CHAPTER 2

Cost assessment of climate change impacts on a railway company

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Abstract

The frequency and severity of climate change impacts on the railway sector are steadily increasing. As a result, railway companies are currently in the process of developing resilience strategies to adapt to these challenges. A key element of this process is the assessment of climate-related risks and the adoption of effective risks mitigation measures. This chapter focuses on the economic dimension of climate resilience by evaluating the financial costs incurred by a railway company due to climate change impacts. Understanding these costs is crucial for assessing the scale of climate risks and for determining the economic efficiency of risk mitigation measures. The chapter identifies, systematizes, and classifies various categories of climate-induced costs borne by railway operators. In addition, it proposes a cost assessment methodology that is particularly suitable for practical application, drawing on a comparative analysis of the best international practices. This approach contributes to informed decision-making in climate adaptation planning for the railway sector.

Keywords

Climate change, railway company, decision making, climate mitigation measures, economic impact, risks assessment, transport-environment interaction.

2.1 Introduction

Climate change has already had significant adverse effects on railway systems worldwide, with projections indicating that these risks will remain high and possibly escalate in the future. According to data from the European Union

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Agency for Railways (ERA), between 2007 and 2023, National Investigation Bodies (NIBs) reported 100 railway incidents directly or indirectly attributed to climatic factors. Weather-related hazards such as heavy snowfall and icing, strong winds, intense rainfall, and fog frequently contribute to train derailments, collisions, and level crossing incidents. Additionally, railway infrastructure is especially vulnerable to flooding – both riverine and coastal – heatwaves, cold spells, and wildfires, although it tends to be less sensitive to windstorms. The recovery period following major flood events can exceed four years, underscoring the prolonged impact of extreme weather events on rail network functionality and resilience [1, 2].

A substantial body of research has addressed the assessment of climate risks at both micro and macro levels within the railway sector, detailing the climatic factors involved, their consequences, and the extent of their impact [1, 3]. There is also extensive documentation of global experience in implementing climate mitigation measures, often with particular attention to regional climatic characteristics [1, 4, 5]. However, despite this knowledge, there remains no comprehensive system of indicators to effectively assess the costs railway companies incur due to the consequences of climate change.

The frequency and severity of climate-related impacts on railways continue to rise, prompting railway operators to develop resilience strategies aimed at adapting to these emerging challenges. Central to these efforts is the systematic assessment of climate risks and the implementation of effective mitigation measures. This chapter focuses on the economic dimension of climate resilience by evaluating the financial costs that railway companies bear because of climate change impacts. Understanding these costs is essential not only for quantifying the scale of climate risks but also for assessing the economic efficiency of various risk mitigation approaches.

In this context, the chapter identifies, systematizes, and classifies different categories of climate-induced costs faced by railway operators. Building upon a comparative analysis of the best international practices, it proposes a practical methodology for cost assessment tailored to the railway sector. This methodology aims to support informed decision-making in climate adaptation planning.

Effective decision-making regarding climate mitigation in railways involves a multi-stage process: beginning with the identification and evaluation of risks and vulnerabilities, followed by the consideration of potential mitigation options, and concluding with the selection of the most effective and feasible strategies (**Fig. 2.1**). This structured approach is critical to enhancing the resilience and sustainability of railway operations in the face of ongoing climatic changes.

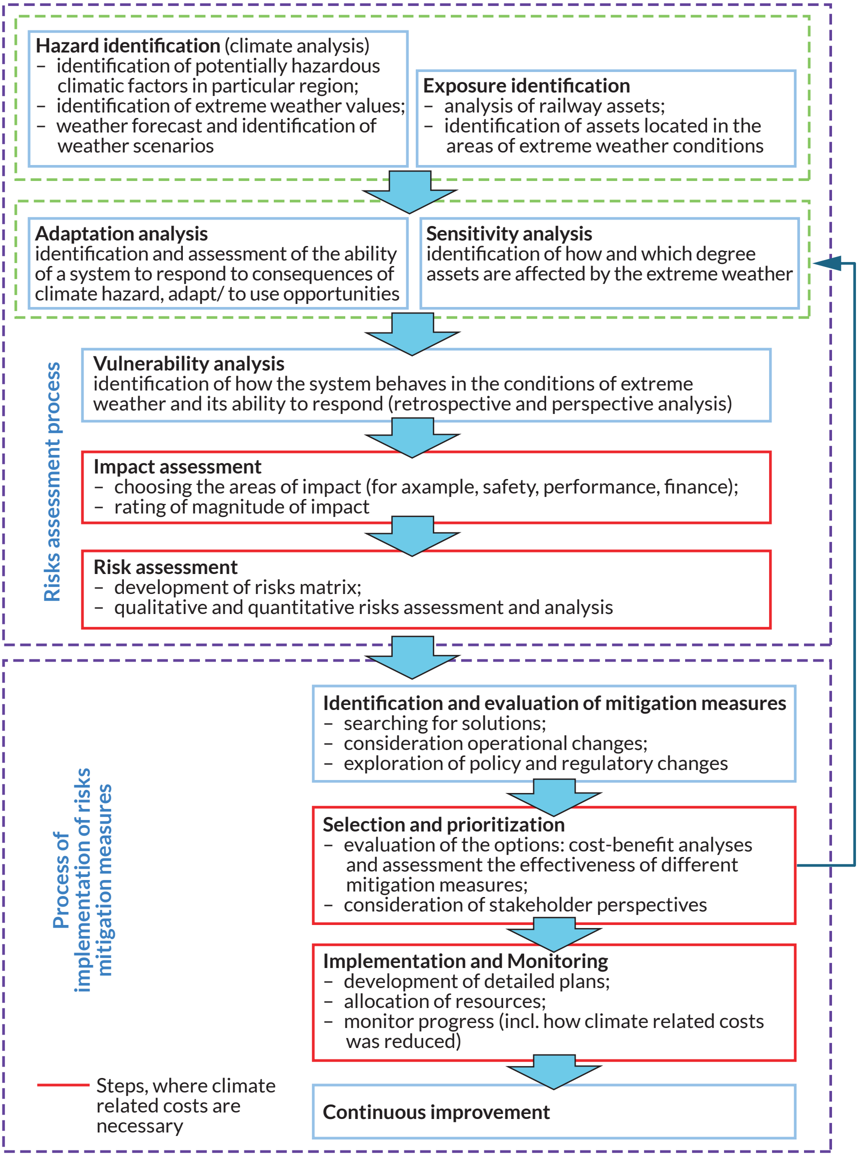

Fig. 2.1 Decision making on climate related risks mitigation measures
Source: authors' development based on [3, 6]

Estimation of climate impact costs is necessary at the following stages of the decision-making process for climate-related risk mitigation measures:

– *impact assessment*: evaluating the extent of climate risk impact on the company's economic performance;

– *risk assessment*: quantitative evaluation of risks expressed in monetary terms;

– *selection and prioritization of risk mitigation measures*: conducting cost-benefit analysis;

– *implementation and monitoring*: assessing the changes in climate impact costs after the implementation of risk mitigation measures.

Based on the analysis of railways worldwide on the climate risks assessment, resilience strategies, climate risks mitigation and adaptation measure the following climate related costs which is taken by the railway company are defined (**Table 2.1**). The costs are classified as direct and indirect.

Table 2.1 Climate related cost of railway company

No.	Cost category	Short description	Direct/ indirect	Methods of calculation
1	2	3	4	5
1	Costs of incidents	General costs related to accidents and emergency situations, including those influenced by climate factors	Mixed	Case analysis, statistical data, expert evaluation
1.1	Costs of injuries and fatalities	Includes medical expenses, production losses, human life valuation, and administrative costs	Direct, Indirect	Actual costs, willingness to pay (WTP)
1.2	Cost of train delays (due to accidents)	Includes delays of locomotives and carriages, extra fuel/electricity consumption, crew overtime, compensations, and penalties	Direct	Actual costs
1.3	Damage costs	Environmental and infrastructure damage caused by accidents or extreme weather	Direct	Actual renovation/recovery costs to initial conditions
1.4	Incident investigation costs	Additional investigation tools and methods applied due to climate-related events	Indirect	Actual costs
2	Maintenance costs	Additional maintenance requirements resulting from extreme weather events	Direct	Life cycle cost analysis (LCCA), actual costs
3	Infrastructure adaptation costs	Investments aimed at increasing climate resilience of railway infrastructure (bridges, tracks, drainage systems)	Direct	Forecasted investment, cost-benefit analysis

Continuation of Table 2.1

1	2	3	4	5
4	Cost of train delays (non-incident causes)	Costs of delays not caused by accidents (e.g., weather disruptions, infrastructure issues)	Direct	Actual costs, time loss valuation
5	Costs related to passenger behavior changes	Costs associated with modal shift caused by climate change (e.g., switch from rail to road or vice versa)	Indirect	Demand modeling, investment analysis, income/expenditure forecasting
6	Costs of reduced worker productivity	Includes loss of wages, medical care, overtime, replacement and training, and reduced performance due to extreme temperatures	Direct, Indirect	Actual costs, labor statistics, productivity models
7	Costs of reputational loss	Includes stock price drop, customer attrition, internal disruption, changes in partnerships, legal consequences	Indirect	Actual costs, event study analysis, market correlation models

Source: authors' development

Direct costs – costs, which railway company can expect to pay out of pocket, immediately after the risk event occurrence. These costs are usually well-dated and easy to keep track of.

Indirect costs – secondary expenses railway company incurs following a risk event occurrence. They accumulate over time. Because of this, Indirect costs can be harder to measure but they generally exceed direct costs.

2.2 Costs of incidents

The variation in the number of weather-related railway accidents over the examined period does not reveal a consistent or discernible trend. While a certain number of such occurrences are investigated annually, the data does not indicate a clear upward trajectory. This is likely influenced by the fact that, in many cases, there is no mandatory requirement to initiate a formal investigation.

NIBs obligatory investigates and report to the ERA on *significant accidents*, which means any train collision or derailment of trains resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other accident with the same consequences which has an obvious impact on railway safety regulation or the management of safety; *extensive damage* means damage that can be immediately assessed by the investigating body to cost at least 2 million EUR in total [7].

Thus, the dataset available in the ERAIL database constitutes only a partial representation of all accidents, reflecting a selected sample rather than the complete scope of incidents.

It is also important to note that, for the years 2022 and 2023, only investigations that had been officially closed were considered in the analysis (**Fig. 2.2**). Moreover, investigation reports frequently lack clear attribution of causes or fail to specify whether weather-related factors played a role. Additionally, the observed decrease in the number of recorded occurrences during the period from 2020 to 2022 – particularly in 2020 and 2021 – can be attributed to the operational impacts of the global COVID-19 pandemic, which led to a significant reduction in railway activity [2].

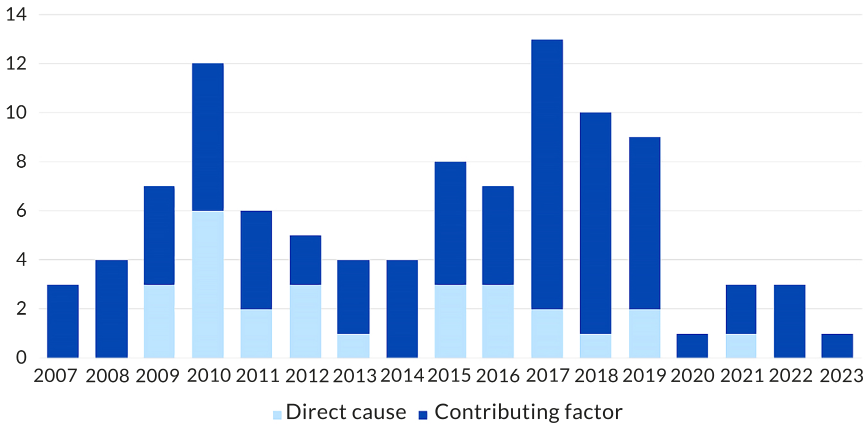

Fig. 2.2 Dynamics of weather-related significant accidents on railway
Source: [2]

National safety authorities shall also report the economic impact of significant accidents.

The EU Directive on Railway Safety [7] set up the following total and relative (to train-kilometers) indicators of economic impact of accidents: number of deaths and serious injuries multiplied by the value of preventing a casualty (VPC), cost of damages to environment, cost of material damages to rolling stock or infrastructure, cost of delays as a consequence of accidents.

When assessing its own costs related to incidents, a railway company cannot rely entirely on the Railway Safety Directive, as the calculation methodology presented there covers both internal and external costs (born by other stakeholders, not the railway company itself) and does not provide a comprehensive list of cost categories.

2.2.1 Costs of people's injury and fatality

Railway staff, passengers or unauthorized users can be affected during railway accidents. Among stakeholders, who take these costs, are transport companies, transport services users (passengers, companies), employers.

Costs of people's injury and fatality include [8, 9]:

– medical costs;

– production losses costs: the loss of production or productive capacities;

– human costs: immaterial cost of lost quality of life and lost life years;

– administrative costs: police, fire service, insurance, legal costs, personal property.

This classification was used in [8] to calculate transport externalities related to accidents and should be analyzed and adopted to be applicable to calculate companies' internal costs of climate related incidents.

Human costs are calculated as a percentage of value of statistical life (VOSL) [8].

The VOSL is the amount of money that a community of people are willing to pay to lower the risk of an anonymous instantaneous premature death within that community. It can be calculated by dividing the amount people are willing to pay by the change in mortality risk. VOLS is defined based on willingness to pay (WTP) studies.

Medical, administrative costs and costs of property damage are calculated based on the actual costs. Based on data gathered from 31 European and non-European countries the values of the costs for using on the macrolevel were estimated [8]. The average values are presented in **Table 2.2**.

The methodology for calculating productivity (or production) losses is described in **Section 2.5**, as the same approach can be applied to estimate both productivity losses due to injury and those resulting from extreme heat exposure.

Table 2.2 External accident cost component per casualty for the EU28, EUR2016

Accident type	Human costs	Production loss	Medical costs	Administrative	Total external cost per casualty
Fatalities	2 907 921	361 358	2 722	1 909	3 273 909
Serious injuries	464 844	24 055	8 380	1 312	498 591
Slight injuries	35 757	1 472	721	564	38 514

Source: [8]

Costs of injury and fatality taken by the company can by direct and indirect.

Direct costs include medical expenses, compensation, disability payments, legal fees, regulatory fines and penalties.

Indirect costs include loss of productivity, operational disruptions, increased insurance premiums, loss of trust from employees, hiring costs, training costs, financial repercussions from reputational damage.

2.2.2 Costs of train delays

In the EU Directive on Railway Safety [7], the costs of delays because of accidents means the monetary value of delays incurred by users of rail transport (passengers and freight customers) because of accidents, calculated by the model of monetary value of travel time savings.

The *monetary value of passenger train travel time savings* represents the amount of money a person is willing to pay to reduce their travel time and is calculated as a percentage of the traveler's hourly wage or income. Different travel purposes (personal, business) and types of travel (local, intercity) may have different values.

The *monetary value of freight train travel time savings* represents the monetary worth of reducing travel time for freight shipments and is usually expressed in money units per hour.

Such an approach is applicable in the context of planning new infrastructure and supporting decision-making primarily at the macro level, as the value of time savings serves as an indicator that incorporates both internal and external costs. Within the framework of the proposed concept for evaluating the internal climate-related costs of a railway company, it is essential to determine the actual costs incurred.

The total trains delay cost is calculated based on the cost per train-hour, the number of trains delayed, and the length of the delay [8]

$$CD_A = CM_P \cdot DT_P + CM_F \cdot DT_F, \tag{2.1}$$

where CM_P – cost of 1 minute of delay of a passenger train; DT_P – total time of all passenger trains delay, minutes; CM_F – cost of 1 minute of delay of a freight train; DT_F – total time of all freight trains delay, minutes.

Train delay costs include:

1. *Cars delay costs* refer to the cost of railroad-owned cars that are delayed and therefore are unavailable for use elsewhere. Privately owned cars shouldn't be

considered, excluded from this analysis because they are not directly paid by the railway company, and considered as external costs.

2. *Locomotive delay costs* are estimated based on the locomotive depreciation that occurs due to the delayed locomotives not being available for use elsewhere.

3. *Extra fuel and electricity costs* are the costs related to extra fuel consumed due to the delay.

4. *Crew labor costs*. Train crews (drivers, conductors, onboard staff) typically work scheduled shifts with strict limits defined by: labor laws, Union agreements, safety regulations. If a train is delayed and a crew's working hours exceed their scheduled duty, the employer must pay overtime rates, possibly provide relief staff or accommodation/transport.

5. *Passenger compensation* under delay refund policies and *penalties* paid to other operators in shared tracks and contractual penalties for delayed cargo [9].

2.2.3 Damage costs

Cost of damage to environment means costs that are to be met by railways, in order to restore the damaged area to its state before the railway accident.

Cost of material damage to rolling stock or infrastructure means the cost of providing new or repair rolling stock or infrastructure, with the same functionalities and technical parameters as that damaged beyond repair, including also costs related to the leasing of rolling stock, as a consequence of non-availability due to damaged vehicles [7].

Both types of costs are calculated as actual costs.

2.2.4 Incidents investigation costs

The objective of accidents investigation is to improve, where possible, railway safety and the prevention of accidents.

As it was mentioned before, NIBs obligatory investigate and report serious incidents. The decision to initiate investigations into other types of incidents is guided by necessity. Considering established evidence indicating a rise in climate-related incidents, such investigations are deemed essential for informing effective preventive measures.

To effectively investigate climate-related accidents in the rail industry, additional tools beyond traditional accident investigations should be applied. These include advanced modeling, predictive analytics, and data-driven risk analysis using techniques like Bayesian networks and machine learning. Integrating historical data with weather forecasting and utilizing knowledge graphs can help identify risk propagation patterns and inform targeted risk mitigation strategies.

By leveraging these tools, railway operators can gain a deeper understanding of climate-related risks, improve accident investigations, and implement more effective mitigation strategies to ensure the safety and reliability of their systems. Attracting additional investigating methods and tools requires additional costs.

Analyzing the report of serious climate related accident of derailment of a passenger train at Carmont (Aberdeenshire, UK) on August 12, 2020 [10] the incident investigation methods and tools related to the climate impact were identified (**Table 2.3**).

Table 2.3 Investigation methods of climate related serious incident

Name of investigation method	**Description of the investigation method**
1	**2**
Not climate related	
On-site inspection	Physical investigation of the accident scene including debris, track damage, and infrastructure condition
Evidence collection	Gathering of CCTV footage, train data recorders, infrastructure records, and witness interviews
Parallel investigations (with ORR/Police)	Legal and regulatory reviews conducted alongside RAIB's technical investigation
Audit and assurance review	Examining project and inspection records, including failures to audit or report design deviations
Train crashworthiness analysis	Technical assessment of how the train design affected derailment outcome and occupant safety
Climate related	
Weather and rainfall analysis	Use of Met Office radar and rainfall modelling to determine the intensity and return period of rainfall leading up to the event
Drainage design and construction review	Assessment of how the drainage system was designed vs. how it was constructed; including structural flaws and bund formation
Infrastructure modelling (AECOM)	Engineering simulations to test how the drainage system would perform under the rainfall conditions
Risk management evaluation	Evaluating network rail's response procedures for extreme weather and how risks were assessed and mitigated
Historical precedent comparison	Comparing findings with past landslips and derailments involving weather or drainage failures
Geotechnical risk monitoring review	Investigating how real-time monitoring tools (e.g., NRWS) were used or neglected during weather events

Continuation of Table 2.3

1	2
Emergency operations assessment	Reviewing operational decisions, route control responses, and failure to reduce speed after extreme rainfall
Partially climate related	
Root cause analysis	Identifying immediate, causal, and underlying factors contributing to the derailment
Safety recommendation development	Issuing formal recommendations to improve safety procedures, design, maintenance, and response

Source: authors' development based on [10]

Short description of the accident: the immediate cause of the derailment was the train striking debris that had been washed out from a steeply sloping drainage trench onto the track following exceptionally heavy rainfall. This rainfall – measured at 51.5 mm in just over 3 hours – was considered a 100- to 144-year return period event, categorized as an extreme climatic event. The drainage system failed to handle the volume and concentration of surface water due to construction defects and deviations from the original design, resulting in a washout and obstruction of the track.

The calculation of additional costs for climate impact-related investigation methods and tools should reflect actual incurred expenditures.

Extreme weather events increasingly affect the integrity and functionality of railway infrastructure, leading to the need for unplanned maintenance and repair activities. These interventions, in turn, result in higher operational and maintenance expenditures for railway companies.

2.3 Maintenance costs

In the context of long-term adaptation strategies, it may become necessary to redesign specific infrastructure components and technical systems to enhance their resilience to extreme climatic conditions. Such engineering and design decisions require substantial financial investment and must be supported by a thorough economic justification.

A widely recognized tool for guiding these investment decisions is *life cycle cost (LCC) analysis*, which offers a comprehensive framework for evaluating the total cost of ownership of an asset over its entire service life. This methodology encompasses all cost components associated with the design, production, installation, operation, maintenance, and eventual disposal or decommissioning of infrastructure assets. *LCC* analysis allows decision-makers to compare alternative adaptation solutions not only in terms of their initial capital costs but also in relation to their long-term economic efficiency and performance under changing climatic conditions. Formula for *LCC* calculation [11]

$$LCC = C_A + C_{OS} + C_{OP}, \tag{2.2}$$

where C_A – acquisition costs: include the costs of design, fabrication, production, manufacture, installation, and other costs related to the development stage; C_{OS} – operation and support costs: include the cost of operations, maintenance (inspections, repairs, and replacements), support, and failure costs during the operational life of the asset; C_{OP} – phase-out costs: net salvage value, which includes residual or salvage value, dismantling cost, and disposal cost.

To evaluate initial climate related maintenance costs the operation and support costs of the *LCC* formula should be considered. The research of switches and crossings maintenance in the extreme weather conditions conducted in Sweden [12] concluded that the frequency of climate related maintenance cases increased.

Table 2.4 presents an overview of maintenance actions performed on switches and crossings (S&C) in Sweden due to climatic failures. The table categorizes these actions by frequency and associated cost shares under both climatic and non-climatic operational modes. The most frequent intervention is snow cleaning (41.88%), accounting for the majority of climatic-related maintenance costs (66%). Other common actions include general cleaning, adjustment, and washing. Less frequent yet significant tasks – such as lubrication, control, repair, and recovery – are also listed, each with cost implications varying between climatic and non-climatic conditions. The table highlights the dominant role of winter-related maintenance in overall S&C upkeep under Sweden's climatic conditions [12].

Maintenance and repair costs reflect the actual expenditures incurred by the railway company as a result of extreme weather impacts. These costs are calculated using a discount rate to account for the time value of money in long-term financial planning [12]

$$LCC = \sum_k \sum_i \sum_j = \frac{1}{(1+r)^k} \frac{1}{MTBF_{ij}(k)} \left\{ C_{P_{ij}} + MTTR_{ij} \left(n_{L_{ij}} C_L + C_{E_{jl}} \right) \right\}, \tag{2.3}$$

where *i* – action type; *k* – year's duration; *j* – component type; $MTBF_{ij}(k)$ – mean-time-between-failure of component *j* and a failure mode associated with action *i* for year k^{th}; $MTTR_{ij}$ – mean-time-to-repair of component *j* (in minute units) and a failure mode associated with action *i*; n_L – number of workers needed to give the action; C_L – labor cost (in monetary units/hour); C_E – equipment cost needed to carry out the intervention.

Table 2.4 Maintenance action with switches and crossings because of climatic failures in Sweden

Action	Frequency, %	% of costs for climatic mode	% of costs for non-climatic mode	Description
Show cleaning	41.88	66	0	Removal of snow and ice during the winter season
Cleaning	26.20	15	4	Remove debris, sand, stones, and other foreign objects
Adjustment	9.6	4	25	Correction of the geometric features or positional misalignment of S&C after standard measurement
Washing	9.47	11	5	Cleaning of turnout components using a fluid or other relevant medium
Lubrication	4.12	1	10	Applying a substance such as oil or grease to S&C components to minimize friction and allow smooth movement
Control	1.84	1	18	Gauging and functional check of the state of the system
Repair	1.33	1	30	Maintenance actions are carried out to return S&C to a state where it can perform the desired function by replacing components, welding, and grinding
Recovery/restoration	1.05	1	9	Resetting and returning the S&C component to initial or calibrated status after failure; performing regular standard operational procedures
Others	4.06	–	–	All other actions, e.g., grinding, tamping, tightening, and etc.

Source: [12]

2.4 Costs associated with shifts in passenger behavior driven by climate change

Modal shift to railway refers to the change in transportation choices where people and goods move from modes like cars, airplanes and trucks to trains. This shift can be influenced by various factors, including environmental concerns, infrastructure improvements, and policies.

Rail transport is often seen as more sustainable and environmentally friendly due to lower CO_2 emissions and greater energy efficiency. 0.5% of greenhouse gas emissions produced by transport refer to railways [1].

In spite on the boosting modal shift at all levels the results still haven't reached the expected level (**Fig. 2.3**). The 7% to 5.1% decline in passenger transport in EU was primarily caused by the COVID-19 pandemic, during which railway travel bans were implemented and public confidence in rail transport significantly declined. The railways have still not fully recovered from the pandemic period. Although the share of passenger transport by rail returned to 8% in 2023, the planned dynamics of modal shift have slowed down. Freight transport experienced a more stable trajectory, as it was not as significantly impacted by the pandemic as passenger transport.

Railways benefit from the modal shift, as a substantial amount of investment has been directed toward the development of railway infrastructure, and additional income is expected from the increase in passenger traffic. This can be considered as an indirect positive impact on railways from climate change. EU supports 55 projects for railway infrastructure on the core Trans-European Transport Network (TNT) on 1.6 billion EUR including Rail Baltica and railway line between Lyon and Turin [13].

It is also expected from railway to co-fund the infrastructure transformation to speed up the modal shift.

The survey shows that for the most regions price, safety, convenience, reliability and speed are the main factors for passengers when choosing their mode of transport (**Fig. 2.4**). Sustainability-related aspects seem to play only a minor role for passengers in their travel selection. The results of the research of sustainability behavior, 87% of customers expressed an interest in sustainable products, but only 12% would be willing to pay a premium for such sustainable products or services. So, modal shift can be driven by promotion of sustainability of railways among civil society and improving quality of rail travels.

Communication with a mass audience is a key component in creating awareness of rail services and fostering the desire to travel again, and rail operators worldwide raced to create vivid and compelling marketing campaigns to do so for after pandemic recovery. This experience is a strong background for further promotion of railway transportation in order to achieve modal shift targets [15].

It's also expected that rail travel demand can change. For example, some share of passenger can prefer rail to air travel as more safe and reliable transport mode in the condition of extreme weather for medium distance trips; some passengers probably will avoid travels at all then the weather conditions are risky; new global trend as teleworking will reduce travels on work purpose at all or if the weather conditions are not preferable.

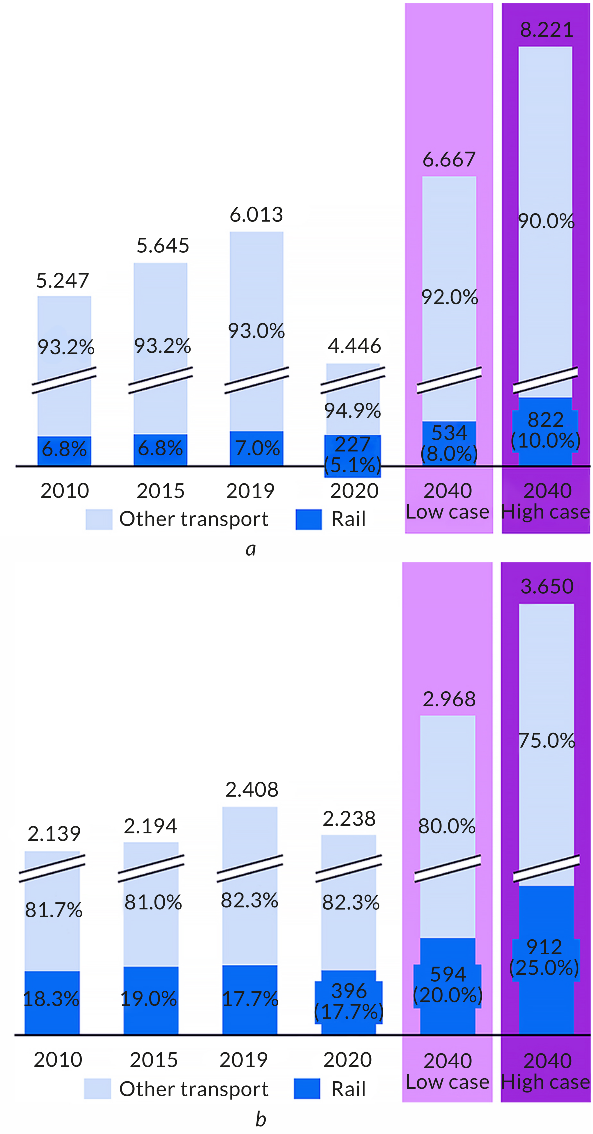

Fig. 2.3 European transport trends:
a – passenger transport, millions pkm; *b* – freight transport, millions tkm
Source: [14]

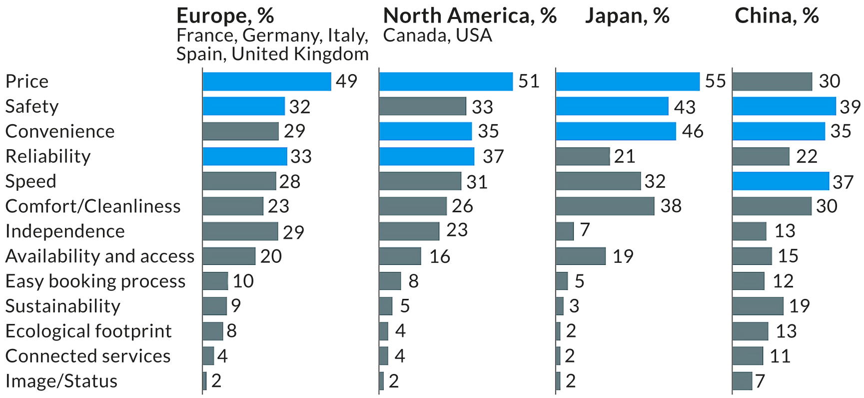

Fig. 2.4 Drivers for passengers when choosing their mode of transport
Source: [16]

In USA 10% of people will work remotely till 2025. Expected decrees in the number of business trips per person is 21% in China, 24% in USA and Europe [16].

Influence of such kind of factors can be evaluated by monitoring the dynamics of trips during different weather conditions, conducting surveys among customers.

A key challenge is to identify and quantify the extent to which cost increases are driven by climate-related causes. Furthermore, the impact of climate change on passenger behavior remains insufficiently studied and represents an ongoing subject of academic inquiry.

2.5 Costs associated with reduced worker productivity caused by extreme temperatures

Railway operational staff frequently work under conditions of extreme heat. Sustained exposure to elevated temperatures can result in a variety of physical and cognitive challenges, including heat stress, dehydration, fatigue, and diminished decision-making capacity. These impacts compromise worker health and safety, elevate the likelihood of human error and equipment malfunction, and contribute to productivity losses.

Certain railway occupations and tasks have been identified as particularly susceptible to high temperatures (**Table 2.5**). *Vulnerability* in this context refers to the extent to which individuals are likely to experience adverse effects from heat exposure. It is typically understood as a combination of two key factors: *exposure* and *sensitivity*.

Exposure denotes the intensity and duration of time workers spend in high-temperature environments. This can be influenced by factors such as geographic location and climate (e.g. seasonal heat patterns, humidity, urban heat islands), environmental settings (sun vs. shade, indoor vs. outdoor workspaces, airflow, and heat-retaining surfaces), as well as the duration, frequency, and scheduling of tasks. Infrastructure characteristics also play a role in determining exposure levels.

Sensitivity relates to how vulnerable a worker is to the effects of heat once exposed. This can vary based on individual attributes (e.g. age, health status, level of acclimatization, hydration, and nutrition), job demands (e.g. physical intensity, mental workload, task importance, stationary vs. mobile work), and the characteristics of the working environment [4].

Understanding which roles within the railway sector are most affected by high temperatures is essential for developing targeted mitigation and adaptation strategies.

Table 2.5 The impact of high temperatures on railway workers' productivity

Occupation	Tasks description	Level of exposure	Level of sensitivity
Maintenance workers	Manual labor such as repairing and maintaining tracks, signaling systems and electrical equipment	High	High
Track inspectors, shunting staff and engineers	Inspection and maintenance of railway tracks and infrastructure, and assessing the condition of critical components such as bridges and tunnels	High	Moderate to high
Train operators	Driving and navigating trains, monitoring signals and responding to operational changes	Moderate to low	High
Signal and control room operators	monitoring and controlling train movements, ensuring the safe operation of railway systems and responding to emergencies	Low to moderate	High
Station and platform staff	Include managing passenger flow, assisting passengers, overseeing ticketing and handling emergencies	High	Moderate to high
Electrical and signaling technicians	Maintaining and repairing electrical and signaling systems and responding to technical failures	High	High
Security and emergency response teams	Ensuring passenger safety, managing emergencies and responding to medical incidents or security threats	Moderate to high	High
Cleaning and support staff	Cleaning stations, platforms and trains and performing maintenance tasks in high-traffic areas	Moderate to high	Moderate

Source: [4]

The estimation of heat effect can be performed by the costs of productivity loss related to paid work, which is calculated by multiplying the relevant number of work days lost with a wage rate estimate [17].

Two types of productivity losses are identified related to paid work: absenteeism and presenteeism [18].

Absenteeism refers to productivity losses related to not attending work due to ill health. Such losses occur if people are too sick to attend work, or if people need to visit medical professionals during working hours.

Presenteeism relates to reduced productivity at work due to health problems. If a person suffers from ill-health but does attend work, he or she may not be able to function equally well in terms of quality and/or quantity compared with when he or she was in full health. The costs associated with presenteeism can be significant and can be influenced by such factors as the social security system in a country. If employees do not get paid during sick leave, they may be more inclined to attend work while being ill. Costs associated with presenteeism seldom included in economic evaluations. Productivity cost estimates based on absenteeism alone will poorly reflect full productivity costs.

Two more aspects should be considered while estimating costs of productivity losses. These are multipliers and compensation [18].

Multipliers is a phenomenon in which the ill-health of an individual employee not only reduces their own productivity but also negatively impacts the productivity of colleagues – particularly in work environments with high team interdependence and limited flexibility for substituting or reallocating tasks among staff.

Compensation is the process by which lost productivity due to an employee's ill-health is offset – either by colleagues assuming additional workload or by the ill individual making up for the lost output upon returning to work. This compensation can occur during normal working hours or through extra work time, and while it may reduce the net societal cost of productivity loss, it can also impose additional strain on the workforce.

2.6 Costs of reputational loss

Disruption of transport operations and infrastructure by extreme weather damage can lead to both revenue and reputation losses for rail operations.

Reputational damage is often difficult to measure directly, but its effects on a company can be substantial. Research shows that shifts in a company's reputation can significantly influence its market value. Since a firm's stock price is essentially based on the present value of its expected future earnings, any incident that harms its reputation – and thereby reduces anticipated cash flows can lead to a decline in share value [19].

Reputational risk can lead to various forms of financial loss, including:

– loss of existing or potential customers, which not only reduces expected revenues but may also increase costs associated with damage control;

– departure of key employees or executives, rising recruitment expenses, or productivity losses due to staff disruptions;

– reduction in the number or quality of current and future business partners;

– higher costs of obtaining financial capital or credit;

– increased expenses resulting from stricter government regulations, fines, or other legal penalties.

To estimate reputation losses of the railway because climate event study methodology can be applied [20]. Here the reputational losses are defined as any financial losses that go beyond the officially disclosed or expected loss. This approach assesses how specific even to (favorable or unfavorable) affects a company's reputation by examining its market reaction to events that have already taken place. To carry out this type of analysis, it is essential to isolate the reputational factors that drive company performance from other influencing variables.

An event study (**Fig. 2.5**) typically involves three key phases [20]:

– the *estimation window*, which serves as the baseline period to establish normal performance;

– the *event window*, during which the actual event occurs and its immediate impact is measured;

– the *post-event window*, which tracks any lasting effects following the event.

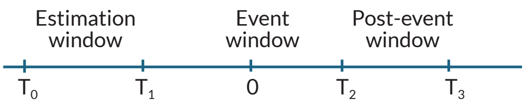

Fig. 2.5 Timeline of event study
Source: [20]

An event is defined as a point in time in which a company makes an announcement, or a significant market event occurs, in that case of a reputational type.

From a quantitative perspective, one established method evaluates the relationship between reputational loss and a company's market value decline. In this approach, reputational loss is defined in economic terms: if the decrease in market value exceeds the amount of the announced operational loss, the difference is attributed to reputational damage. The method takes into account factors such as the size and nature of the loss, as well as the company's corporate governance structure, using the stock market's response to the public announcement of the loss as an indicator of reputational impact [19].

2.7 Conclusions

Although many of the cost categories examined in this Chapter – such as incident-related costs and maintenance expenditures – have long existed in the operational framework of railway companies, climate change introduces a new dimension to their evaluation. It is essential to distinguish which portions of these costs can be directly attributed to climate-related impacts. Such differentiation enables a more accurate assessment of how climate change affects the overall economic performance of a railway company.

A critical task in this process is the detailed analysis of costs within each identified category to prevent double counting. Without this precision, estimates may become inflated or misleading, undermining the reliability of economic evaluations and risk assessments.

Another priority is the establishment of a comprehensive, structured database of baseline and climate-related cost data. This would serve as a foundation for consistent and repeatable calculations, thereby supporting informed decision-making on climate adaptation strategies.

Additionally, the methods for estimating costs associated with changes in passenger behavior due to climate change remain insufficiently studied. Given the potential implications of modal shifts, altered travel preferences, and reduced demand in extreme weather conditions, further research in this area is both timely and necessary.

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