particularly in high-speed rail, can increase operational costs due to an increased axle load, intensified vibration, failed braking processes, or a degraded dynamic performance (Gao et al. 2020). Cold temperatures, according to Kostianaia et al. (2021), cause changes in the mechanical characteristics of wheel bandage material as well as embrittlement of the material due to a lack of flexibility. The most important effects of ice and snow on rolling stock are mentioned in Table 3.

Xie and Gao (2017) used a discrete phase model (DPM) to study the flow field that carried snow particles in a high-speed train bogie area. They monitored the movement of snow particles and showed that the air flow in regions with cavities will rise and affect the wheels, electromotors, and other parts of the bogie area. Also, the snow particles follow the air's path line. These snow particles become trapped and consolidated in the bogie area. Ice accumulation also poses a hazard to pneumatic, magnetic, and disk braking systems, and can result in lower brake capacity and a fail of the braking process, resulting in longer breaking distances. To address these issues, train lengths or speeds should be decreased, affecting service capacity and quality. Also, ice accumulation on the suspension system might stiffen its components and make it difficult to be flexible enough. In this situation wheel and rail friction can be reduced, resulting in increased wear and bandage issues (Gao et al. 2020; Kostianaia et al. 2021; Seglins 2018; Tahvili 2016). As a concern on the train body, ice accumulation might cause issues with opening and closing doors (NetworkRail 2022). In some special condition, due to the falling of snow or ice accumulation on the bottom surface of vehicles, the ballast flying phenomenon can also happen and damage the train body (Michelberger et al. 2017).

Table 3 Possible problems due to snow and ice in rolling stocks (Gao et al. 2020; Kostianaia et al. 2021; Tahvili 2016; Thaduri et al. 2021)

Rolling stock issues related to icing	Malfunction in Braking system (fail to break or release) Ice/snow packing at lower section of bogies Car doors jamming Malfunction in Suspension system and tilt mechanism Wheel-Rail friction Couplers Power cars, motors, and electrical components Deterioration of the mechanical properties of the material of wheel bandage More frequent and costly maintenance

In 2020, Liu et al. (2020) constructed a computational fluid dynamics-based model of the bogie region to evaluate the mathematical model of the ice melting in an experimental and numerical examination on a real high-speed train unit. The airflow in the baffle-enclosed area was computed using a numerical simulation, and the effects of interactions between air and the ice body on heat transfer and phase change were anticipated. In addition, this work describes a research approach for simulating gravity shedding in complicated models (Liu et al. 2020). In another study on high-speed trains, snow accumulation on bogies is studied. The influence of appropriate anti-snow flow control techniques for guiding the underbody airflow during motion and the accumulation of snow in the bogies' installation zone is discussed (Gao et al. 2020).

By studying bogie suspension elements, researchers showed that the damping and stiffness properties of these suspensions are greatly affected by ice and extreme low-temperature conditions. This may impact the vehicle's dynamic performance and the vehicle's operational safety is seriously in danger (Luo et al. 2020).

3.1 Ice and snow mitigation methods for rolling stocks

According to the classification of ice mitigation methods mentioned in the infrastructure section, these categories are also applicable for rolling stocks ice mitigation systems as well. Table 4 highlights these methods.

Regarding the application in the real world, there are some actions required to mitigate the accumulation of ice and snow under the rolling stocks. The first step is to optimize the bogie structure, which is applicable for newly designed products, then to reduce snow accumulation on the subgrade, and melting snow and ice accumulation in the cavity. But these methods have been discovered to be ineffective options for long-distance HSRs in snowy and cold climates (Gao et al. 2020). Nowadays, the following four methods are commonly used to de-icing the train bogies.

(1) *Mechanical de-icing*: this involves removing ice manually.

Table 4 Solutions for facing winter problems in rolling stocks (Liu et al. 2020; Michelberger and Haas 2015; Tahvili 2016)

	Design aspects	Systems and equipment	Instruction and action
Rolling Stock	Material	Automatic protection systems	Surface covering
	Additional weight for snow and ice	Detection systems	Ice/snow removal
	Round shape	Air dryer filters	Inspection/maintenance
		Heaters and ventilators	
		Electrical de-icing and anti-icing	
		Wheel-rail friction modification systems	
		Deflectors and snow ploughs	
		De-icing boots	

(2) *Hot-water melting*: this method involves using hot water; snow and ice on the bogies are melted automatically, in some cases by adding propylene-glycol to the water; the bogie surface can be protected against ice formation for 24 h (Michelberger and Haas 2015).
(3) *Ethylene glycol melting*: ethylene glycol is implemented in order to improve the effectiveness of the snow removal operation.
(4) *Hot air melting under the train*: heated air is released to heat snow and ice on the bogie surface. Hot-air melting is the most common method in real applications, and it can be divided into convection melting which is mostly used for thin ice bodies, and gravity shedding melting for thick ice bodies (Liu et al. 2020).

The feasibility, application, and meaningfulness of an intelligent monitoring system for identifying critical ice buildup on train bodies to avoid ballast fly introduced by ice fall was investigated in the EISMON project. This project brought together a number of universities and organizations and showed that “the detection of ice on railway vehicles and the development of an intelligent monitoring seem to be possible with existing technologies, but a proof of concept in terms of field tests is necessary”. The primary concept behind this suggestion for an intelligent wayside monitoring system is the combination of different information. The central assessment unit receives data from trains, weather, infrastructure, and other measurement systems, and an ice detection measurement system predicts the risk of icing (Michelberger et al. 2017).

4 Railway operation

In all industries, tangible expenses are simple to understand and evaluate. Similarly, when the word *costs* is discussed in the railway industry, the emphasis is focused on the infrastructure and rolling stocks. However, both the operating expenses and the benefits are significant. For instance, the annual cost of

Fig. 1 Overhead lines damage due to ice accretion (The Railway Transport Union of Slovenia 2014)

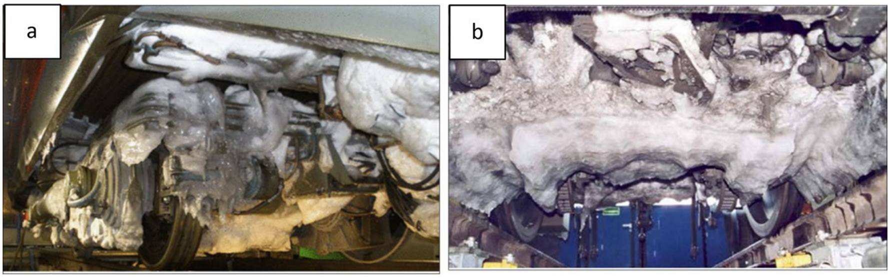

Fig. 2 **a**, **b** Snow accretion under the bogie area (Gao et al. 2020)

main-line delays compared to the annual cost of track and equipment losses caused by mechanical main-line derailments looks important. The average overall train delay cost in the United States is estimated to be around $213 per train hour (Schlake et al. 2011). Researchers presented a value of reduced transportation time variability associated to freight trains of around €4 per delay-tonne (Krüger and Vierth 2015). Also, the cost of an hourly loading delay is over $523 per train-hour, while railway operations and their capacity to sustain service are affected by winter situations (Lovett et al. 2015; Seglins 2018). Studies present that most operation issues due to ice and snow are more delay and reduced punctuality, accidents and lower capacity (due to a decrease in the train length and speed) (Økland and Olsson 2021; Tahvili 2016; Wang et al. 2021; Zakeri and Olsson 2018) (Figs. 1, 2).

4.1 Causes and effects of ice and snow

Besides low temperature and high humidity which are detrimental to railway punctuality, a study on hourly accumulated ice and snow shows that a snow/ice precipitation of 46% increases the transition intensity from non-delayed to delayed states in their model (Wang et al. 2021). In Økland and Olsson (2021), the authors introduced the following reasons responsible for delays in Norwegian railway: low temperatures and snowfall, shortened train lengths, and an increase in the amount of rail services. Passenger loading and unloading processes, processing inbound trains, building outbound trains; inspecting inbound and outbound trains, switching out and repairing defective cars and locomotives and consequently the stopping times and delays will be longer due to ice accumulation on steps, couplers, the train body and the bogies (Seglins 2018).

Since there is a strong correlation between delay hours and reduced seat capacity in passenger trains, ice and snow can also affect the capacity of trains. Furthermore, the impact of snow and ice on railway damages are higher than those of rain and wind (Zakeri and Olsson 2018). In the winter months another significant challenge for railway authorities is maintaining railway platforms safety against ice and snow. Otherwise, any accidents due to slippery surfaces at these places might be catastrophic (Omer et al. 2013). Railroad accidents are more prevalent in the winter than in other months and most of these accidents occur due to snow and ice conditions. Ice and snow play a significant role in producing a range of initial and secondary repercussions in different accidents, such as derailments and collisions, switch blockage, track breakage and other property damage. So, the buildup of snow and ice is the second-most frequently reported cause of accidents/incidents (Kostianaia et al. 2021; Rossetti 2003). Moreover, snow and ice conditions are the top-third cause of more than half of all derailments and they are also among the top weather-related causes of collisions (Rossetti 2007). Researchers used Pearson correlation and multiple regression approaches to investigate the relation between passenger train punctuality and weather conditions in a line in Norway. They demonstrated that by managing winter phenomena, the probability of having trains arrive on time can be increased. Although low temperature and deep snow are associated with punctuality problems in their case, snow depth has the strongest relation with delays. Low temperature is a greater challenge for urban commuter trains than snow, whereas snow depth is a greater challenge for long-distance passenger trains (Zakeri and Olsson 2018).

4.2 Ice and snow mitigation methods for railway operation

In addition to anti-icing and de-icing of infrastructure and rolling stock, special ice mitigation in operation might relate to clearing stairs and platforms. Physical efforts to clear snow or ice, such as plowing, sweeping, blowing, and so on, are suitable in this case. Platforms are also required to be de-iced. DLA (Direct Liquid Application) is an anti-icing technique in which the de-icer is administered in a liquid state. Chemicals which are often used for railway platforms include sodium chloride, sodium formate, potassium formate, urea, potassium acetate, calcium chloride, and sodium acetate (Omer et al. 2013).

5 Discussion

According to its definition, every condition which has the possibility to cause injuries, fatalities, property and infrastructure damages, an interruption of business, etc., should be considered as a hazard (FEMA 1997). Ice and snow, coming from low temperature in winter seasons are hazards for railway operation. According to the definition of disturbance, these phenomena can cause unplanned, high probability disturbances with high impacts on railway transportation (Ge et al. 2022).

Figure 3 shows how these phenomena can disturb the railway operation. These phenomena can reduce safety, capacity, and customers and increase delays, accidents, and costs. For vulnerable railways, it is important to investigate each issue separately, to find out its potential and consequences. On the other hand, a comprehensive risk assessment is needed case by case to identify high risk spots and implement risk mitigation tools.

Figure 3 shows that in the proper situation, snow starts to build up on infrastructure, also ice begins to accumulate on infrastructure and rolling stocks. Everything up to this point is natural, and snow and ice act normally. These phenomena start to show their consequences when the accumulation grows abundantly. So, they have the potential of destroying overhead lines, disconnecting the power, hampering the switch performance, and affecting sleepers and tracks characteristics. Also, ice on the train body can cause difficulties for the crew to carry out their operations and for passengers to reach and get on the train.

Another direct consequence of icing is related to the bogies and wheels which can weaken the suspension, the braking, and electrical systems and change the characteristics of wheels. These problems first lead to delays, and then result in high maintenance expenses. If the maintenance and measurements do not suffice to stabilize the situation, the safety can be affected and, derailment or collisions might happen. In the long run, this phenomenon's final indirect effect is a loss of clients and a reputation that is difficult to make up for. To control the situation, some actions in each level can be performed. From hazard to impact, it is possible to modify the situation in a way that ice and snow accumulation decrease, or after the impact level, mitigate the direct consequences.

6 Conclusion

According to the literature, several research studies have been conducted on the impact of climate change, winter phenomena, and temperature on the transportation and railways. It is found that each of those events needs to be investigated independently and in more depth. Ice is one of those phenomena where possible consequences necessitate a thorough investigation, particularly in railway infrastructure. Many studies propose de-icing and anti-icing technologies that can be used in the railways, but still a wide knowledge gap exists. This review study finds that not much work has been carried out by researchers so far to better understand the

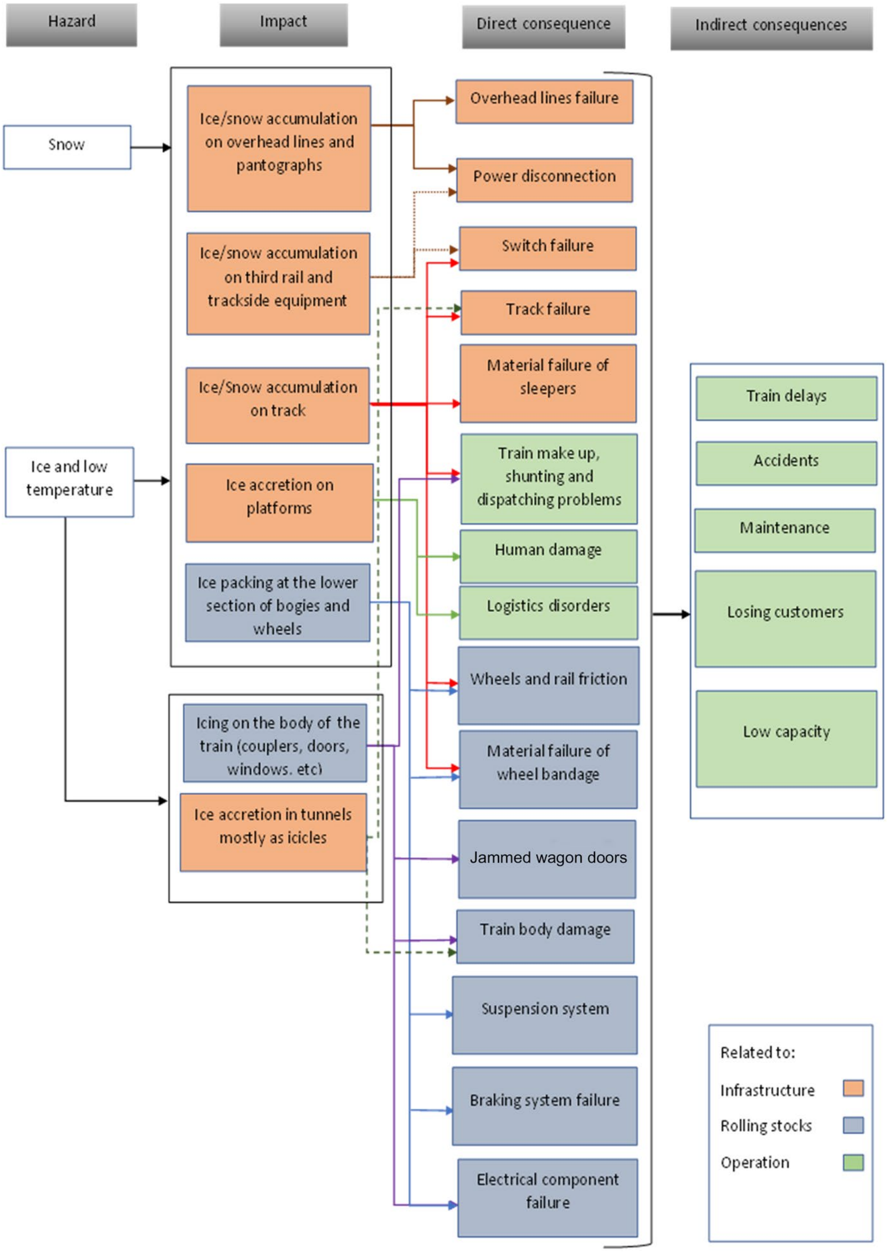

Fig.3 Impact of ice and snow on railways

ice accretion on railway infrastructure and finding suitable solutions; therefore, it is important to enhance knowledge in this area and design optimal and cost-effective ice mitigation methods to decrease icing effects on railway operations and safety.

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Declarations

Conflict of interest All authors confirm that they have no conflicts of interest.

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