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Climate Threats and Resilience Assessment of Road and Railway Networks: Scenario Analysis for 2025, 2030, 2050

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ABSTRACT

Road and railway networks are significantly impacted by climate change, facing various climate extremes on different scales (de Miranda Pinto et al., 2018; Hooper and Chapman, 2012; Nemry and Demirel, 2012). Forecasting the future impacts on these essential transport and logistics links, vital for human lives, goes beyond likelihood and risk severity. Resilience, a key factor, is evaluated uniquely in this study. We employ Bayesian network analysis to assess the strength of road and railway systems in relation to various climate-induced threats under changing climatic conditions (Zhou et al., 2017). This research model explicitly impacts road networks for 2025, 2030, and 2050 by analysing the likelihood of occurrences, the extent of damage, and overall resilience. Understanding the urgency of these impacts is essential for proactive planning and policymaking. This study, with its comprehensive framework that integrates various factors influencing the resilience of transportation networks, is a proactive step. It highlights the importance of incorporating resilience assessments into infrastructure planning and management, which will help mitigate potential disruptions and ensure the continued functionality and reliability of transport networks in the face of climate change.

Keywords: Climate resilience, Road network assessment, Climate change impact, Scenario analysis, Infrastructure adaptation

INTRODUCTION

Road and railway networks are significantly impacted by climate change, facing various climate extremes on different scales (de Miranda Pinto et al., 2018; Hooper and Chapman, 2012; Nemry and Demirel, 2012). Forecasting the future impacts on these essential transport and logistics links, vital for human lives, goes beyond likelihood and risk severity. Resilience, a key factor, is evaluated uniquely in this study. We employ Bayesian network analysis to assess the strength of road and railway systems in relation to various climate-induced threats under changing climatic conditions (Zhou et al., 2017). This research model explicitly impacts road networks for 2025, 2030, and 2050 by analysing the likelihood of occurrences, the extent of damage, and overall resilience.

Understanding the urgency of these impacts is essential for proactive planning and policymaking. This study, with its comprehensive framework that integrates various factors influencing the resilience of transportation networks, is a proactive step. It highlights the importance of incorporating resilience assessments into infrastructure planning and management, which will help mitigate potential disruptions and ensure the continued functionality and reliability of transport networks in the face of climate change.

METHODOLOGY

Background

Building upon the previous study's methodology for analysing climate change impacts on the UK's road transportation and rail transportation, this revised approach aims to assess further the trends in climate change and the development of adaptation measures (Wang et al., 2019; 2020). The methodology will now incorporate an advanced assessment of the road network's resilience by adding three new sub-items: resilience capacity, the length of disruption period, and recovery cost.

The study will continue to employ the Fuzzy Bayesian Reasoning (FBR) model to evaluate the uncertainty-laden climate risks within road transport networks and rail transport, enhancing the understanding of the potential temporal distribution of climate threats, their likelihood, and the severity of their consequences (Yang et al., 2008). The expansion to a multi-tier risk evaluation framework allows for a more nuanced assessment of the severity of implications by including economic loss, environmental damage, and human casualties as distinct sub-attributes (Yang et al., 2018).

Incorporating new dimensions of resilience into the assessment framework, this study meticulously evaluates the robustness and adaptability of the road and rail network's resilience capacity, focusing on structural and functional durability in the face of climate-induced disruptions (Manyena, 2006). Furthermore, it examines the length of the disruption period to gauge the impact of climate events on the network's operational efficacy and continuity (Baghersad and Zobel, 2022). Additionally, it quantifies the cost of recovery, forecasting the financial requirements necessary for the network's post-event recovery and restoration (Dormady et al., 2022). These integrated resilience aspects provide a more holistic understanding of the network's ability to cope with and recover from climate threats, informing strategic adaptation planning for a sustainable transportation future.

This methodology will enable a comprehensive and dynamic understanding of the road and rail network's resilience against climate change. It aims to guide policymakers and planners in the road and rail sectors by providing actionable insights and adaptation plans for the related road and rail shareholders. This approach ensures that both current resilience and future adaptation planning are addressed with a clear understanding of economic, environmental, and social impacts, leading to sustainable and resilient road and rail transport systems.

Key Framework

This paper introduces a new approach to improving how transportation systems deal with climate change. It outlines a framework that focuses on understanding and managing these risks through four main steps:

- Identify potential climate threats to transportation systems.
- Assess the risks (for the year 2025) these threats pose to transportation systems.
- Predict the future (years 2030 and 2050) changes and impacts of these threats on transportation systems.
- Analyse the factors that affect these risks, such as geographic location, different types of transportation, and the roles of operators, looking ahead to the years 2025, 2030, and 2050.

The Flow of the Study

Beginning in May 2023, questionnaires will be circulated among professional networks linked to road and rail networks. The data collected from these questionnaires will be used to build an FBR model. This model will consist of several components: “likelihood,” “damages to property,” “injuries and loss of lives,” “damages to the environment,” “resilience capacity,” “length of disruption period,” and “cost of recovery.” Additionally, the model includes two pivotal connecting components, “damage” and “resilience,” which integrate all the other components to assess the overall “climate risk” levels, as illustrated in Figure 1.

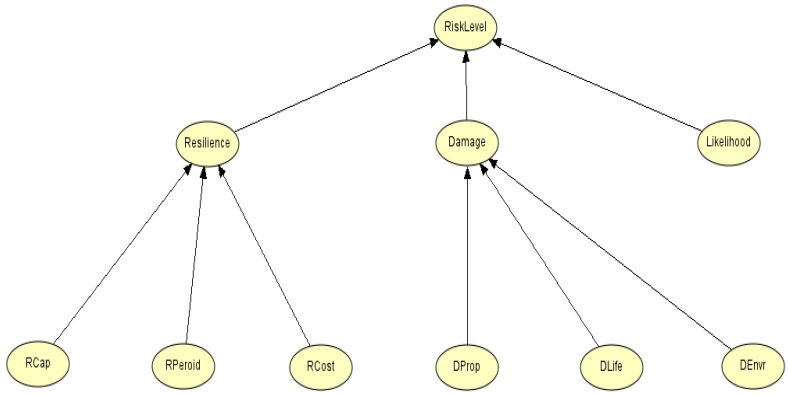

Figure 1: The structure of FBR model for climate resilience.

This paper develops a three-layer hierarchy to model new CSC climate risk assessment parameters. They include a single parameter on the top layer, namely Climate Risk Level (RiskLevel), which is influenced by related sources (Yang et al., 2018; Wang et al., 2019; 2020). A few parameters are added for a more comprehensive resilience analysis, timeframe (T) is removed from the network, and three scenarios will be run in the experiment sections. Damage to property (DProp), Injuries and loss of lives (DLife), and Damage to environment (DEnvir) are used to evaluate the damage. Resilience capacity (Rcap), Length of disruption (RPeriod) and Cost of recovery (RCost) are used to assess resilience. Then, damage, resilience and likelihood are used to assess RiskLevel. Then, it is noticed that all three gates (resilience, damage and RiskLevel) have three parameters. They include 15 (5 + 5 + 5) linguistic variables assembled to generate 125 (5 × 5 × 5) antecedents.

The impacts of climate change are measured across seven parameters for three different scenarios (2025, 2030, and 2050). These parameters include damaging cyclones, sea-level rise, warming trends/extreme temperature/drought, heavy precipitation, snow cover/frost cover, seasonal changes in fog events, and seasonal changes in wind speed and direction. This results in a total of 21 cases (7 parameters x 3 scenarios). To quantify the RiskLevel, values are assigned to each linguistic variable as follows: Very High (Grade 5 = 1), High (0.75), Medium (Grade 3 = 0.5), Low (Grade 2 = 0.25), and Very Low (Grade 1 = 0).

This structured approach allows for a detailed analysis of the potential impacts on road networks, enabling a comprehensive assessment of future risks. By assigning numerical values to qualitative risk assessments, this method facilitates more precise modelling and comparison of different climate scenarios.

RESULT

The findings, generated from the expertise of seven road experts and fourteen rail experts, highlight the superior resilience of rail networks, attributed to their robust construction and centralized management, compared to road networks that are more vulnerable to extreme weather conditions like flooding and heat damage.

From 2025 to 2030, the impact of damaging cyclones on road networks saw a significant increase, with the risk level rising from 0.4801 to 0.5596. Sea-level rise also showed a notable increase from 0.5602 to 0.6675, indicating a growing concern. The impact of warming trends/extreme temperatures/drought increased from 0.5583 to 0.6075. In contrast, heavy precipitation saw a slight decrease from 0.5315 to 0.5305. There was a significant decrease in the impact of snow cover/frost cover from 0.4155 to 0.3707, and seasonal changes of fog events decreased markedly from 0.2801 to 0.3313. Seasonal changes to wind speed and direction also decreased slightly from 0.3625 to 0.3908.

Table 1. Linguistic terms of all variables in the FBR model.

Grade	RiskLevel	Likelihood	Damage	Resilience	DProp	DLife	DEnvir	RCap	RPeriod	RCost
5	Very High	Very High	Catastrophic	Very Low	Catastrophic	Catastrophic	Catastrophic	Very Weak	Very Long	Catastrophic
4	High	High	Critical	Low	Critical	Critical	Critical	Weak	Long	Critical
3	Medium	Medium	Major	Medium	Major	Major	Major	Average	Average	Major
2	Low	Low	Minor	High	Minor	Minor	Minor	Strong	Short	Minor
1	Very Low	Very Low	Negligible	Very High	Negligible	Negligible	Negligible	Very Strong	Very Short	Negligible

Table 2. RiskLevel of road networks.

Year	RiskLevel	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes of fog events	Seasonal changes to wind speed and direction
2025	VL	19.05%	26.85%	27.70%	17.20%	1.59%	0.00%	0.00%
	L	22.22%	26.85%	19.13%	24.87%	18.73%	6.98%	19.64%
	M	14.29%	10.58%	15.32%	22.35%	37.30%	26.98%	28.74%
	H	20.63%	14.95%	24.48%	24.47%	29.05%	37.14%	28.61%
	VH	23.81%	20.77%	13.37%	11.11%	13.33%	28.89%	23.00%
	Final value	0.4801	0.5602	0.5583	0.5315	0.4155	0.2801	0.3625
2030	VL	31.55%	40.87%	34.44%	11.64%	4.76%	3.17%	3.17%
	L	15.28%	23.48%	15.87%	27.78%	18.10%	13.89%	21.16%
	M	12.10%	14.35%	10.91%	24.87%	16.51%	17.06%	25.66%
	H	27.58%	4.37%	35.79%	32.54%	41.90%	44.05%	28.84%
	VH	13.49%	16.93%	2.98%	3.17%	18.73%	21.83%	21.16%
	Final value	0.5596	0.6675	0.6075	0.5305	0.3707	0.3313	0.3908
2050	VL	46.03%	53.17%	48.68%	29.10%	10.16%	10.16%	6.35%
	L	1.59%	14.55%	9.52%	27.25%	26.03%	26.03%	29.10%
	M	6.35%	12.70%	19.31%	14.55%	11.11%	11.11%	24.07%
	H	31.75%	8.47%	20.90%	27.51%	35.56%	35.56%	22.49%
	VH	14.29%	11.11%	1.59%	1.59%	17.14%	17.14%	17.99%
	Final value	0.5834	0.7255	0.7070	0.6369	0.4413	0.4413	0.4583

Between 2030 and 2050, the impact of damaging cyclones on roads continued to rise, increasing from 0.5596 to 0.5834. Sea-level rise showed a substantial increase from 0.6675 to 0.7255. The impact of warming trends/extreme temperatures/drought rose significantly from 0.6075 to 0.7070. Heavy precipitation's impact increased from 0.5305 to 0.6369. The impact of snow cover/frost cover increased slightly from 0.3707 to 0.4413, and seasonal changes of fog events also increased from 0.3313 to 0.4413. The impact of seasonal changes to wind speed and direction showed an increase from 0.3908 to 0.4583.

For rail networks, the period from 2025 to 2030 saw a slight decrease in the impact of damaging cyclones, with the risk level dropping from 0.5240 to 0.5182. The effect of sea-level rise decreased from 0.5979 to 0.5618, and warming trends/extreme temperatures/drought also decreased from 0.5926 to 0.5702. Heavy precipitation's impact was slightly reduced from 0.6041 to 0.5940. Conversely, the impact of snow cover/frost cover increased from 0.7016 to 0.7241. Seasonal changes of fog events showed a decrease from 0.7537 to 0.6859, and seasonal changes to wind speed and direction decreased from 0.6852 to 0.6568.

From 2030 to 2050, the impact of damaging cyclones on rail networks increased from 0.5182 to 0.5689. The impact of sea-level rise increased from 0.5618 to 0.5916. The influence of warming trends/extreme temperatures/drought decreased slightly from 0.5702 to 0.5543. Snow cover/frost cover impact decreased from 0.7241 to 0.6800. Seasonal changes of fog events showed a slight increase from 0.6859 to 0.6868, and the impact of seasonal changes to wind speed and direction decreased marginally from 0.6568 to 0.6551.

Table 3. RiskLevel of rail networks.

Year	RiskLevel	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes of fog events	Seasonal changes to wind speed and direction
2025	VL	21.55%	17.86%	20.11%	23.41%	3.24%	5.56%	14.29%
	L	18.83%	23.28%	31.48%	21.56%	24.79%	13.10%	14.68%
	M	35.23%	24.74%	26.46%	34.92%	40.78%	39.29%	37.83%
	H	11.17%	25.13%	18.65%	17.59%	26.37%	37.96%	29.23%
	VH	13.68%	8.99%	3.31%	2.51%	4.82%	4.10%	3.97%
	Final value	0.5240	0.5979	0.5926	0.6041	0.7016	0.7537	0.6852
2030	VL	20.88%	23.54%	13.76%	19.44%	5.62%	4.10%	4.76%
	L	22.34%	25.66%	41.80%	39.55%	16.79%	9.66%	16.67%
	M	34.37%	24.21%	30.69%	25.00%	56.78%	42.72%	32.54%
	H	9.65%	19.31%	9.66%	16.01%	20.02%	30.69%	31.75%
	VH	12.76%	7.28%	4.10%	0.00%	0.79%	12.83%	14.29%
	Final value	0.5182	0.5618	0.5702	0.5940	0.7241	0.6859	0.6568
2050	VL	28.19%	34.43%	29.55%	35.92%	10.38%	11.24%	12.96%
	L	19.87%	17.52%	27.96%	26.31%	22.34%	11.24%	14.42%
	M	24.81%	21.61%	33.70%	29.66%	39.26%	26.72%	24.21%
	H	21.30%	25.58%	8.79%	7.14%	24.79%	40.21%	36.90%
	VH	5.82%	0.85%	0.00%	0.96%	3.24%	10.58%	11.51%
	Final value	0.5689	0.5916	0.5543	0.5152	0.6800	0.6868	0.6551

Both road and rail networks show an increasing trend in the impacts of sea-level rise over time, highlighting it as a significant concern for future infrastructure planning. Warming trends/extreme temperatures/drought continue to impact both networks, though with varying degrees of change. Seasonal changes in fog events show a general decrease from 2025 to 2030 for both networks, but increase again from 2030 to 2050, indicating fluctuating patterns.

However, there are notable differences between the two networks. For roads, heavy precipitation decreases from 2025 to 2030, followed by an increase till 2050. In contrast, rail networks experience a consistent decrease in the impact of heavy precipitation from 2025 to 2050. The effect of snow cover/frost cover on roads increases over time, whereas rails see a decrease from 2030 to 2050. Additionally, roads generally show an increasing impact of seasonal changes of fog events and wind speed and direction over time, while rails exhibit mixed trends with decreases in some periods.

CONCLUSION

This study provides critical insights into the differing resilience capacities of road and rail networks facing climate-induced threats. The findings highlight the superior resilience of rail networks, attributed to their robust construction and centralised management, compared to road networks that are more vulnerable to extreme weather conditions like flooding and heat damage.

From 2025 to 2030, road networks saw significant increases in the impact of damaging cyclones and sea-level rise, while warming trends/extreme temperatures/drought also posed an increasing threat. However, there was a slight decrease in the impact of heavy precipitation, a marked reduction in snow cover/frost cover, and seasonal changes in fog events. Between 2030 and 2050, these impacts continued to rise, with substantial increases in sea-level rise and warming trends/extreme temperatures/drought. Heavy precipitation, snow cover/frost cover, and seasonal changes of fog events also showed an increasing impact.

For rail networks, the period from 2025 to 2030 saw a slight decrease in the impact of damaging cyclones, sea-level rise, and warming trends/extreme temperatures/drought. Heavy precipitation's impact slightly decreased, while snow cover/frost cover impact increased. Seasonal changes in fog events and wind speed and direction also showed a decrease. From 2030 to 2050, the effect of damaging cyclones and sea-level rise on rail networks increased, while the impact of warming trends/extreme temperatures/drought and heavy precipitation decreased. The impact of snow cover/frost cover decreased, and seasonal changes in fog events and wind speed and direction showed mixed trends.

Both road and rail networks show an increasing trend in the impacts of sea-level rise over time, highlighting it as a significant concern for future infrastructure planning. Warming trends/extreme temperatures/drought continue to impact both networks, though with varying degrees of change. Seasonal changes in fog events show a general decrease from 2025 to 2030 for both networks, but increase again from 2030 to 2050, indicating fluctuating patterns.

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These results underscore the urgency for targeted infrastructure enhancements and strategic planning to bolster the weaker segments of transportation networks. Moving forward, this research will inform policymakers and planners in prioritising and implementing effective climate adaptation strategies, ensuring the sustainability and safety of transportation systems in the face of evolving climate challenges. Future updates will provide more detailed recommendations based on extended analysis and further data collection. This fundamental study may further develop other modes of transportation to conduct a comparative study in the following research study.

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