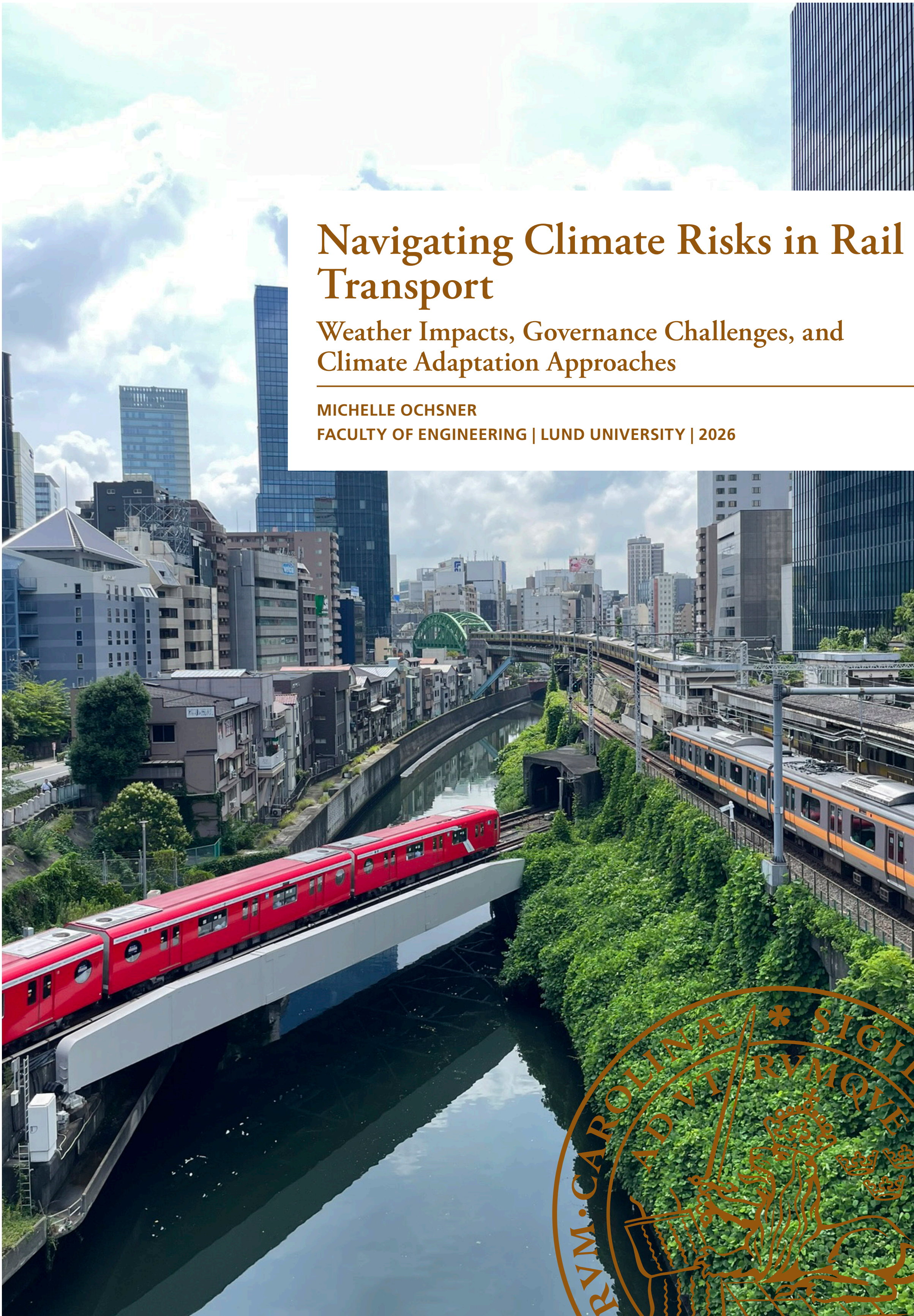
Navigating Climate Risks in Rail Transport

Weather Impacts, Governance Challenges, and Climate Adaptation Approaches

MICHELLE OCHSNER

FACULTY OF ENGINEERING | LUND UNIVERSITY | 2026



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Michelle Ochsner

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract:

Railways play an important role in the energy transition by offering a low-carbon, energy-efficient means of transporting goods, people, and services. However, this role is increasingly at risk as extreme weather events associated with a changing climate grow in severity and frequency, compounded by uncertainties in future climate conditions.

This thesis aims to advance the understanding of climate adaptation processes, using the railway sector in the Swedish context as a lens. By employing an interdisciplinary and mixed-methods approach, I address this aim through six research articles. Paper I quantifies the impact of weather on railway disruptions, while Paper II quantified the impacts of weather on railway infrastructure. Paper III explores past research trends on the effects of flooding on railway infrastructure. Paper IV builds upon the Dynamic Adaptive Pathways Planning approach to explore approaches to climate adaptation and the barriers and opportunities to more dynamic adaptation. Paper V utilises interviews to explore the barriers to the implementation of climate adaptation in Sweden. Finally, Paper VI builds upon interviews to understand climate adaptation efforts in Japan, offering an international perspective on climate adaptation approaches and governance.

The research findings indicate that adverse weather conditions – particularly high snow depth, low temperatures, and high wind speeds – currently have the greatest impact on Swedish railway operations and infrastructure, with track assets being the most impacted. Due to climate change, impacts are expected to shift towards those associated with high temperatures and increased rainfall, raising the likelihood of flooding and heat-related faults. Governance challenges – including legislation, resources, prioritisation, and knowledge – hinder climate adaptation. Lessons from climate adaptation approaches highlight the importance of dynamic approaches, underpinning climate adaptation with other domains such as disaster risk reduction and integrating both structural and non-structural measures to support long-term resilience in the railway sector.

The contributions of this thesis are five-fold. I i) provide empirical evidence on the impacts of weather on railway operations and infrastructure in Sweden, including a baseline for current impacts; ii) offer insights for asset managers to support resilience planning and inform climate adaptation approaches, including the identification of weather-related thresholds; iii) explore a range of climate adaptation approaches and assess their opportunities and limitations in the railway context; iv) disentangle the barriers to climate adaptation within current governance structures; and v) draw upon insights from global perspectives and relate it to Sweden. In doing so, I critically engage with knowledge at the policy and science interface to gain a deeper understanding of how to adapt railway infrastructure to climate change so that railways can provide safe and reliable services for all.

Key words: climate adaptation, railways, infrastructure, climate change, climate resilience

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MADE IN SWEDEN

To my mom and in loving memory of my dad and grandfather,
my three greatest supporters

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Acknowledgements

My journey as a PhD student has felt long and slow yet fast all at the same time. As I reflect on the past four and half years, there are many people who have contributed to my journey in numerous ways, and I am so grateful for all the support I have received throughout the years.

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I also had the opportunity to connect with other people in my field from other institutions. To Sarah and Rachel thank you for being excellent co-authors but also for welcoming me to Birmingham and London on several occasions. I am also grateful for having you as friends and for being some of the few other people in my life who love discussing climate adaptation of transportation systems as extensively and enthusiastically as me. A big thank you also to Emma F. for being my discussant at my midterm seminar and to Andrew for agreeing to be my opponent at my defence and for our previous brief chats.

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Michelle
Malmö, 2026

“The climate is changing why aren’t we?”

Daisy Kendrick

Abstract

Railways play an important role in the energy transition by offering a low-carbon, energy-efficient means of transporting goods, people, and services. However, this role is increasingly at risk as extreme weather events associated with a changing climate grow in severity and frequency, compounded by uncertainties in future climate conditions.

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Popular Science Summary

The climate is changing, bringing about more extreme weather events such as heatwaves, storms, and floods. These events disrupt essential infrastructure, such as railways, leading to delays or cancellations of the services that depend on them. When an extreme weather event such as a flood hits a railway line, trains can be delayed or cancelled, and safety concerns may arise. Railways are often seen as an environmentally friendly alternative to cars or planes, but if they become unreliable or unsafe, they may lose their appeal. This is why understanding how railways can cope with extreme weather both today and in the future, known as climate adaptation in this thesis, is so important.

While many studies have examined how weather causes delays and cancellations, far fewer have investigated how climate adaptation is planned and governed in practice, and even fewer consider the broader climate adaptation process as a whole. The thesis presented here focuses on how the Swedish railway sector can adapt to a changing climate. It addresses three main questions: i) how railway operations and infrastructure are impacted by weather; ii) what challenges can arise when trying to adapt railway infrastructure to climate change; and iii) what lessons Swedish railways can take from various approaches to adapting to climate change.

This thesis combines multiple methods and insights from various scientific disciplines to answer these research questions. It includes analyses of weather data from the Swedish Meteorological and Hydrological Institute, and data on delays and infrastructure failure from the Swedish Transport Administration, in order to understand how weather affects train delays and infrastructure failures. In addition, literature from scientific sources, government organisations, and railway companies was reviewed, and workshops and interviews were conducted to explore the challenges of climate adaptation and the approaches that can be used.

The findings of this thesis show that most train delays and infrastructure failures in Sweden occur under freezing temperatures, heavy snowfall, and strong winds. Among railway assets, tracks are the most vulnerable to weather impacts. With climate change expected to bring higher temperatures and more rainfall, Sweden may face more delays and failures caused by heat- and flooding-related extreme weather events.

Adapting railway infrastructure to climate change comes with several challenges: legislation, resources, prioritisation, and knowledge. In Sweden, the main responsibility for climate adaptation lies with property owners. This becomes complicated when multiple owners are affected by the same extreme weather event, making it unclear who should pay for protection or climate adaptation. Limited financial and human resources also create challenges. There is a struggle to prioritise climate adaptation, because climate change is seen as a distant issue compared to

short-term goals. Finally, a lack of knowledge about climate adaptation not only poses a challenge on its own but also reinforces the other barriers.

The findings of this thesis show that adapting railways to climate change works best when the approach is flexible and considers more than just engineering solutions. For example, combining structural approaches (such as building better drainage) with non-structural approaches (such as cancelling building rights in flood risk areas and implementing early-warning systems) can make the system more adapted to climate change. Lessons from other sectors also highlight the value of linking climate adaptation to disaster risk reduction, so that railways are prepared not only for gradual climate changes but also for more sudden extreme events.

This thesis presents results that can help planners and decision-makers to prepare railways for a changing climate. It also provides evidence of how weather affects train delays and infrastructure, creating a baseline for understanding the current risks. It offers insights for asset managers, such as identifying weather thresholds that can guide climate adaptation planning. This thesis also explores different approaches for climate adaptation, highlighting what may or may not work well in the railway context, and what barriers exist to adaptation. Finally, this thesis draws lessons from some global experiences and relates them to Sweden.

Building a railway system that is prepared for the effects of climate change will improve reliability and safety for both passengers and freight. This is not only beneficial for the environment and the economy but also for society, because everyone should have access to safe and reliable rail transport.

Populärvetenskaplig sammanfattning

Klimatförändring medför fler extrema väderhändelser som värmeböljor, stormar och översvämningar. Dessa händelser utsätter viktig infrastruktur, såsom järnvägar, för risk för förseningar och/eller inställningar. När en extrem väderhändelse som en översvämning drabbar en järnvägslinje kan tåg bli försenade eller inställda, och säkerhetsproblem kan uppstå. Tågtrafik ses också ofta som ett miljövänligt alternativ till fossila fordon (till exempel bilar och flyg), men om de blir opålitliga eller osäkra kan de förlora sin attraktionsförmåga. Därför är det viktigt att förstå hur järnvägar kan hantera extremväder både idag och i framtiden. Detta kallas klimatanpassning.

Många vetenskapliga studier har undersökt hur vädret orsakar förseningar och inställningar av tåg, men betydligt färre har undersökt hur klimatanpassning planeras och utförs i praktiken, och ännu färre har beaktat den bredare klimatadaptationsprocessen i sin helhet. Denna avhandling fokuserar på hur den svenska järnvägssektorn kan anpassa sig till ett förändrat klimat och besvarar tre huvudfrågor: i) hur järnvägsdriften och infrastrukturen påverkas av vädret, ii) vilka utmaningar som kan uppstå när man försöker anpassa järnvägsinfrastrukturen till klimatförändringarna, och iii) vilka lärdomar den svenska järnvägen kan dra av olika metoder för att anpassa sig till klimatförändringarna.

Avhandlingen kombinerar flera metoder och insikter från olika vetenskapliga discipliner för att besvara dessa forskningsfrågor. Den innehåller analyser av väderdata från Sveriges meteorologiska och hydrologiska institut (SMHI) samt data om förseningar och infrastrukturfel från Trafikverket för att förstå hur vädret påverkar tågförseningar och infrastrukturfel. Dessutom har litteratur från vetenskapliga källor, statliga organisationer och järnvägsföretag granskats, och workshops och intervjuer har genomförts för att undersöka utmaningarna med klimatanpassning och de metoder som kan användas.

Resultaten av denna avhandling visar att de flesta tågförseningar och infrastrukturfel i Sverige inträffar vid minusgrader, kraftiga snöfall och starka vindar. Bland järnvägsanläggningarna är spåren mest utsatta för väderpåverkan. Eftersom klimatförändringarna förväntas medföra högre temperaturer och mer nederbörd kan Sverige komma att drabbas av fler förseningar och problem orsakade av värme och översvämningsrelaterade extrema väderhändelser.

Anpassningen av järnvägsinfrastrukturen till klimatförändringarna medför flera utmaningar: lagstiftning, resursfördelning, prioritering och kunskap. I Sverige ligger huvudansvaret för klimatanpassningen hos fastighetsägarna och detta blir komplicerat när flera ägare drabbas av samma extrema väderhändelse, vilket gör det oklart vem som ska betala för skydd eller anpassning. Begränsade ekonomiska och personella resurser skapar också utmaningar. Klimatanpassning prioriteras ofta inte eftersom klimatförändringarna ses som avlägsna jämfört med kortsiktiga mål.

Slutligen utgör bristen på kunskap om anpassning inte bara en utmaning i sig, utan förstärker också de andra hindren.

Resultaten visar att anpassning av järnvägarna till klimatförändringarna fungerar bäst när tillvägagångssättet är flexibelt och tar hänsyn till mer än bara tekniska lösningar. Till exempel kan en kombination av strukturella åtgärder, såsom att bygga bättre dräneringssystem, med icke-strukturella åtgärder, såsom att upphäva byggrätter i områden med översvämningsrisk och införa system för tidig varning, göra systemet mer anpassat till klimatförändringarna. Erfarenheter från andra sektorer visar också på värdet av att koppla klimatanpassning till katastrofriskreducering, så att järnvägarna är förberedda inte bara på gradvisa klimatförändringar utan också på mer plötsliga extrema väderhändelser.

Resultaten från denna avhandling kan hjälpa tjänstemän och beslutsfattare att förbereda järnvägarna för ett förändrat klimat. Den ger belägg för hur vädret påverkar tågförseningar och infrastruktur, vilket skapar en grund för att förstå de aktuella riskerna. Den erbjuder praktiska insikter för tillgångsförvaltare, såsom att identifiera vädertrösklar som kan vägleda planeringen av klimatanpassningen. Avhandlingen undersöker också olika tillvägagångssätt för klimatanpassning och belyser vilka lösningar som kan fungera bra eller mindre bra i järnvägssammanhang och vilka hinder som finns för anpassning. Slutligen drar avhandlingen lärdomar från några globala erfarenheter och relaterar dem till Sverige.

Att bygga ett järnvägssystem som är förberett för effekterna av klimatförändring kommer att förbättra tillförlitligheten och säkerheten för både passagerare och gods. Detta är inte bara fördelaktigt för miljön och ekonomin utan också för samhället, eftersom alla bör ha tillgång till säkra och tillförlitliga järnvägstransporter.

Populärwissenschaftliche Zusammenfassung

Das Klima verändert sich und bringt extremere Wetterereignisse wie Hitzewellen, Stürme und Überschwemmungen mit sich. Diese Ereignisse gefährden wichtige Infrastrukturen wie Eisenbahnen. Wenn ein extremes Wetterereignis wie eine Überschwemmung eine Eisenbahnstrecke trifft, kann es zu Zugverspätungen oder -ausfällen kommen sowie Sicherheitsbedenken auftreten. Eisenbahnen gelten als umweltfreundliche Alternative zu Autos oder Flugzeugen, jedoch gefährden Unzuverlässigkeit und Unsicherheit ihre Attraktivität. Deshalb ist es wichtig zu verstehen, wie Eisenbahnen heute und in Zukunft mit extremen Wetterbedingungen umgehen; was nachfolgend in dieser Arbeit als Klimaanpassung bezeichnet wird.

Während zahlreiche Studien untersucht haben, wie wetterbedingte Einflüsse zu Verspätungen und Ausfällen führen, gibt es kaum Forschung dazu, wie die Klimaanpassung in der Praxis geplant und gesteuert wird; Studien, die den gesamten Klimaanpassungsprozess betrachten, fehlen bislang vollständig. Die vorliegende Arbeit fokussiert sich darauf, wie sich der schwedische Eisenbahnsektor an den Klimawandel anpassen kann. Sie befasst sich mit drei Hauptfragen: i) Wie werden der Eisenbahnbetrieb und die Infrastruktur durch das Wetter beeinflusst? ii) Welche Herausforderungen können bei der Klimaanpassung der Eisenbahninfrastruktur auftreten? iii) Welche Erkenntnisse kann die schwedische Eisenbahn aus verschiedenen Ansätzen zur Klimaanpassung ziehen?

Für die Beantwortung dieser Forschungsfragen wurden mehrere Methoden und Erkenntnisse aus verschiedenen wissenschaftlichen Disziplinen kombiniert. Die wetterbedingten Einflüsse auf Zugverspätungen und Infrastrukturausfälle wurden mittels Analysen von Wetterdaten des Schwedischen Meteorologischen und Hydrologischen Instituts sowie Daten zu Verspätungen und Infrastrukturausfällen der Schwedischen Verkehrsverwaltung untersucht. Darüber hinaus wurden wissenschaftliche Quellen sowie Dokumente von Regierungsorganisationen und Eisenbahnunternehmen ausgewertet und Workshops und Interviews durchgeführt, um die Herausforderungen der Klimaanpassung und die möglichen Ansätze zu untersuchen.

Die Ergebnisse dieser Arbeit zeigen, dass die meisten Zugverspätungen und Infrastrukturausfälle in Schweden bei Minustemperaturen, starkem Schneefall und starkem Wind auftreten, dabei sind insbesondere die Gleisinfrastrukturen anfällig. Da der Klimawandel voraussichtlich höhere Temperaturen und mehr Niederschläge mit sich bringt, könnte Schweden zusätzlich mit vermehrten Zugverspätungen und -ausfällen aufgrund von Hitze und Überschwemmungen konfrontiert werden.

Die Anpassung der Eisenbahninfrastruktur an den Klimawandel bringt mehrere Herausforderungen mit sich: Gesetzgebung, Ressourcen, Priorisierung und Wissen. In Schweden liegt die Hauptverantwortung für die Klimaanpassung bei den Grundstückseigentümern. Wenn mehrere Eigentümer von demselben

Wetterereignis betroffen sind, dann wird die Verantwortungszuteilung für Schutz und Anpassung zusätzlich erschwert. Begrenzte finanzielle und personelle Ressourcen stellen eine weitere Herausforderung dar. Des Weiteren wird die Klimaanpassung oft nicht priorisiert, da der Klimawandel im Vergleich zu kurzfristigen Zielen als weit entferntes Problem angesehen wird. Schließlich stellt mangelndes Wissen über Anpassungsmaßnahmen nicht nur an sich eine Herausforderung dar, sondern verstärkt auch die anderen Herausforderungen.

Die Ergebnisse der Arbeit zeigen, dass die Klimaanpassung der Eisenbahn am besten funktioniert, wenn der Ansatz flexibel ist und mehr als nur technische Lösungen berücksichtigt. Beispielsweise kann die Kombination von baulichen Maßnahmen wie der Verbesserung der Entwässerung mit Strategischen Ansätzen wie der Aufhebung von Baurechten in hochwassergefährdeten Gebieten und Frühwarnsystemen dazu beitragen, das System besser an den Klimawandel anzupassen. Erfahrungen aus anderen Sektoren unterstreichen den Nutzen der Verknüpfung von Klimaanpassung und Katastrophenvorsorge, damit die Eisenbahn nicht nur auf allmähliche Klimaveränderungen, sondern auch auf plötzlich auftretende Extremereignisse vorbereitet ist.

Die Ergebnisse dieser Arbeit können Planungsverantwortlichen und Entscheidungsträgern dabei helfen, die Eisenbahn auf den Klimawandel vorzubereiten. Sie liefert Evidenz, wie sich Wetterereignisse auf Zugverspätungen und Infrastruktur auswirken, und schafft damit eine Grundlage für das Verständnis der aktuellen Risiken. Sie bietet praktische Einblicke für Asset Managers, beispielsweise durch die Ermittlung von Wettergrenzwerten, die als Leitfaden für die Klimaanpassungsplanung dienen können. Diese Arbeit untersucht zudem verschiedene Klimaanpassungsansätze und zeigt auf welche Ansätze im Eisenbahnkontext gut funktionieren und welche Hindernisse bestehen. Schließlich zieht diese Arbeit Erkenntnisse aus einigen globalen Erfahrungen und bezieht diese auf den schwedischen Kontext.

Die Entwicklung eines Eisenbahnsystems, welches auf die Auswirkungen des Klimawandels vorbereitet ist, wird die Zuverlässigkeit und Sicherheit sowohl für Passagiere als auch Güter verbessern. Dies ist nicht nur für die Umwelt und die Wirtschaft von Vorteil, sondern auch für die Gesellschaft, indem Zugang zu einem sicheren und zuverlässigen Schienenverkehr gewährleistet wird.

List of Papers

Paper I

Ochsner, M., & Palmqvist, C.-W. (2022). Weather and Train Disruptions in Sweden, 2011–2019. *WIT Transactions on The Built Environment, 213*, 113-120. https://doi.org/10.2495/cr220101

Paper II

Ochsner, M., Fisher, R., & Palmqvist, C.-W. (2024). The impacts of weather on railway infrastructure in Sweden. *Sustainable and Resilient Infrastructure*, *9*(6), 582-598. https://doi.org/10.1080/23789689.2024.2340371

Paper III

Ochsner, M., Palmqvist, C.-W., Olsson, N.O.E., & Winslott Hiselius, L. (2023). The effects of flooding on railway infrastructure: A literature review. *Transportation Research Procedia, 72*, 1786–1791. https://doi.org/10.1016/j.trpro.2023.11.654

Paper IV

Ochsner, M., Göransson, G., Hagström. J., & Palmqvist, C.-W. (2026) Barriers and Opportunities for Dynamic Adaptation of Coastal Railways. *Transportation Research Part D: Transport and Environment, 151*. https://doi.org/10.1016/j.trd.2025.105129

Paper V

Ochsner, M., Göransson, G., Ganslandt, E., Winslott Hiselius, L., & Palmqvist, C.-W. Barriers to Climate Change Adaptation in Swedish Railway Infrastructure. (*Under review*).

Paper VI

Ochsner, M., Greenham, S., del Barrio Álvarez, D., & Kato, H. (2025). On Track to Climate Resilience? Insights from Japanese Railways. *International Conference on Advanced Systems in Public Transport and TransitData 2025,* Kyoto, Japan. (*peer-reviewed*).

Author's Contributions to Papers

Paper I

I am the first author of this paper. The original idea stemmed from my Master's thesis at Aalborg University, conducted in collaboration with Carl-William Palmqvist, who initially proposed the research topic. I was responsible for the visualisation of the data analysis, working closely with Carl-William, who curated the data, contributed to the analysis, and co-authored parts of the method section. He also supported the development of the methodology and assisted in reviewing the manuscript.

Paper II

I am the first author of this paper. The original idea stemmed from discussions with Rachel Fisher, and later Carl-William Palmqvist. The methodology builds on Rachel Fisher's previous work; she contributed to developing the method and supervised the data analysis. Carl-William Palmqvist assisted with data curation and contributed to the data analysis. Both Rachel Fisher and Carl-William Palmqvist drafted parts of the literature review and method section. I was responsible for visualising the data analysis and drafting the remainder of the manuscript, with all co-authors reviewing the manuscript and providing feedback.

Paper III

I am the first author of this paper. I developed the original idea in collaboration with my co-authors and was responsible for the literature search, conducted under their supervision. Carl-William Palmqvist assisted with the abstract screening stage of the review. I synthesised the literature and drafted the manuscript, with all co-authors contributing through review and feedback.

Paper IV

I am the first author of this paper. The original idea emerged from discussions with Gunnel Göransson, Carl-William Palmqvist, and later Johannes Hagström. All co-authors contributed to data curation by facilitating the workshops where the data were collected. All co-authors also contributed to the development of the methodology. I was responsible for the data analysis, with all co-authors providing feedback, and I drafted the manuscript, which was reviewed and commented on by all co-authors.

Paper V

I am the first author of this paper. The original idea was formulated based on discussions with all co-authors. Together with Gunnel Göransson and Lena Winslott Hiselius, I defined the scope and research questions. I proposed the methodology and conducted all interviews. The interview guide was developed by me, with feedback from Gunnel Göransson, Lena Winslott Hiselius, and Emilia Ganslandt. I was also responsible for analysing the interview data, with input from the same co-authors. Finally, I drafted the manuscript, with all co-authors providing feedback and reviewing the text.

Paper VI

I am the first author of this paper. The original idea was initiated by me, building on earlier discussions with Sarah Greenham. The methodology was developed collaboratively by all co-authors. I primarily conducted the interviews, with some carried out jointly with Daniel del Barrio Álvarez and Hironori Kato. I analysed the data and drafted the manuscript, which was reviewed and refined with feedback from all co-authors.

Other Publications and Conferences

Palmqvist, C.-W., & **Ochsner, M.** (2023). Train Delays due to Extreme Weather Events in Sweden 2001-2020. *The World Conference on Transport Research (WCTR)*, Montréal, Canada.

Palmqvist, C.W., **Ochsner, M.,** Jamali, S., Hashemi, H., Nilfouroushan, F., Bagherbandi, M., Toller, E., Kour, R. & Karim, R. (2023). Satellite Monitoring of Railways using Interferometric Synthetic Aperture Radar (InSAR): A Case Study in the North of Sweden. *The World Conference on Transport Research (WCTR)*, Montréal, Canada.

Kuipers, R.A., & **Ochsner, M.** (2023). The Impact of Weather Phenomena on Passenger Volumes for Commuter Trains. *The Symposium of the European Association for Research in Transportation (hEART)*, Zürich, Switzerland.

Krits-kollektivet[1] (2023). Vägen till ingenstans – smart mobilitet i bilismens kölvatten. In T. Joelsson, M. Henriksson, & Balkmar (Eds.), *Rättvist Resande? Villkor, utmaningar och visioner för samhällsplaneringen.* ISBN 978-91-88651-19-8

[1] The chapter was written by Dalia Mukhtar-Landgren, Kelsey Oldbury, Jens Portinson Hylander, Chiara Vitrano, Mats Fred, Janet van der Meulen, Karin Winter, **Michelle Ochsner**, and Joel Göransson Scalzotto; Dalia, Kelsey, Jens and Chiara acted as editors. The idea for this text was discussed at a seminar at the Swedish Knowledge Centre for Collective Mobility (also known as K2, and volunteers then contributed to the creation of the text in accordance with the principle "from each according to ability".

List of Key Terms

Climate Adaptation	Proactive approaches that reduce vulnerability and enhance resilience to the impacts of climate change (Biesbroek et al., 2010).
Climate Mitigation	Human intervention to reduce emissions or enhance the sinks of greenhouse gases (IPCC, 2022).
Deep Uncertainty	A state of incomplete knowledge that can result from a lack of information, or from disagreement about what is known or knowable (IPCC, 2022).
Disruption	A delay of more than 60 minutes, or cancellation.
Extreme Weather Event	Rare weather events that significantly deviate from the norm and can cause substantial damage to life, infrastructure, and the environment (IPPC, 2012)
Hazard	A physical event or trend, whether natural or human-induced, that has the potential to cause harm to society, infrastructure, or the environment (IPPC, 2012). In this thesis, related to weather and climate.
Impact	The consequences of risk (interaction between hazard, vulnerability, and exposure).
Infrastructure Fault	Any unexpected or abnormal infrastructure condition (not only those that result in service delays, which is typically classified as a failure.
Maladaptation	Occurs when a climate adaptation approach inadvertently increases vulnerability. (Schipper, 2020).
Resilience	A system's ability to evolve and respond in response to both known and unknown threats (Amekudzi-Kennedy, 2023).
Risk	The potential for events with adverse consequences for human or ecological systems, shaped by the interaction of hazards, exposure, and vulnerability (IPPC, 2012).
Vulnerability	The susceptibility of railway operations or infrastructure to be adversely affected by a hazard.

1 Introduction

The urgency of the need to respond to the negative effects of climate change is increasing (IPPC, 2021; 2022). Extreme weather events such as heatwaves, storms, and floods are increasing in both severity and frequency due to climate change, posing serious risks to both human systems and infrastructure (IPCC, 2021; 2022). These changes are driven by anthropogenic climate change, and even small increases in global temperature have been shown to amplify the intensity and frequency of such events (IPCC, 2021).

In response to this, climate mitigation – efforts made to reduce greenhouse gas emissions – has gained global attention in both policy and research (Dechezleprêtre et al., 2025). However, mitigation alone is no longer sufficient. There is growing recognition of the need for climate change adaptation (hereafter referred to as climate adaptation), which includes proactive approaches to reducing vulnerability and enhancing resilience to the impacts of climate change (Biesbroek et al., 2010). Climate adaptation is particularly urgent for critical infrastructure sectors, including transportation, which must be resilient to both anthropogenic drivers and environmental drivers of climate change (OECD, 2019).

Globally, the transportation sector accounts for approximately 15% of greenhouse gas emissions (UN, 2025). Railways are widely recognised as a low-carbon, energy-efficient mode of transport, essential for enabling a modal shift away from private vehicles and towards more sustainable modes of transport (Baker et al., 2010; Blayac & Stéphan, 2021). Their role in supporting climate mitigation goals is therefore significant; yet, to fulfil this role, railway systems must be safe and reliable. Climate change challenges this reliability, with extreme weather events causing service disruptions, infrastructure damage, and increased maintenance costs (Garmabaki et al., 2022). Compared to other transport modes, railways are particularly vulnerable due to limited rerouting options and capacity constraints (Mattsson & Jenelius, 2015).

Recent incidents across the globe, including derailments and service suspensions, illustrate the nature of these risks. In Sweden, flood-induced derailments in 2023 and 2025 demonstrate the vulnerability of the railway system to changing weather patterns, and highlight the urgency of enhancing climate resilience in the railway sector. Yet the track to achieving said resilience is not straightforward. Adapting railway infrastructure to climate change is particularly challenging due to its long lifespan, complex governance structures, and uncertainties surrounding the timing and magnitude of climate projections (Stanton & Roelich, 2021). The severity of climate impacts on railway infrastructure is also dependent on factors such as design, age, usage (Attoh et al., 2022), and maintenance (Taylor, 2020). The Swedish context adds further complexity, with a decentralised governance structure and fragmented responsibilities complicating climate adaptation efforts (Knaggård et al., 2020; Rylenius & Hamza, 2024).

1.1 The Impacts of Weather on Railway Operations and Infrastructure

Even without the added pressure of anthropogenic climate change, existing climate variability already poses significant challenges for transport infrastructure (Lindgren et al., 2009). Adverse weather conditions and extreme events can lead to service disruptions, increased maintenance costs, and heightened safety concerns, all of which impose financial burdens on infrastructure managers and railway operators (Greenham et al., 2020; Garmabaki et al., 2022; Lindgren et al., 2009; Palin et al., 2021). Jaroszweski et al. (2014) explain that weather can affect transport systems in two primary ways: through behavioural changes in operators due to weather-related stress (e.g., reduced visibility during heavy snowfall), and through physical damage to infrastructure (e.g., track buckling).

Due to the complexity and interconnectivity of railway systems, weather-related impacts are rarely linear. They can affect not only infrastructure but also operations and safety, with both immediate and long-term consequences for asset management (Palin et al., 2021). The consequences of an infrastructure fault depend on the nature of the fault, whether it requires routine repair or major replacement, and its impact on dependent users and services, with both direct (e.g. asset loss, fatalities) and indirect (e.g. revenue loss) implications (Palin et al., 2021). Figure 1 presents examples of hazards that can impact railway infrastructure.

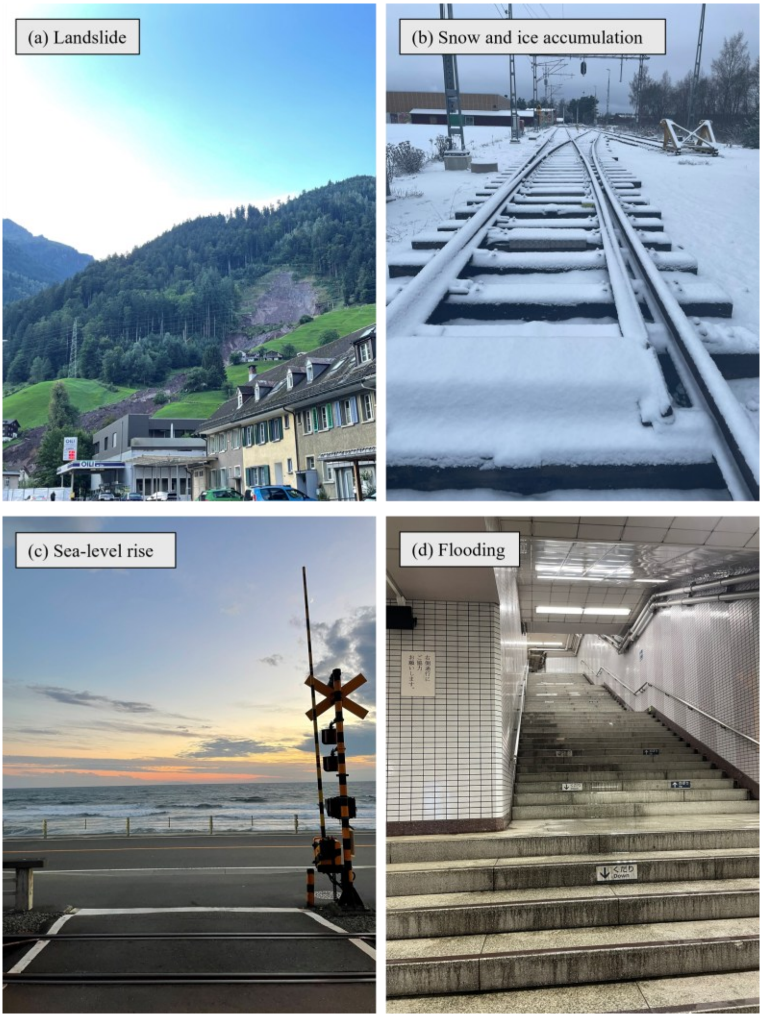

Figure 1. Examples of hazards that can impact railways.
(a) Landslide near Schwanden Station, Switzerland in September 2023. (b) Snow and ice accumulation on tracks at Nässjöakademin, Sweden in December 2022. (c) Tracks near the sea in Kamakura, Japan in December 2023. (d) Water residue after the cleaning of Ichigaya station in August 2024, following flooding in Tokyo, Japan (Photographs by Michelle Ochsner).

Extreme weather events are increasing in severity and frequency, impacting railways in more severe ways (Vajda et al., 2014; Vranešić et al., 2025). Globally, several examples illustrate how extreme weather impacts railway infrastructure and operations. In 2026, one train derailed in Switzerland due to an avalanche, and in 2023, two trains derailed in Switzerland due to high wind speeds. In the UK, a heatwave in 2022 led to emergency speed restrictions on railway operations due to the risk of track buckling. The winter of 2023 brought extreme snowfall to southern

Germany, causing many rail services to be suspended. Finally, in Japan, Typhoon 19 in 2019 flooded the Nagano Train Depot, resulting in the decommissioning of 120 Shinkansen (high-speed rail) rolling stock wagons.

In Sweden, there have been two particularly notable flooding events in recent years that have impacted railway infrastructure and operations. On August 7, 2023, a storm (Hans) passed through Sweden, with over 100 millimetres of rain falling within a 10-hour period (SHK, 2024; Figure 2). This led to an embankment failure and the subsequent derailment of a passenger train. Fortunately, no injuries were reported, but approximately 40 metres of track collapsed, causing extensive damage (SHK, 2024). Two years later, in September 2025, heavy precipitation led to two derailments of freight trains in northern Sweden. Not only was there significant infrastructural damage but also affecting passenger train traffic for several weeks (*Sydsvenskan*, 2025). These events highlight that extreme weather events, such as flooding, are increasing not only globally but also in Sweden, highlighting the importance of understanding how to enhance the resilience of railway systems.

Figure 2. Train derailment near Hudiksvall in August 2023.
Reproduced with permission (Mats Andersson / TT News Agency).

1.2 Aim and Research Questions

The aim of this thesis is to advance the understanding of climate adaptation processes, using the railway sector in the Swedish context as a lens to examine how climate adaptation is approached and implemented in practice. I do this by answering the three following research questions (RQs):

- RQ 1: How does weather impact railway operations and infrastructure in Sweden?
- RQ 2: What are the challenges involved in adapting the railway sector to climate change within current governance structures in Sweden?
- RQ 3: What lessons can be drawn from different climate adaptation approaches to inform climate resilience in Swedish railways?

More detail on the research questions, their connections, and how they relate to the included papers can be found in *Section 5.3*.

1.3 Structure of the Thesis

This thesis is structured as follows. *Section 2* conceptualises climate adaptation and defines the important concepts utilised in this thesis. This section first discusses important concepts in literature and ends by defining how these concepts are used in the rest of the thesis. In *Section 3* the field of research is introduced. Here, previous research on weather and the impacts of climate change on railway operations and infrastructure are introduced, as is previous research on climate adaptation approaches. These streams of research are brought together to highlight a research gap that this thesis aims to contribute to. *Section 4* provides background on the Swedish context, describing how the climate is changing in Sweden and how climate adaptation is currently governed.

Following the presentation of the background information, *Section 5* introduces the research design and its philosophical underpinnings, connections between the papers and the research questions, and justification for utilising a mixed-methods and interdisciplinary approach. The data-collection process and geographical scope are described in *Section 6*, and the methods used for the data analysis are presented in *Section 7.*

A summary of the included papers is provided in *Section 8*, with the answers to the research questions presented in *Section 9.* The thesis is rounded off with the discussion in *Section 10*, which also points to limitations and future research; policy recommendations are presented in *Section 11*, and a conclusion in *Section 12.*

2 Conceptualising Climate Adaptation

This thesis utilises several key concepts and terms related to weather and climate change. This chapter discusses the foundational concepts that underpin this work. These include risk as a function of hazard, exposure, and vulnerability; the nature of extreme weather, climate change, and their impacts; and the framing of resilience and climate adaptation.

2.1 Risk, Hazard, Exposure, and Vulnerability

Risk, in the context of climate change, is often characterised as a function of *hazard*, *exposure*, and *vulnerability* (IPCC, 2012; Simpson et al., 2021; Zebisch, et al., 2020; Figure 3).

Figure 3. The “risk propeller”, which conceptualises interactions between the determinants of risk – hazard, vulnerability, and exposure. (Source: IPCC, 2022; p. 145)

Figure 3 illustrates how *hazard*, *exposure*, and *vulnerability* interact to produce *risk*. *Hazard* refers to a physical event or trend, whether natural or human-induced, that has the potential to cause harm to society, infrastructure, or the environment, in this thesis it is related to weather and climate. *Exposure* is related to the presence of elements or assets, such as people and their livelihoods; infrastructure; or social, economic, or cultural assets that would be adversely affected. *Vulnerability* is related to how something (for example, a railway switch asset) may be adversely affected (IPCC, 2012; 2022).

Vulnerability, which is defined by the IPCC as the propensity to be adversely affected, is further described by Smit and Wandel (2006) as a function of *exposure, sensitivity*, and *adaptive capacity*. Here, *exposure* is the degree to which a system experiences hazards or climatic conditions; *sensitivity* refers to the susceptibility of the system to harm when exposed; and *adaptive capacity* is the system's ability to cope with, adjust to, or recover from those conditions. Smit and Wandel (2006) also emphasise that vulnerability is dynamic, context-specific, and shaped by social, economic, political, and environmental factors.

An example of climate risk in the Swedish railway system is flooding caused by intense rainfall. Heavy precipitation leading to flooding represents the *hazard*; low-lying railway infrastructure represents the *exposure*; and ageing assets with insufficient drainage capacity reflect the *vulnerability*. These factors combine to create a risk of service disruption and infrastructure damage. Weather or climate-change impacts alone are not inherently hazardous; they become so when they interact with exposed and vulnerable systems (Fisher, 2021; Nightingale, 2016; Palin et al., 2021; Adger, 2006). Furthermore, vulnerability is also shaped by socio-political processes (Smit & Wandel, 2006).

2.2 Extreme Weather, Climate Change, and Impacts

One important distinction in understanding climate impacts is between weather, adverse weather, and extreme events. *Weather* refers to short-term atmospheric conditions that are experienced daily, including temperature, precipitation, wind, and humidity (Edwards & Challenor, 2013). *Adverse weather conditions* are those that negatively affect human activities and infrastructure, such as heavy snowfall which can cause railway disruptions (Palin et al., 2021).

Extreme weather events are rare occurrences that significantly deviate from the norm and can pose a significant threat or life, or cause substantial damage, infrastructure or the environment (Olaoluwa et al., 2022; IPCC, 2012; Stephenson, 2008). These include hurricanes, heatwaves, droughts, floods, and severe storms. Such events are typically characterised as events near the tails of climate variable distributions, with thresholds that vary by region and time (IPCC, 2012).

In relation to climate change, *weather* refers to short-term phenomena (i.e., daily, hourly, yearly), while *climate* refers to long-term trends and averages (Markolf et al., 2019). The IPCC (2021) defines *climate change* as long-term alterations in the average state or variability of the climate system, typically observed over decades or longer. These changes may arise from natural processes or be driven by human activity, such as the emitting of greenhouse gases. In contrast, *global warming* denotes a rise in the global average surface temperature over time, relative to a defined historical baseline. This warming trend is typically assessed over a longer period of time, in order to account for short-term fluctuations and interannual variations. A changing climate can alter how often, how intensely, where, and when extreme weather events occur, and can potentially lead to events that are unprecedented in nature (IPCC, 2012). In addition, these changes in extremes may result from changes in the mean, variance, or shape of probability distributions, or from a combination of all three (IPCC, 2012; see Figure 4).

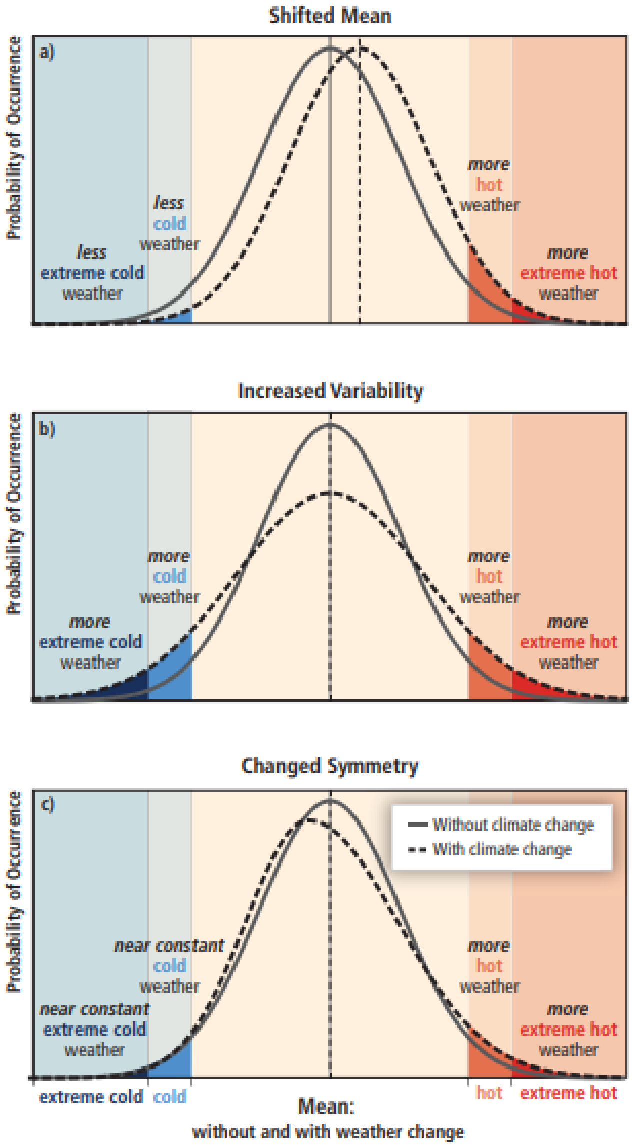

Figure 4. The effects of changes in temperature distribution on extremes weather events. Different changes in temperature distributions between the present and future climate and their effects on extreme values of distributions (IPCC 2012; p. 7).
(a) The effects of a simple shift of the entire distribution towards a warmer climate; (b) the effects of an increase in temperature varability with no shift in the mean; (c) the effects of an altered shape of the distribution – in this example, a change in asymmetry towards the hotter part of the distribution.

Impacts are the outcomes of climate-related risks, which arise from the interaction between hazards (such as extreme weather or climate events), exposure, and vulnerability. These effects can be either harmful or beneficial, and may influence human health, livelihoods, ecosystems, infrastructure, and socio-economic systems (IPCC, 2021).

2.3 Resilience

Resilience is a term that lacks a universally agreed definition and varies by context, even within fields (Amekudzi-Kennedy et al., 2023; Fleming & Ledogar, 2008; Garrett et al., 2025; Mingarini & Larsson, 2025). Most definitions in the literature describe *resilience* as a cycle of *disruption*, *response, absorption, recovery, and learning* (Chan & Schofer, 2016). The IPCC defines resilience as:

> *The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation* (IPCC, 2012; p. 2246).

Regarding railway infrastructure, *resilience* is often discussed in relation to operations, and the ability to bounce back quickly after a disruptive event. Bešinović (2020; p. 461) defines *resilience* as "the ability of a railway system to provide effective services in normal conditions, as well as to resist, absorb, accommodate, and recover quickly from disruptions or disasters." Key concepts include *vulnerability*, i.e. the system's susceptibility to disruptions; *robustness*, its ability to handle everyday delays; and *survivability*, its capacity to degrade gracefully when disruption occurs, rather than collapsing abruptly. The *response* involves immediate actions to maintain service and safety, while *recovery* refers to how quickly the system returns to normal. Depending on the disruption, some stages may be skipped or extended.

Typically, *resilience* in railway operations is discussed in terms of maintaining or returning to a "normal state" following a disruption. Mingarini and Larsson (2025) note that in Swedish public policy, resilience in crisis management is often framed around resistance to change or building systems that are capable of withstanding shocks. In environmental and climate policy, *resilience* is used more variably, encompassing both resistances to change and climate adaptation, although recent years have seen a growing emphasis on resistance.

In contrast, Amekudzi-Kennedy et al. (2023) and Markolf et al. (2019) advocate for a shift towards *adaptive resilience* in transportation systems, particularly under conditions of deep uncertainty linked to climate change. *Adaptive resilience* refers to a system's capacity to evolve and respond to both known and unknown threats. These researchers emphasise that *resilienc*e is not a fixed outcome but a dynamic process involving continuous learning, adjustment, and transformation, implying that the "normal state" itself may change over time. Similarly, the Stockholm Resilience Centre report on *Resilience Science Must-Knows* states that resilience is "not just about bouncing back – it is about building the capacity to cope with shocks, adapt to change, and transform systems away from undesirable trajectories" (Norström et al., 2025; p. 8).

These two *resilience* perspectives – resistance and climate adaptation – are reflected in the UNDRR (2017) definition of resilience:

> *the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management*.

This definition positions resilience as both the ability to withstand and recover from shocks, and to adapt and transform in response to evolving risks.

2.4 Climate Adaptation

Central to this thesis is the concept of *climate adaptation.* There is a growing recognition that climate mitigation alone is insufficient in tackling the climate crisis, and that society-wide adjustments to current and future climate are urgently needed (Biesbroek et al., 2010; IPCC, 2022).

The IPCC (2022) defines *climate adaptation* in relation to both human and natural systems. In human systems, it is the process of adjustment to an actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, it is the process of adjustment to an actual climate and its effects; human intervention may facilitate adjustment to an expected climate and its effects.

Adaptive capacity is, according to the IPCC (2022), "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences." Smit and Wandel (2006) describe it in a similar manner, as a system's ability to cope with, adjust to, or recover from hazardous conditions, and see it as closely related to resilience. *Adaptive capacity* is also dynamic and context-specific, varying across places, sectors, and times.

Climate adaptation encompasses both the enhancement of *adaptive capacity* and the implementation of climate adaptation measures (i.e., translating capacity into concrete actions) (Adger et al., 2005). Such measures are not taken in isolation but are shaped by broader demographic, cultural, and economic changes, as well as shifts in technology, governance, and global flows of capital and labour (Adger et al., 2005).

Historically, hazard and risk management across Europe has relied on expert-led engineering approaches, with structural measures designed to keep hazards at bay (Brink, 2018; Newig et al., 2014). However, increasing climate variability and extreme weather events are challenging the adequacy of these approaches, which are proving to be costly and ecologically disruptive (Doswald et al., 2014; Piggot-McKellar et al., 2020; Schoonees et al., 2019; IPCC, 2022).

Climate adaptation is not uniform. It varies by scale and actor, and success at one level may not translate to another (Adger et al., 2005; Eriksen et al., 2011). Climate adaptation approaches may be deliberate responses to climate risks or emerge from broader socio-economic changes, and they may be reactive or anticipatory. Importantly, not all climate adaptation is beneficial. Some approaches may inadvertently increase *vulnerability*, a phenomenon known as *maladaptation* (Schipper, 2020). Figure 5 presents a conceptual diagram illustrating how climate adaptation outcomes can evolve over time, including the potential for maladaptive trajectories.

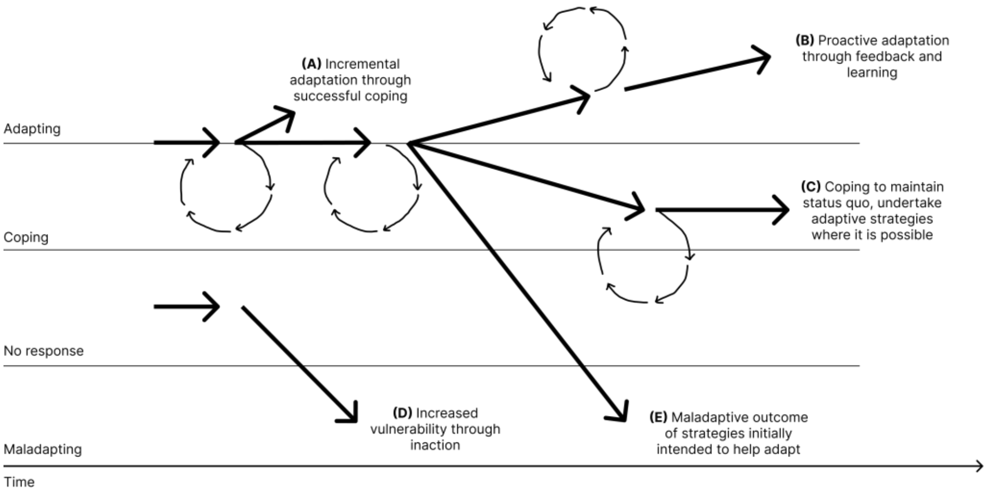

Figure 5. A conceptual diagram showing different climate adaptation outcomes over time. Adapted from Schipper (2020).

2.5 Concepts in Relation to the Thesis

The concepts outlined above are complex and context-dependent. In this thesis, I adopt the definition of *climate adaptation* of Biesbroek et al. (2010), which describes *climate adaptation* as proactive approaches (including policies) to reducing vulnerability and enhancing resilience to the impacts of climate change. Applied to the railway sector, climate adaptation is conceptualised as the process of modifying railway infrastructure and operations to respond to both current and future climate-related impacts in order to increase resilience.

Vulnerability is the susceptibility of railway operations or infrastructure to being adversely affected by a hazard, while *impact* refers to the consequences of such interactions. Although *exposure* is not treated as a standalone concept, it is implicitly considered, particularly in Paper IV, which examines a coastal railway in southern Sweden. *Vulnerability* is also shaped by governance structures; for example, if responsibility is unclear then the system may be less prepared.

This thesis focuses on *weather and/or climate-related hazards and risks*, encompassing hydrological, climatological, and meteorological phenomena. *Hazards* include events such as floods, sea-level rise, and storms, while *weather- and/or climate-related risks* are the potential negative consequences of these hazards for society, the economy, and railway infrastructure managers. In this framing, extreme weather events are considered to be climate-related hazards.

Resilience is understood as a dynamic process that incorporates adaptive capacity, drawing on the concept of *adaptive resilience* as defined by Amekudzi-Kennedy et al. (2023). It refers to a railway system's ability to evolve and respond to both known and unknown threats. Resilience is not a fixed outcome but a continuous process that is particularly relevant under conditions of deep uncertainty, where the notion of a "normal state" may itself shift over time. In this thesis, increased resilience is viewed as a key outcome of successful climate adaptation. *Adaptive capacity* underpins resilience, enabling systems to adjust and recover from climate-related hazards.

Papers I and II of this thesis examine the impacts of specific weather variables - temperature, snow depth, wind, and precipitation - on the Swedish railway system. Although these papers are based on present-day weather data, the findings are interpreted within the broader context of a changing climate. The term *climate change* is used throughout the thesis to reflect a wider range of climatic changes beyond rising sea surface temperatures, distinguishing it from global warming. Papers I–III primarily examine weather-related impacts, while Papers IV–VI focus on climate adaptation and governance dimensions.

3 The Field of Research

This chapter provides an overview of existing research on the impacts of weather and climate change on railway operations and infrastructure, as well as of studies that address various climate adaptation approaches. It also positions the thesis within these research streams, and identifies the research gaps addressed by this work.

3.1 Weather and Climate Change Impacts on Railways

Table 1 gives an overview of the ways in which weather can affect railway operations and infrastructure.

Table 1. Examples of the relationships between weather phenomena, their associated hazards, and possible effects on railway operations and infrastructure.
Adapted from Palin et al. (2021). This list is not exhaustive.

Weather phenomenon	Associated weather hazard	Secondary associated hazards(s)/impacts(s)	Possible effects on railway operations and infrastructure
Temperature	High temperature	Heatwaves; wildfire	Track buckling; thermal expansion in structres; damage to catenaries; delays; cancellations
	Low temperature	Cold snaps; ice formation; frost	Freezing of switches; tunnel icing; slippery tracks; breakage of rails; damage to catenaries and signals; delays; cancellations
	Zero-crossing and large seasonal temperature range	Freeze-thaw action	Rockfalls; unstable permafrost; track misalignment; delays; cancellations
Precipitation	Excess precipitation	Snowfall; flooding (fluvial or pluvial); landslide	Embankment failure; bridge scour; snow blockages/build-up on tracks or switches; flooding of tracks or depots; water damage to catenaries or signals; delays; cancellations
	Precipitation deficit	Drought; drying of soil; shrinkage; soil cracking; landslide	Embankment failure; track misalignment; misalignment of poles supporting catenary lines; delays; cancellations
Wind	Windstorms	Tree fall; wind-blown objects	Downed catenary lines; structural damage due to fallen trees/wind-blown objects; rolling stock derailment; delays; cancellations
Sea-level rise	Short and long-term changes to coastal water levels	Coastal flooding; wave overtopping; tidal river floods	Scour; erosion; structural damage; flooding of tracks and/or tunnels; delays; cancellations

Table 1 presents examples of how weather can affect railway infrastructure and subsequent operations. Weather phenomena such as temperature and precipitation are not inherently hazardous, but become so when they manifest in ways that can damage railway infrastructure (Fisher, 2021; Palin et al., 2021; Nightingale, 2016).

Table 1 also highlights the impacts of individual weather phenomena. While many of these are not extreme in themselves, extreme weather events often arise from the interaction of multiple phenomena. For example, a winter storm may include heavy snowfall, high wind speeds, and low temperatures, or a sudden increase in temperature may lead to snowmelt and subsequent flooding. Compound events are weather and climate phenomena that can result from the combination of multiple hazards (Zscheischler et al., 2020). For example, a dry summer in British Columbia, Canada in 2021 led to wildfires that destroyed slope-stabilising vegetation. This was followed by a mass flooding event in November caused by an atmospheric river,[2] leading to an estimated CAD $9 billion in infrastructure damage, including to the Trans-Canada railway (Richards-Thomas et al., 2024).

3.1.1 Weather Impacts on Railway Operations

Many empirical studies have investigated the relationship between adverse weather conditions and railway operations; some have focused on delays and disruptions (see, for example, Brazil et al., 2017; Dobney et al., 2010; Fabella & Szymczak, 2021; Greenham et al., 2020; 2023; Kamalian et al., 2025; Nezval et al., 2024; Palmqvist et al., 2017; Vranešić & Haladin, 2025; Zakeri & Olsson, 2018), while others have investigated how temperature, high wind speeds, heavy precipitation, snow, and leaf fall have strongly impacted passenger train services (Xia et al., 2013; Vranešić & Haladin, 2025).

Kamalian et al. (2025) developed a data-driven Bayesian Network to predict train delays caused by extreme weather, using 1530 incidents exceeding 60 minutes recorded in the United Kingdom between 2022 and 2023. Fabella and Szymczak (2021) reported that railway operations in Germany were most affected by flooding, followed by mass movements and treefalls. In Dublin, Ireland, rainfall had the greatest impact on train delays, especially when this coincided with high wind speeds (Brazil et al., 2017); while a storm on 28 June 2012 caused 10,000 minutes of delays in England and Scotland (Jaroszweski et al., 2015). Nezval et al. (2024) reported 3917 hours of train delays caused by 14,786 storm-related incidents in Czechia between 2002 and 2021.

Several studies have examined the impact of extreme heat. For example, strong relationships have been demonstrated between heat and delays on the London Underground (Greenham et al., 2020), and heat and switch asset vulnerability (Greenham et al., 2023). These relationships are expected to be exacerbated under climate change projections (Greenham et al., 2020; 2023). In Great Britain, delays

[2] Atmospheric rivers are long, narrow corridors of concentrated moisture transport in the atmosphere, primarily responsible for the poleward movement of water vapour from tropical to midlatitude regions (Gimeno et al., 2014).

related to extreme heat cost a baseline amount of £9.2 million in 2003 (Dobney et al., 2010), and this cost is expected to rise under future climate scenarios (Dobney et al., 2009; 2010). In 2015, heat-related delays resulted in 220,000 delay minutes due to incidents such as track buckling and emergency speed restrictions (Ferranti et al., 2018).

Finally, literature also addresses the impacts of winter conditions, particularly in the Nordic countries. Ludvigsen & Klæboe (2014) examined the harsh winter of 2010 in Sweden, Norway, Finland, Poland, and Switzerland, and concluded that prolonged low temperatures combined with heavy snowfall and strong winds had the greatest impact on freight-train punctuality. In Norway, extreme snowfall and low temperatures were the main factors reducing passenger-train punctuality (Zakeri & Olsson, 2018). Palmqvist et al. (2017) found that low and high temperatures, high wind speeds, increased precipitation, and snow depth affected railway operations in Sweden.

Overall, these studies indicate that adverse weather conditions consistently lead to delays and cancellations across railway networks. In addition, these studies typically focus on specific regions and short-term impacts. The literature predominantly focuses on the United Kingdom, with less comparative insight into how impacts vary by geography or jurisdiction. Persistent data gaps on how weather-related events affect railway operations remain across most European countries (European Union Agency for Railways, 2024). While these studies are valuable, they often emphasise modelling approaches to predicting delays and analysing past events. There is also a stream of literature that focuses on the economic costs of delays. Less research focuses on how organisations and/or governance structures can manage these hazards.

3.1.2 Impacts of Weather on Railway Infrastructure

Another body of literature focuses on the impact of weather on physical railway infrastructure, rather than on operations. Research often examines specific assets, such as tracks (Dobney et al., 2009; 2010), embankments (Powrie & Smethurst, 2019), and switches (Garmabaki et al., 2022), as well as interdependencies between railways and power systems (Johansson et al., 2011). Ferranti et al. (2016) found that most heat-related failures in south-east England occur in early summer, and that incidence declines over the rest of the summer, despite the high temperatures – a phenomenon known as *failure harvesting*. Wind-related failures typically involve wind-blown objects blocking tracks or damaging catenaries (Palin et al., 2021), and several studies have explored methods to predict this (Fu & Easton, 2018; Szymczak et al., 2022; Wang et al., 2018). Schriewer et al. (2025) developed a multi-criteria framework to classify flood and flash-flood damage, applying it to Germany's Eifel route after the July 2021 flood event. Nearly half of the damage affected the track superstructure, with erosion and debris deposition as dominant processes, highlighting the vulnerability of assets located within 50 metres of rivers. Szymczak et al. (2026) developed an integrated climate impact analysis tool with the Network of Experts from the German Federal Ministry for Digital and Transport (BMDV) to assess the current and future climate impacts on the transport sector. They applied it to a rockfall event near Kestert, Germany to assess the impacts on federal roads and railways.

Silva et al. (2025) reported that meteorological hazards caused a total of 170,000 disruptions and €15 million in annual costs for the French railway network between 2001 and 2019, with thunderstorms, strong winds, and flooding being the most financially damaging. Wutti et al. (2026) used physical model experiments to demonstrate that flooding triggers ballast layer breaching in embankments, progressing through erosion, with higher discharge rates and sleeper presence accelerating failure and increasing vulnerability.

In Sweden, research has quantified the risks of weather on railway infrastructure and how climate change might impact maintenance. Switches are the most vulnerable to failure during winter, when work orders double or triple (Garmabaki et al., 2022; Stenström et al., 2012). Mirzanamadi et al. (2024) investigated lateral track buckling in Sweden, highlighting that inadequate maintenance is a more significant contributor to buckling than temperature alone. Due to climate change, Sweden is expected to see an increase in railway maintenance and disturbance costs (Thaduri et al., 2021), and the amount of climate adaptation approaches needs to be increased (Garmabaki et al., 2021; Lindgren et al., 2009).

Some research has focused on quantifying the impact of weather on railway infrastructure for informed decision-making, maintenance, and overall extreme weather management, to increase the resilience of railway infrastructure and operations. One such approach uses thresholds, which can be used to inform preventative asset management in preparation for extreme weather. Oslakovic et al. (2013) concluded that failure occurrence on two railway lines in the Netherlands was most significant when temperatures fell below –12°C or exceeded +35°C, and when daily snowfall exceeded 58mm. Fisher (2021) quantified weather-related rates of faults in Great Britain by considering the frequency of exposure of railway assets to different types of weather. The results show that the fault-rate relationship between track temperature and peak daily temperature becomes significant at air temperatures of 30°C and above. Greenham (2023) extended this fault-rate analysis to inform predictions of future frequencies of switch fault events on the London Underground today and in the future, for various future emissions scenarios.

Overall, these studies on infrastructure impacts are fewer than those on operations. A limited number of studies have examined multiple weather variables or a broad range of asset fault types, and even fewer adopt a comprehensive, system-wide perspective (Fisher, 2021). Many combine infrastructure-failure impacts with operational effects and cost estimates. Flooding hazards are among the most studied; however, as noted in *Section 3.1.1*, these studies rarely compare across regions and often overlook governance structures and organisational approaches to managing risk.

3.1.3 Impacts of Future Climate Change on Railways

There also is a body of literature dedicated to understanding the future impacts of climate change on both railway operations and infrastructure. For instance, Bubeck et al. (2019) estimated the current annual cost of damage from flood events on railways in Europe to be roughly €581 million; due to climate change, it is expected that this will increase by 310% under a 3 °C warming scenario. Palin et al. (2013) quantified the impact of temperature-related climate change impacts on Great Britain's railway network, while Powrie & Smethurst (2019) concluded that there will be a greater risk of embankment slope failures due to increased temperatures. Sea-level rise also puts coastal railways at risk due to coastal flooding (Dawson et al., 2016). Conversely, studies have also found that failures related to low temperatures and snow are expected to decrease in light of climate change in certain contexts (Kellermann et al., 2016a; Oslakovic et al., 2012).

Greenham et al. (2023) examined the impacts of rising temperatures on metro infrastructure in London in light of climate change. They found that asset failure rates increased significantly at high temperatures, particularly in tunnels where heat accumulation is exacerbated by limited ventilation and legacy design constraints, and that these impacts will increase due to climate change.

In a Swedish context, research has been conducted on the impact of climate change on railways. Soleimani-Chamkhorami et al. (2024) estimated the life-cycle cost of railway infrastructure under climate change using the Cox Proportional Hazard Model, showing that future climate scenarios could increase maintenance costs by around 11%. Snow- and ice-related failures are the costliest, highlighting the need for climate-informed maintenance planning. Kasraei and Garmabaki (2024) assessed the reliability of urban railway assets across Swedish climate zones, identifying precipitation and humidity as key drivers of failure risk. Their findings show that increased rainfall can reduce asset reliability by up to 60%, highlighting the importance of region-specific climate adaptation approaches. Kasraei et al. (2024) introduced a methodology that combines climate data and reliability modelling to assess infrastructure vulnerability, demonstrating how snow, ice, and extreme temperatures significantly affect railway asset failure rates and laying the foundation for future studies of climate resilience. Lastly, Garmabaki et al. (2024) developed a risk- and vulnerability-assessment framework for Swedish urban railway infrastructure, focusing on the impacts of extreme temperatures on assets such as switches and crossings. Using 19 years of empirical data and expert surveys, the study identified high risks from low temperatures and medium risks from heat-related track buckling and vegetation fires.

Overall, these studies offer valuable insights into how climate change may affect railway operations and infrastructure. However, most climate impact studies focus primarily on infrastructure, while research on weather-related impacts under today's climate is more developed within operations than infrastructure. Moreover, this body of work generally does not incorporate uncertainties in climate change projections or examines institutional factors such as governance arrangements and maintenance practices, which are critical for understanding and managing long-term vulnerabilities.

3.2 Approaches to Adapting to Climate Change

This section reviews some approaches to climate adaptation in infrastructure planning, focusing on dynamic frameworks, integration with related domains, and railway-specific practices.

The IPCC (2022; p. 2898) defines climate adaptation options or approaches as "the array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional, ecological, or behavioural." Such approaches are intended to reduce the negative impacts of climate change or take advantage of potential opportunities, by enhancing resilience and lowering vulnerability (Gregg et al., 2018). For simplicity, this thesis classifies approaches as either structural or non-structural. Structural ones include hard, physical measures such as seawalls or floodgates, typically designed to keep hazards at bay (Brink, 2018). Non-structural measures reduce risk without physical construction, and typically rely on aspects such as policies, knowledge, and behavioural change. In addition, this thesis uses the term *climate adaptation approaches*, rather than *solutions* or *strategies*, to encompass the full range of ways in which climate adaptation may occur, including formal, planned, systematic, and incremental or ad-hoc responses. The term *measures* is used when referring specifically to structural and non-structural interventions, as one category of climate adaptation approach.

Despite this broad range of climate adaptation approaches, most literature on railways focuses on the impacts of extreme weather or climate change on operations and infrastructure. Less attention is paid to how railways can adapt proactively and manage uncertainties associated with future climate conditions.

3.2.1 From Static to Dynamic Adaptation

Infrastructure planning has traditionally relied on a *predict-and-act* paradigm (Stanton & Roelich, 2021), which assumes a limited set of future scenarios and often lacks flexibility to respond to unexpected changes or deep uncertainties (Kwakkel, 2020; Wall et al., 2015). Such approaches can result in rigid systems and path dependencies that hinder adaptive or transformative responses (Siebenhüner, 2021). In the Swedish context, previous research has suggested a tendency to rely on static and conservative climate adaptation approaches due to uncertainties in climate change projections (Carstens et al., 2019; Göransson et al., 2023; Metzger et al., 2021).

In contrast, decision-making under deep uncertainty (DMDU) offers tools for navigating unpredictable futures where conventional planning falls short (Kwakkel et al., 2016). One such method is Dynamic Adaptive Pathways Planning (DAPP); this builds on earlier work known as Dynamic Adaptation Policy Pathways, and supports flexible, staged decision-making that can adjust over time as conditions evolve (Haasnoot et al., 2024; Haasnoot et al., 2013).

DAPP was originally developed for water management in the Netherlands, and has been expanded to other countries around the world. DAPP uses adaptation tipping points (the conditions under which an action no longer meets the objective(s) (Werners et al., 2021)) and different adaptation pathways in order to support decision-making and avoid maladaptation, and combines adaptive policymaking with adaptation tipping points and adaptation pathways (Walker et al., 2013). The steps of DAPP are highlighted in Figure 6.

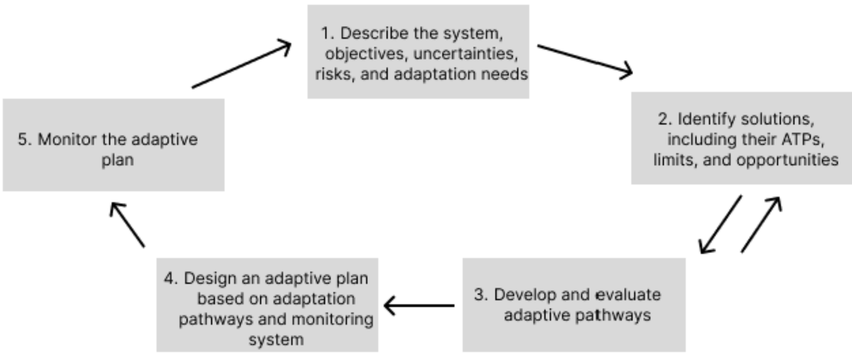

Figure 6. The five steps of the Dynamic Adaptive Pathways Planning (DAPP) approach, highlighting the stepwise approach of DAPP; arrows indicate the sequence of steps.
Adapted from Haasnoot et al. (2024) and adopted from Paper IV. ATP stands for Adaptation tipping point.

The process begins with identifying goals and uncertainties within the current situation that are relevant for decision-making. Next, solutions are identified, as are adaptation tipping points (ATPs), limits, and opportunities. Step 3 involves developing and evaluating adaptive pathways. In Step 4, an adaptive plan based on adaptation pathways is established and a monitoring system is developed. Finally, Step 5 involves monitoring the adaptive plan.

In this way, climate adaptation is increasingly understood as a dynamic process, where plans are monitored and adjusted over time in response to evolving uncertainties around climate change and socio-economic conditions. An example of an adaptation pathways map is presented in Figure 7.

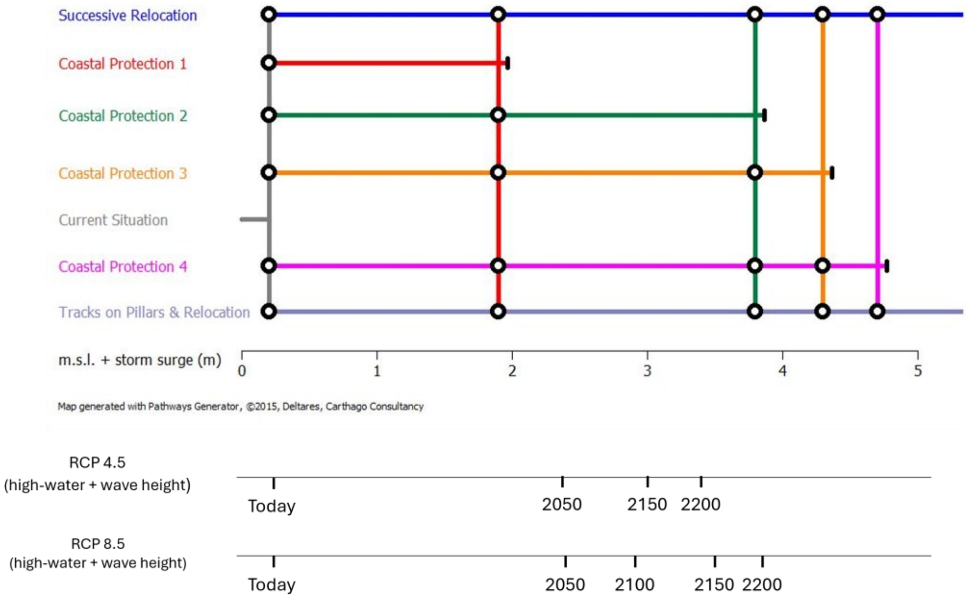

Figure 7. Example of adaptation pathways map under RCP 4.5 and 8.5 (adopted from Paper IV). Each action is delineated by a line or pathway. Solid black lines highlight adaptation tipping points , while black-and-white nodes indicate decision points where one action can transfer to another. The Representative Concentration Pathway (RCP) of 8.5 is a high-emissions scenario, while 4.5 is a moderate-emissions scenario.

Since the development of DAPP, it has been expanded and applied to various countries, such as the UK (Bloemen et al., 2018), as well as to sectors including urban planning, wastewater management, and coastal retreat strategies (Allison et al., 2024; Jeuken et al., 2015; Kool et al., 2020; Lawrence et al., 2025; Mendoza et al., 2018). Various studies have expanded on DAPP to develop other frameworks, including resilience pathways (Zorita et al., 2025), Collaborative Risk Informed

Decision Analysis (CRIDA; Mendoza et al., 2018), approaches that address multi-risk scenarios and compounding hazards (Kool et al., 2024; 2020; Schlumberger et al., 2022; 2024), and climate resilient development pathways that integrate sustainable development and climate mitigation (Langendijk et al., 2025). Carstens et al. (2019) introduced DAPP-light, which emphasises bottom-up vulnerability assessments and actor engagement to describe a situation, identify potential actions, and co-develop adaptation pathways (i.e., Steps 1–3 in Figure 6).

Studies that apply DAPP or other DMDU methods often focus on methodological development, and tend to emphasise structural climate adaptation approaches in their adaptation pathway maps. These studies also tend to rely on quantitative approaches for determining ATPs, although actor involvement remains an important component. Few studies explore the use of DAPP for transportation infrastructure, or examine how such methods might interact with climate adaptation in other sectors. In addition, governance aspects that shape climate adaptation decision-making and enable or hinder the use of DAPP as a climate adaptation option are less considered.

From an industry perspective, adaptation pathways have been acknowledged as potential climate adaptation approaches (Ferranti et al., 2021). For example, they are mentioned in Network Rail's adaptation strategy (Network Rail, 2021), and incorporated into a British Standard in the UK (BSI, 2021) and by the UN Economic Commission for Europe Inland Transport Committee (Hashmi et al., 2023a; 2023b).

3.2.2 Integration with Disaster Risk Reduction and Other Framings

One approach to climate adaptation is to draw inspiration from, and potentially integrate, other related policy streams, such as disaster risk reduction.

Climate adaptation and disaster risk reduction have generally been developed in parallel with each other, but are on separate tracks in terms of policy and funding opportunities (Becker et al., 2013; Lei & Wang, 2014; Schipper, 2009). However, there is growing interest in strengthening climate adaptation through disaster risk reduction in both the disaster risk and climate change research fields (Lei & Wang, 2014).

Schipper (2009; p. 19) defines climate adaptation as:

> *the process of adjusting to a changing climate, through explicit and planned interventions, or spontaneously as a consequence of inherent flexibility. Because climate change will affect every aspect of society, environment and economy, adaptation includes activities that are both directly and indirectly related to the impacts of climate change.*

and disaster risk reduction as:

> *the suite of interventions, approaches and policy frameworks needed to avoid or minimise the impacts of natural hazards on vulnerable societies and the environment, focusing on reducing vulnerability to hazards. Disaster risk reduction includes the concept of disaster risk accumulation, i.e., it reflects that each disaster event reduces the ability to cope with the next event.*

Over time, disaster risk reduction has moved away from how to respond to the aftermath of a disaster, and towards more proactive activities, i.e. how to prepare for a disaster and manage the associated risks (Becker et al., 2013). The 2004 Indian Ocean Tsunami was a keystone event that led to the signing of the Hyogo Framework for Action at the World Conference on Disaster Reduction, held in Kobe, Japan (Becker et al., 2013). This was the predecessor to the current Sendai Framework for Disaster Risk Reduction 2015–2030, which was signed in 2015 by UN Member States at the Third UN World Conference on Disaster Risk Reduction in Sendai City, Japan.

Climate change is projected to increase the frequency and severity of extreme weather events such as flooding, wildfires, and storms (including hurricanes, typhoons, and cyclones), thereby heightening both disaster risk and vulnerability to climate impacts. As a result, climate adaptation is becoming increasingly central to sustainable disaster risk reduction, with a growing call for a framework that unites the two (Lei & Wang, 2014; Schipper, 2009). While disaster risk reduction and climate adaptation are distinct, they share a common focus on reducing vulnerability and enhancing long-term resilience to climate-related hazards and disasters (Schipper, 2009). Disaster risk reduction typically addresses short-term, event-specific risks, whereas climate adaptation tends to focus on long-term systemic changes (Lei and Wang, 2014). Nonetheless, integrating both approaches offers potential to reduce the risks associated with climate change more effectively.

However, as highlighted by Dias et al. (2021) and Majlingova & Kádár (2025), integration remains challenging in practice. Dias et al. (2021) identify fragmented governance, uncoordinated actor activities, and lack of funding as persistent barriers to integrating disaster risk reduction and climate adaptation. Majlingova and Kádár (2025) argue that while international frameworks like the Sendai Framework and Paris Agreement promote integration, implementation is often hindered by sectoral silos, inconsistent data, and limited financing.

Research by Barquet et al. (2024a; 2024b), Eglund and Barquet (2023), and Rhinard et al. (2023) has investigated how climate adaptation is framed in Sweden and other European countries. They reveal that climate adaptation is increasingly framed through a *riskification* lens, mostly viewing climate adaptation from a technocratic, risk governance perspective. Collectively, these studies also highlight the fragmentation of governance as a barrier to both climate adaptation and the integration of climate adaptation and other framings, such as risk management or disaster risk reduction.

Overall, these studies highlight the importance of integrating disaster risk reduction and climate adaptation in order to streamline action across governance levels and address competing funding priorities. However, integration efforts remain hindered by sectoral silos and governance fragmentation. In addition, climate adaptation research is more prevalent in European and North American contexts, whereas research into disaster risk reduction is more common in Asian and African contexts. This distinction may partly be due to differences in hazard exposure, policy patterns, and governance structures.

3.2.3 Railway-Specific Adaptation Practices and Barriers to Adaptation

Some studies focus specifically on climate adaptation planning in the railway sector. For example, Thaduri et al. (2021) concluded that Sweden will experience a wetter and warmer climate as a result of climate change. They argue that, to plan for these uncertainties, climate adaptation awareness should increase, and that emergency planning, vulnerability assessments, and risk assessments are important prerequisites for climate adaptation of railway systems. Similarly, Garmabaki et al. (2021) studied climate adaptation of railway maintenance in Sweden using qualitative methods. Their interview results indicate that the level of climate adaptation needs to be increased, and that better coordination between organisations regarding climate adaptation approaches is necessary. The predominant risks identified were signal failures, track buckling, insufficient drainage, and bridge scour.

Other studies have examined climate adaptation approaches in different geographical and organisational contexts. Doll et al. (2014) considered climate adaptation approaches in relation to flooding of alpine railways, concluding that preventative maintenance is a key part of climate adaptation. Kellermann et al. (2016b) emphasise the importance of integrating both structural and non-structural measures into climate adaptation planning. Dépoues (2017) explored how the French railway company SNCF integrates climate adaptation into its decision-making. The study found that a lack of climate change knowledge and institutional frameworks hinder climate adaptation efforts, and recommended a stronger emphasis on bottom-up approaches involving all relevant actors.

Several frameworks have been developed to support climate adaptation planning and implementation. Quinn et al. (2018) presented a framework for organisations to adapt transport infrastructure, including railways, to climate change. The framework aligns with existing ISO standards for asset management and climate adaptation policy cycles, and aims to bridge the gap between climate adaptation strategies and implementation plans. Pritchard et al. (2025) highlighted how Transport Infrastructure Ireland has developed a six-stage climate adaptation strategy to assess and manage climate risks across its transport assets, including rail. This approach combines high-level screening, detailed risk assessments, and adaptation planning, supported by technical standards, climate projections, and actor collaboration to build long-term resilience.

Mullard and Clément (2025) discuss the progress of the EU's climate adaptation strategy (2021) as applied to the railway sector through the Rail4EARTH project. This project focuses on improving the resilience of European railway assets to climate change. It centres on two pillars of the EU climate adaptation strategy: *Smarter adaptation*, which involves identifying climate-sensitive assets and developing standards and tools for resilience, and *Faster adaptation*, which benchmarks technical solutions from regions already experiencing future European climate conditions. The study highlights the importance of correlating climate data with maintenance and operational incidents, and the need for tailored climate data and expert input to guide asset design.

Despite these efforts, previous research has also pointed out persistent barriers to climate adaptation approaches and implementation. These include a lack of clearly defined responsibilities (Persson et al., 2021), insufficient funding (Malik & Ford, 2024), and competing priorities (McClure & Baker, 2018). Eghdami et al. (2023) emphasise the need for stronger coordination among actors. In a Swedish context, Knaggård et al. (2020), Rylenius and Hamza (2023), and Storbjörk (2007) all highlight the challenges posed by Sweden's decentralised and fragmented climate adaptation governance, which results in unclear responsibilities, limited knowledge dissemination, and insufficient financial support. Such studies have examined climate adaptation from a local or municipal perspective. However, barriers exist across multiple levels of governance, and the adapting of railway infrastructure in particular is underexplored.

Beyond technical and governance barriers, Puig et al. (2025) argue that climate adaptation effectiveness is often limited by an overreliance on economic metrics and market-based mechanisms, which often overlook non-market values such as culture and wellbeing. To address these limitations, four strategic shifts are proposed: (i) accommodating diverse ethical positions through transparent, inclusive decision-making; (ii) aligning climate adaptation with social norms via community-led initiatives; (iii) overcoming path dependence by revising governance arrangements and adopting innovative approaches; and (iv) enfranchising marginalised groups through knowledge co-production and participatory processes. These changes reflect a broader call for devolved decision-making, pluralised information, and adaptive governance, in order to enhance resilience and equity in climate adaptation.

Overall, these studies highlight that climate adaptation research for railway infrastructure has progressed, but still lags behind other sectors. Within the railway sector, research predominantly focuses on the impacts of weather and climate change on operations and infrastructure, with fewer studies analysing potential climate adaptation approaches and the barriers to their implementation. Furthermore, a majority of research is situated in a European context, leaving other regions of the world underexplored.

3.3 Research Gap

The need for climate adaptation has gained increasing attention in recent years. However, the impacts of adverse weather conditions and climate adaptation on transportation have generally received less attention compared to other sectors (Attoh et al., 2022; Koetse & Rietveld, 2009).

As highlighted in *Sections 3.1* and *3.2*, there exist two main bodies of literature on climate adaptation of railways: i) studies that quantify the impacts of weather and climate change on railway operations and infrastructure, and ii) research that explores climate adaptation approaches and decision-making processes for climate adaptation in the railway sector.

Despite growing awareness, there is limited integration of climate adaptation into railway planning and asset management. Existing studies often focus on operational disruptions (e.g., Brazil et al., 2017; Zakeri & Olsson, 2018) or specific hazards, such as flooding and heat (e.g., Bubeck et al. 2019; Greenham et al., 2023); few address the full spectrum of weather-related vulnerabilities or the governance barriers to implementing climate adaptation approaches.

Within the first body of literature outlined above, many studies have focused on quantifying the impact of weather on railway operations, particularly in relation to train delays and network disruptions (Brazil et al., 2017; Fabella & Szymczak, 2021; Zakeri & Olsson, 2018). However, relatively few studies have examined multiple weather variables or a broad spectrum of types of asset fault (Fisher, 2021). Among those that do investigate infrastructure impacts, the focus is often limited to high temperatures and flooding (Palin et al., 2021), with limited application of fault-rate thresholds to inform asset management (Fisher, 2021; Greenham, 2023). Additionally, many of these studies concentrate on specific regions and short-term impacts (Wang et al., 2020), leaving a gap in understanding in terms of long-term and system-wide vulnerabilities.

The second body of literature addresses climate adaptation approaches and decision-making processes. For instance, the Rail-Adapt framework developed by Quinn et al. (2018) aims to integrate climate adaptation strategy with implementation. Dépoues (2017) and Rotter et al. (2016) have both examined barriers to climate adaptation in the sector. Additionally, some studies have addressed climate adaptation approaches and how to prioritise them (Andersson-Sköld et al., 2021; Blackwood et al., 2022; Kellermann et al., 2016a). However, this body of literature remains comparatively underdeveloped. In addition, there is a focus primarily on technical solutions for climate adaptation, and a lack of consideration of the interactions between values, knowledge, cultures, and institutions (O'Brien & Selboe, 2015; Wise et al., 2014).

Taken together, these gaps point to a lack of systematic assessment of climate risks and corresponding climate adaptation approaches for railway infrastructure. This thesis aims to bridge these two streams of literature, by assessing weather impacts on railway infrastructure and operations, identifying barriers to climate adaptation, and exploring various climate adaptation approaches that can support long-term resilience. Although this thesis does not explicitly examine the roles of values and cultures in climate adaptation decision-making, it does address broader climate adaptation approaches beyond traditional technical solutions, and examines the governance barriers that influence their implementation.

4 The Swedish Context

The Swedish context is the main case presented in this thesis. This section discusses how the climate is changing in Sweden, and how climate adaptation is governed.

4.1 Climate Change in Sweden

Sweden is a Nordic country that is located on the Scandinavian Peninsula. According to Beck et al. (2018) there are four Köppen-Geiger climate zones in Sweden: Cfb, Dfb, Dfc, and ET. The Köppen-Geiger system classifies climate into five classes with 30 sub-types based on seasonality of monthly air temperature and precipitation (Beck et al., 2018). Cfb is a temperate climate, Dfb is a humid continental climate, Dfc is a sub-Arctic climate, and ET a polar, tundra climate (Figure 8).

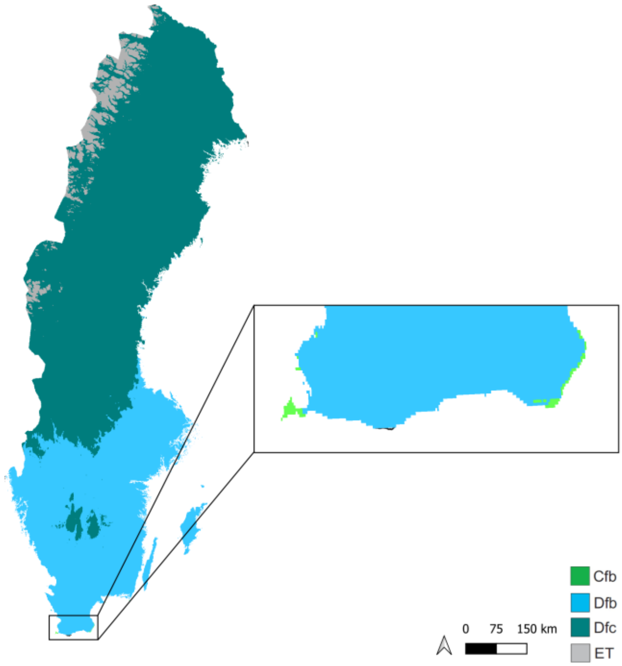

Figure 8. Swedish Köppen-Geiger climate zones.
Data from Beck et al. (2018) and the University of Texas. Figure adapted from Paper II. The inset map to the right shows the parts of Sweden that are categorised as climate zone Cfb.

The Swedish Meteorological and Hydrological Institute (SMHI) is responsible for forecasting and understanding meteorology, hydrology, climatology, and oceanography in Sweden. This includes climate change projections for the country. Sjökvist et al. (2025) produced a report on how the climate is changing in Sweden, which was intended to be used in the National Expert Council for Climate Adaptation's national climate risk and vulnerability analysis in preparation by the Council. The report utilises two Representative Concentration Pathways (RCPs), which are projections of future greenhouse gas emissions used to model climate change. RCP 8.5 and 4.5 are typically used by many Swedish government agencies and authorities for their climate projections and climate risk and vulnerability assessments, and are defined as:

- RCP 8.5: a future with a continued sharp increase in greenhouse gas emissions.
- RCP 4.5: a future with continued increases in greenhouse gas emissions until the middle of the century, after which they decrease.

Most Swedish municipalities use RCP 8.5 for their climate adaptation planning; the Swedish Transport Administration uses RCP 8.5 for sea-level rise and RCP 4.5 for all other climate risks in its climate adaptation planning.

Figure 9 summarises climate change projections on a basic level, based on the work of Sjökvist et al. (2025).

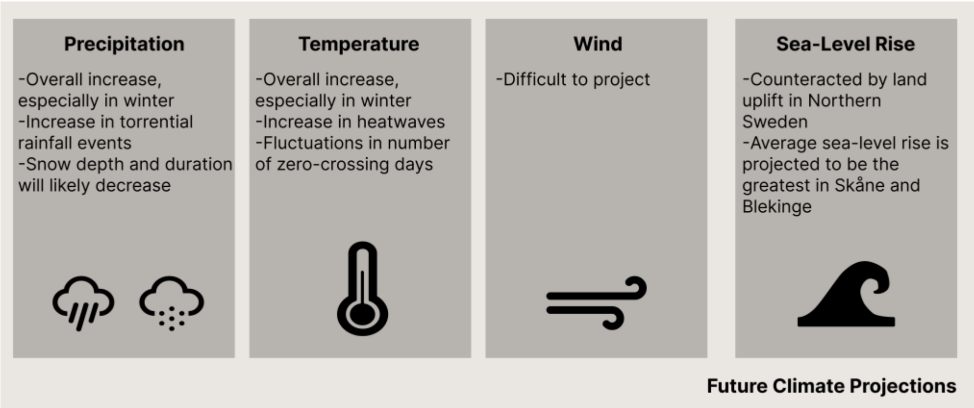

Figure 9. Climate change projections for Sweden.
Based on Sjökvist et al. (2025).

Annual precipitation in Sweden has increased in recent decades, with the highest levels observed along the west coast and northern mountain ranges. The most significant future changes are expected in winter, particularly in northern Sweden. The number of days with extreme precipitation (≥20 mm) and cloudburst events (≥50 mm rainfall in one hour, or ≥1 mm in one minute) are projected to rise. Snow depth and duration are expected to decrease significantly with climate change. Under RCP 4.5, snow will remain in most areas but be several decimetres thinner, while under RCP 8.5 snow may become rare in some places.

The average temperature in Sweden has increased by 1.9°C since the mid-nineteenth century, with the greatest warming in the north. Summer and autumn are expected to warm more slowly, but still significantly, especially in northern and coastal regions.

There is no clear historical trend in wind patterns. Some factors, such as warmer seas and increased atmospheric moisture, suggest more storms; other factors, such as reduced temperature contrasts between air masses, may counteract this. At the same time, warming seas may reduce the formation of low-pressure systems in the northern hemisphere.

Sea levels are rising due to increased sea temperatures. In northern Sweden, this rise is partially offset by land uplift. The greatest sea-level rise is expected in Skåne and Blekinge, in southern Sweden, where land uplift is minimal.

4.2 Climate Adaptation Governance in Sweden

Sweden is a member state of the European Union. Under the European Climate Law (European Parliament and Council of the European Union, 2021) and Article 7 of the Paris Agreement (UN, 2015), all member states must work towards reducing the risks of climate change. In addition, all member states must biannually report their strategies, plans, and climate adaptation implementations to the European Union. Other directives, such as the Flood Directive (European Commission, 2007), include elements of climate adaptation. Sweden has also signed onto the United Nations Agenda 2030 (UN, 2015) and the Sendai Framework for Disaster Risk Reduction (UN, n.d.), which discuss the need to reduce climate-related risks and disasters such as flooding.

Sweden introduced its first National Climate Change Adaptation Strategy in 2018 (Swedish Government, 2024), and this is updated every five years. Under the strategy, a new coordinating role was given to the National Board of Housing, Building and Planning for climate adaptation in relation to new and existing buildings, the built environment, and spatial planning. In addition, an expert council on climate adaptation was formed, consisting of eight researchers; this is tasked with informing the national government on climate adaptation work to help shape the upcoming national climate adaptation strategy. In 2019, Ordinance 2018:1428 (2018) was implemented, obliging 32 government agencies and 21 county administrative boards to "mandate, initiate, support, and evaluate climate adaptation work." Under this Ordinance, the 32 agencies and 21 county administrative boards must annually report their activities to the Ministry under which the Agency falls and to the SMHI, with the latter in turn submitting a summary analysis to the Government every April. In addition, all agencies and county administrative boards must produce a climate risk and vulnerability analysis every five years.

Figure 10 presents the overall governance structure of Sweden in terms of climate adaptation. It shows that the responsibility for implementation of climate adaptation is bottom-up, with the greatest responsibility put on the individual property owner; directives for climate adaptation, including Ordinance 2018:1428, are implemented top-down by the Swedish state.

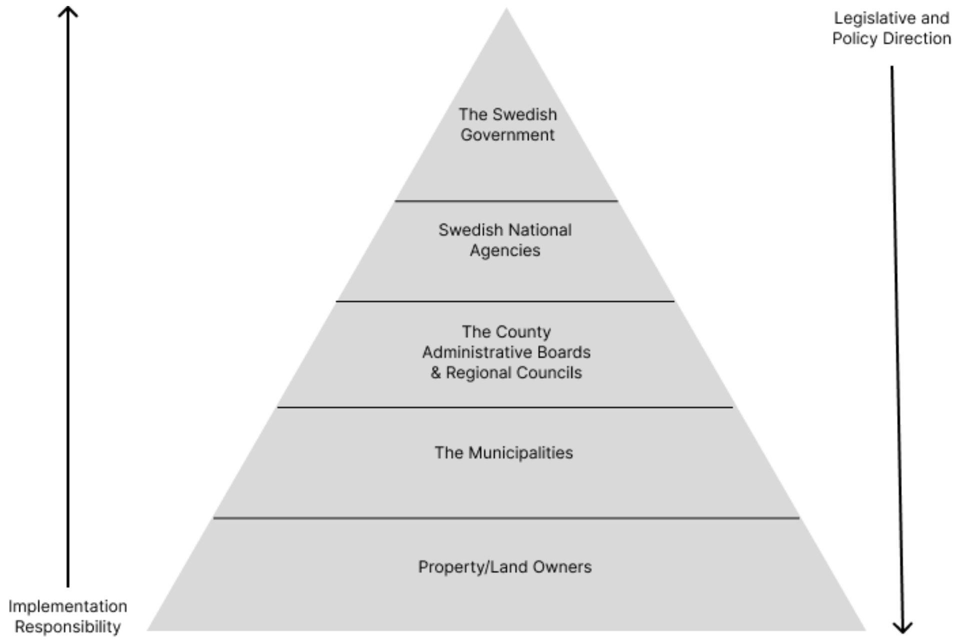

Figure 10. The responsibility for adaptation under Ordinance 2018:1428: the directive is top-down (from the state) but the implementation is bottom-up, with the greatest responsibility put on the property owner.
Figure adopted from Paper V.

Swedish is divided into 21 county administrative boards, 21 regions, and 290 municipalities (Figure 11). The county administrative boards are appointed by the government and act as an arm of the state, with the responsibility to ensure that policies on the national level are implemented in their jurisdictions. In contrast, regions are councils which are democratically elected (The Swedish Government, 2020). The main responsibility for protecting property or assets and adapting to climate change lies primarily with the owners of property; however, there is no legal obligation for them to adapt. This also means that the responsibility for financing climate adaptation efforts falls almost entirely on property owners (Rylenius & Hamza, 2024).

Figure 11. 290 Muncipialites (left) and 21 county administrative boards (right).
The regions and county administrative boards share the same geographical borders (data from Statistics Sweden).

The municipalities are their own authorities, and are responsible for numerous tasks – both climate-related and not – including issuing building permits to property owners and working with environmental protection and nature conservation within their jurisdiction. In addition, municipalities report climate-related risks to county administrative boards, and include these in their municipal plans. However, they have no obligation to report their climate adaptation work to county administrative boards. Municipalities are also responsible for adapting their own property, for example municipal roads and schools, to climate change, and for developing their own climate adaptation strategies. Since 2018, municipalities have been expected to assess risks to the built environment linked to climate change in their comprehensive plans. Under the Building and Planning Act (2010:900), municipalities are also required to consider climate change impacts when building new structures. Finally, municipalities have a planning monopoly in Sweden, meaning that only the municipality can regulate construction and land-use planning within their jurisdiction, leading to a decentralised approach to land-use regulation.

The county administrative boards are responsible for initiating and supporting climate adaptation work in the municipalities within their region. They must approve the comprehensive and detailed plans put forward by the municipalities, in accordance with the Building and Planning Act. In addition, the county administrative boards must also produce their own climate risk and vulnerability analyses under Ordinance 2018:1428. All agencies, municipalities, and county administrative boards must also send their risk analyses to the Swedish Civil Defence and Resilience Agency[3], which is responsible for coordinating the Sendai Framework for Disaster Risk Reduction, biannually.

The regions in Sweden are responsible for regional development, mainly in terms of healthcare, dental care, public transport (the Public Transport Authorities), and regional development. They do not have any obligation to adapt to climate change; however, they play a role in crisis management and follow Ordinance 2017:583 (2017), which states that regional growth should be undertaken in an economically, socially, and environmentally sustainable way, which can include climate-related risks. This makes their role in climate adaptation vague and unclear.

In general, climate adaptation in Sweden is a fast-developing field and political arena. Many government agencies were updating their climate adaptation strategies and action plans and conducting climate risk and vulnerability assessments during the period in which this thesis was being written. In addition, in May 2025, an investigation was conducted by the Swedish Government, which resulted in the proposing of several changes to different pieces of legislation to enable better conditions for adaptation (SOU, 2025). These changes include a proposed new financing model to ensure fairer cost sharing of climate adaptation approaches, and amendments to existing laws such as the Planning and Building Act, the Environmental Code, and the Road and Railway Acts to facilitate climate adaptation. The resulting report also recommends that the state assume responsibility for permanent coastal flood protection in areas of national interest.

[3]At the time this research was conducted, the name of the agency was the Swedish Civil Contingencies Agency (MSB); however, as of January 2026, the organisation is called Swedish Civil Defence and Resilience Agency (*Myndigheten för civilt försvar* in Swedish).

5 Research Design

This thesis employs a mixed-method, interdisciplinary approach and aims to advance understanding of climate adaptation processes, using the railway sector as a lens and Sweden as the primary case. Japan is also used as a case in one of the included papers, but to a lesser extent than – and in relation to – the Swedish case. More information on the cases used is presented in *Section 6.1*.

5.1 Philosophical Underpinnings

The process of climate adaptation is inherently complex for several reasons.[4] First, it is a multidimensional process that varies in terms of intent, spatial and temporal scales, and sectors, which creates challenges as regards developing shared understandings of how to adapt (Holman et al., 2019). Second, uncertainties in climate projections and as regards future socio-political developments make it difficult to determine the appropriate level and timing of climate adaptation (Adger et al., 2003; Sepúlveda-Carmona, 2022; Simonovic, 2017). Third, climate adaptation requires coordination among multiple actors operating at different governance levels (Adger et al., 2005; Amundsen et al., 2010; Muccione, 2024; Sepúlveda-Carmona, 2022; Simonovic, 2017), often with conflicting values and objectives that lead to trade-offs (Simonovic, 2017). Finally, climate adaptation is not a one-off intervention but a continuous process that must evolve with changing conditions (Sepúlveda-Carmona, 2022), while also accounting for interdependencies between sectors and the potential for cascading effects (Muccione, 2024).

These characteristics highlight that climate adaptation cannot be understood through a single, universal perspective. Therefore, this thesis is grounded in situated knowledges (Haraway, 1988), aligning with interpretivist epistemologies. Situated knowledges emphasise that all knowledge is partially produced and has specific social, cultural, and material contexts. This perspective is particularly relevant for climate adaptation research, where responses to climate risks are shaped not only by biophysical processes but also by governance structures and lived experiences.

[4] It should be noted that the list of reasons given for this is not exhaustive.

Building on this foundation, I adopt a plural-epistemologies approach (Nightingale, 2003; Nightingale, 2016), which recognises the legitimacy of situated knowledges and multiple ways of knowing, and the value of integrating diverse perspectives. In climate adaptation research, Nightingale (2016) identifies two dominant epistemological streams: one focused on biophysical impacts, and the other on socio-political processes. Rather than privileging one over the other, methodological triangulation can generate richer understandings by drawing insights from different analytical entry points. Plural epistemologies also align with an inductive approach, which particularly underpins the qualitative data analyses in this thesis (*Sections 6* and *7*). Insights were developed mainly inductively from empirical observations rather than pre-existing theoretical frameworks. This approach enables a more nuanced understanding of climate adaptation processes by prioritising a listening stance in data analysis, and incorporating multiple perspectives and ways of knowing.

Therefore, plural epistemologies and triangulation informed my decision to employ a mixed-methods research design, combining quantitative analyses of weather impacts with qualitative inquiry into climate adaptation processes. This integration enabled a more holistic understanding of both the physical impacts of railway infrastructure and the socio-political dynamics that shape climate adaptation decisions.

Knowledge is shaped by the lived experiences of individuals, and the qualitative components of this research are grounded in that paradigm. At the same time, I recognise that this contrasts with the more positivist assumptions that often underpin quantitative research, and the pragmatic traditions of mixed-methods approaches. However, I argue that quantitative data are not treated as purely objective, but is interpreted within the social, institutional, and political context in which it was generated. For example, data on infrastructure faults might be analysed not just for frequency but also for how reporting practices or organisational priorities shape what is recorded. Given the inherent uncertainty in climate change projections and the limitations of quantitative methods for fully capturing socio-political dimensions, I argue that a mixed-methods approach is necessary.

Ontologically, I conceptualise climate adaptation in relation to the railway sector in *Section 2*. I understand climate change as an observable phenomenon, and see its biophysical effects as evident. However, the vulnerabilities, risks, and responses to these changes are shaped by governance dynamics (Adger, 2006). As Nightingale (2016) illustrates, rain is not inherently a hazard – it becomes one when it interacts with infrastructure, such as when it causes flooding on railway tracks. Moreover, the actions taken to reduce such risks are influenced by individuals' experiences, values, and interpretations of risk (Eiser et al., 2012). For example, in Japan, climate adaptation is predominantly framed through the lens of disaster risk management (Paper VI).

5.2 Positionality

I recognise that personal, interpersonal, and social contexts have influenced my methodological choices and the interpretation of the data (Plano Clark & Ivankova, 2016). This aligns with Haraway's (1988) notion of situated knowledge, which emphasises that all knowledge is produced from specific positions and partial perspectives. First, I believe that climate change is an observable phenomenon shaped by biophysical factors and social dynamics. I am personally committed to advancing climate adaptation to support a resilient society that is capable of coexisting with natural hazards. I therefore acknowledge that scientific bias cannot be fully removed from this work.

Second, my academic background as a geographer has informed my preference for mixed-methods approaches, particularly in addressing complex problems in interdisciplinary contexts. This orientation guided how I designed the studies, selected methods, and interpreted findings.

Finally, I recognise that this thesis has been shaped by a range of relational and institutional influences, including the participants in my studies, my co-authors, the academic traditions of my department, and the reviewers of the papers included in this thesis. Conducting this research in Sweden also influenced the availability of data and the selection of cases.

5.3 Research Questions and Connection to Papers

As mentioned in *Section 1.2*, the three research questions of this thesis are:

- RQ 1: How does weather impact railway operations and infrastructure in Sweden?
- RQ 2: What are the challenges involved in adapting the railway sector to climate change within current governance structures in Sweden?
- RQ 3: What lessons can be drawn from different climate adaptation approaches to inform climate resilience in Swedish railways?

In addition, the six research papers included in this thesis are:

- Paper I. Weather and Train Disruptions in Sweden, 2011–2019
- Paper II. The Impacts of Weather on Railway Infrastructure in Sweden
- Paper III. The Effects of Flooding on Railway Infrastructure: A Literature Review

- Paper IV. Barriers and Opportunities for Dynamic Adaptation of Coastal Railways
- Paper V. Barriers to Climate Change Adaptation in Swedish Railway Infrastructure
- Paper VI. On Track to Climate Resilience? Insights from Japanese Railways

Section 8 gives a more detailed summary of each of the included papers.

This thesis was initially positioned within the broader field of climate adaptation in the railway sector, with a primary focus on quantifying the impacts of weather on railway punctuality (Paper I). As the analysis developed, it became evident that infrastructure faults contribute to delays, highlighting the need to examine how weather impacts infrastructure performance. This recognition motivated the research presented in Paper II. The findings and discussions with the Swedish Transport Administration and researchers working on climate adaptation presented in that paper led to the notion that climate adaptation requires more than understanding biophysical impacts and must extend to include insights into available climate adaptation approaches and the barriers that hinder their implementation. These considerations informed the development of Papers III–VI. Collectively, these developments shaped the approach of the thesis into a mixed-methods, interdisciplinary one, with a focus on climate adaptation in railway systems.

Table 2 maps the contributions of each paper to the research questions.

Table 2. Contributions of each paper to the research questions.

	Paper Number					
Research Question	**I**	**II**	**III**	**IV**	**V**	**VI**
RQ 1	X	X	X			
RQ 2				X	X	
RQ 3			X	X		X

Research Question 1 examines how weather impacts railway operations and infrastructure in Sweden. Papers I and II analyse the Swedish context, using empirical data to quantify how different weather conditions impact operations and infrastructure. Together, these papers establish a baseline for understanding the current impacts of today's climate conditions. This supports informed decision-making regarding climate adaptation, and helps to identify where targeted climate adaptation approaches may be needed. Additionally, Paper I informs operational planning, and Paper II informs asset management. While both papers identify weather-related impacts, Paper I focuses on operations (delays and cancellations), whereas Paper II examines infrastructure and fault thresholds. This distinction is important because operational disruptions may occur even without an asset fault –

and, conversely, infrastructural faults may not immediately lead to disruptions. Paper III systematically reviews flooding impacts on railway infrastructure globally, to provide a focused entry point for understanding climate risks before broadening to other weather hazards.

Research Question 2 investigates the governance-related challenges of adapting the railway sector to both current and future climate risks. Paper IV applies the DAPP-light approach to the case of a coastal railway in Trelleborg, Sweden, revealing the complexities of coordinating between municipal and national actors. Paper V identifies key barriers to climate adaptation in Sweden. These papers together highlight how governance structures shape capacity to adapt, and show where changes in governance practices or improved coordination may be needed.

Finally, *Research Question 3* synthesises lessons from various climate adaptation approaches so that these can be applied to Swedish railways. Paper IV explores the opportunities and barriers relating to applying DAPP-light in a Swedish municipal context. Paper VI presents a range of climate adaptation approaches used in Japanese railways, offering an international perspective on climate adaptation approaches and governance. Paper III contributes by discussing some of the approaches to managing flood risks in railway systems discussed in previous research. This question takes a broader view than *Research Questions 1 and 2*, synthesising insights across contexts to identify lessons for strengthening climate resilience in the Swedish railway sector.

The three research questions were inspired by climate adaptation policy cycles, and by the idea that enhancing railway resilience should be approached as an iterative process rather than a static one. As climatic conditions shift and infrastructure continues to grow, existing plans must be flexible and open to revision (Greenham et al., 2022). Policy cycles provide a systematic, structured framework that ensures that all aspects of policy development and implementation are considered (Hansson et al., 2015). The iterative nature of these cycles allows for continuous adjustments and improvements, making it possible to respond effectively to new challenges and changing conditions (Rangwala, 2024).

Although there are many versions of policy cycles and climate adaptation frameworks (see e.g., Lim et al. (2005); OECD (2024)), and one that is more focused on railway climate adaptation (RailAdapt; see Quinn et al., 2018), most follow a sequence of: i) risk assessment; ii) mapping of climate adaptation approaches; iii) implementation; and iv) monitoring and evaluation. Monitoring and evaluation are outside the scope of this thesis because monitoring programmes can take decades to develop and follow up on (Haasnoot et al., 2018). Hence, rather than focusing on a single stage of the climate adaptation policy cycle, this thesis adopts a holistic perspective, examining how different elements of the policy process interact to shape climate adaptation in the railway sector.

5.4 Mixed Methods

The use of a mixed-methods approach can provide a deeper understanding of research questions than relying solely on either quantitative or qualitative methods (Creswell & Creswell, 2023; Plano Clark & Ivankova, 2016). There are multiple rationales for employing mixed methods (see e.g., Plano Clark & Ivankova, 2016), and this thesis adopts a complementary rationale. In this context, mixed methods were used to generate more comprehensive insights by combining quantitative and qualitative approaches, allowing for complementary perspectives on different facets of the same phenomenon (Greene et al., 1989; Plano Clark & Ivankova, 2016). For example, the quantitative analyses in Papers I and II provide empirical evidence regarding the impacts of weather on railway operations and infrastructure, while the qualitative studies in Papers III–VI offer insights into decision-making processes and potential climate adaptation approaches. This thesis follows a concurrent mixed-methods design, in which quantitative and qualitative methods were employed either simultaneously or independently, with the aim of merging results to produce more robust and validated conclusions (Plano Clark & Ivankova, 2016). Table 3 provides a summary of the methodological approaches taken in each paper.

Table 3. Methodological approaches utilised in each paper.

	Paper number					
Methodological approach	I	II	III	IV	V	VI
Quantitative	X	X				
Qualitative			X	X	X	X

5.5 Interdisciplinarity

Interdisciplinary approaches are important in climate adaptation research due to the complex and multifaceted nature of climate change itself (Krellenberg & Katrin, 2014). This aligns with the concept of plural epistemologies, which emphasises the need to draw on diverse forms of knowledge to fully understand and address such challenges (Nightingale, 2016). Climate adaptation cannot be effectively addressed from within a single discipline; instead, it requires an interdisciplinary approach that draws on diverse forms of knowledge and expertise (Thorén et al., 2021).

This thesis crosses traditional disciplinary boundaries and integrates insights from transportation engineering, public transport, climate adaptation, and sustainability science. Parts of this research have been presented at conferences across these fields. Moreover, the research has been conducted in collaboration with co-authors from engineering, natural sciences, and social sciences, each contributing distinct ontological and epistemological perspectives. This integration of disciplinary viewpoints has enabled a deeper engagement with the complexity of climate adaptation, and supported the use of mixed methods to explore both biophysical impacts and governance processes.

This work draws on a diverse range of data sources and employs various methods, each with their own limitations. I have highlighted the importance of using plural epistemologies to address climate adaptation. However, it is important to acknowledge that there are still limitations and considerations when employing mixed-method and interdisciplinary approaches. Challenges arise when combining methods that reflect fundamentally different worldviews (Nightingale, 2016). Each discipline has its own methodological traditions, as well as distinct ontological and epistemological foundations, which require consideration when integrating approaches (Nagatsu et al., 2020; Thorén et al., 2021). Furthermore, conceptual understandings of key terms such as *resilience* are often contested between the natural and social sciences in sustainability research (Nagatsu et al., 2020). Conducting interdisciplinary research frequently involves mixed-methods designs, which can be resource intensive. Such research is often time-consuming, resource-demanding, and difficult as regards data integration (Pranesti & Romadhon, 2025). Finally, interdisciplinary and mixed-methods approaches may be criticised as being "jack of all trades, master of none."

As a geographer, I am trained in interdisciplinary approaches and feel that I was well equipped to integrate different methods and successfully communicate and work with researchers across different disciplines. Interactions with researchers from a range of disciplines, research visits to the University of Birmingham and the University of Tokyo, and collaborations with co-authors from diverse institutional and disciplinary backgrounds were important enablers of my interdisciplinary research practice.

6 Data Collection and Geographical Scope

An overview of the various datasets used in the six papers is presented in Table 4. These datasets include weather data, operations data, infrastructure-fault data, and Köppen-Geiger climate-zone data used for quantitative analysis. Regarding qualitative data, workshop transcriptions and notes, interviews, and reviewed literature were utilised.

Table 4. Data types.
Overview of the different types of data used in the six papers.

Dataset	Paper numbers	Origin	Quantitative/qualitative
Weather data	I & II	SMHI	Quantitative
Operations data	I	Swedish Transport Administration	Quantitative
Infrastructure-fault data	II	Swedish Transport Administration	Quantitative
Köppen-Geiger climate-zone data	II	Beck et al. (2018)	Quantitative
Data from workshop transcriptions and notes	IV	Actor-Generated/ fieldwork	Qualitative
Interview data	V & VI	Fieldwork	Qualitative
Data from reviewed literature	III & IV	Scopus/expert generated/websites	Qualitative

A number of different geographical scopes, scales, and cases were utilised in this thesis. A description of the scopes and cases selected for data collection is presented in *Section 6.1*.

6.1 Geographical Scope and Cases for Data Collection

Sweden serves as the primary geographical focus of the thesis, providing the context for most of the empirical work. However, broader perspectives are also incorporated: Paper III adopts a global lens, while Paper VI draws on a Japanese case, with both offering comparative insights that are subsequently related back to the Swedish context. These varied geographical perspectives enrich the analysis and help to highlight both context-specific and potentially transferable lessons for climate adaptation in railway systems.

This approach aligns with Flyvbjerg's (2006) argument that context-specific knowledge is important for developing expertise and understanding complex issues such as climate adaptation within the railway sector. In climate adaptation planning, context matters – climate adaptation approaches developed for Japan, for example, cannot be directly applied in Sweden without first understanding the Swedish governance, climatic, and infrastructural context. In addition, drawing upon Lund's (2014) analytical matrix, this thesis moves between more specific and concrete cases, for instance local climate adaptation in Trelleborg (Paper IV), and more general insights, such as the barriers to climate adaptation in Sweden (Paper VI). In doing so, knowledge with a variety of scopes and scales is generated, which can help to understand climate adaptation in a greater sense.

6.1.1 The Global Perspective in Paper III

A global perspective was adopted in the systematic literature review in Paper III, although majority of the studies included in the review were from a European perspective with a strong emphasis on the United Kingdom. Additionally, the scale ranged from nationwide, urban, to even asset level. This allowed for a wide array of studies that lead to an understanding of research conducted on a global level.

Flooding was chosen to allow for a more in-depth and systematic synthesis of existing knowledge on climate adaptation approaches, and infrastructure vulnerabilities related to flooding. Flooding is also one of the most well-documented climate risks for railway infrastructure (Ochsner et al., 2024). This provided a focused starting point for my research, which later broadened to encompass additional climate-related factors.

6.1.2 The Swedish National Perspectives in Papers I, II, and V

Papers I and II utilised data on weather, railway operations, and infrastructure faults from across Sweden, while Paper V drew on interviews with representatives of 17 governmental agencies, spanning multiple governance levels. As with any research, my institutional position shaped my access to data and choice of cases (Lund, 2014).

Being based at a Swedish university, I focused on the Swedish railway sector, which provides a highly relevant case, particularly due to its decentralised and fragmented climate adaptation governance structure. When it comes to public transport governance in Sweden, responsibilities are distributed across various organisations. Regional Public Transport Authorities (PTAs) are responsible for procuring local and regional services. National rail services, on the other hand, operate under an open-access model, where operators can apply for track access through competitive bidding. The Swedish Transport Administration is the main infrastructure manager for railway infrastructure, and is responsible for maintaining infrastructure, timetabling, signalling, and traffic control. This division of responsibilities creates a context for examining the complexities of climate adaptation decision-making.

6.1.3 The Local Perspective in Papers IV and VI

Papers IV and V take a more local perspective than the other papers, with Paper IV investigates Trelleborg, Sweden as a case. The DAPP approaches used in the paper was selected on the basis that it is suitable for local contexts (Haasnoot et al., 2024). DAPP was originally developed for long-term planning in the Netherlands (Haasnoot et al., 2013), particularly in response to sea-level rise, rise, making it suitable for studying coastal flooding, which was the primary hazard addressed in Paper IV.

Trelleborg was selected for several reasons. The first was its location in the region of Skåne, Sweden, which has been identified as a high-risk area for sea-level rise, coastal flooding, and erosion (SGI & MSB, 2021). It is also the southernmost of Sweden's five core ports, and the largest freight port on the Baltic Sea; due to its strategic location, it serves as a key multimodal hub, integrating sea, road, and rail transport. It hosts the largest railway port in the Baltic Sea, with ferry connections to continental Europe and some of the world's largest railway ferries operating from the port (Trelleborgs Hamn, n.d.). Moreover, as discussed in *Section 4.2,* climate adaptation responsibilities in Sweden are fragmented. This makes Trelleborg a relevant case, as the municipality and the Swedish Transport Administration have differing goals and approaches to climate adaptation.

Finally, in response to climate-related uncertainties, Trelleborg Municipality has developed a long-term, adaptable coastal protection plan (known as *Kuststad*) for the harbour area, including elevated infrastructure and nature-based solutions such as wetlands, dunes, and dykes. The Port of Trelleborg has relocated most of its operations eastwards, with elevated quays to accommodate sea-level rise, while the former western port area is being transformed into a new residential and commercial district called *Sjöstaden* (Trelleborgs Kommun, 2022). These factors together led to Trelleborg being chosen as a case for Paper IV.

In Paper VI, Tokyo – and Japan more broadly – is used as a case. In contrast to Sweden, the governance of Japanese passenger railways is vertically separated. As a result, most railway companies in Japan are privately owned, and are responsible for their own infrastructure, operations, and maintenance (Kurosaki, 2018; Kurosaki & Alexandersson, 2018). Japan also operates some of the most reliable and punctual railway services in the world, with a punctuality rate of 98% (Palacin, 2018). At the same time, Japan is located along the Pacific Ring of Fire and so is frequently exposed to natural hazards such as earthquakes, volcanic eruptions, and tsunamis due to tectonic activity. It also experiences extreme weather events, including typhoons and heatwaves, which can lead to flooding, landslides, and infrastructure damage. These conditions of high hazard exposure yet high performance make Japan an interesting case for comparison with Sweden. Even though the contexts are very different, there is still value in learning from other countries – especially a country such as Japan, which is exemplary as regards the punctuality of railway services, despite their exposure to various natural hazards.

6.2 Quantitative Data

The quantitative data used in this thesis relate to weather, climate zones, railway operations, and railway infrastructure. This was used to quantify the impacts and vulnerabilities of weather on railway operations (Paper I) and railway infrastructure (Paper II).

6.2.1 Weather and Climate-Zone Data

Weather Data

Papers I and II made use of open-access weather data from SMHI. Table 5 gives an overview of the weather data used in Papers I and II. SMHI operates weather stations that each capture temperature, precipitation, snow depth, or wind speed; in other words, not all stations record the same variable. The number of data points was related to the number of weather stations that were in operation during the process of conducting the research. Paper I considered 2011–2019, while Paper II considered 2006–2020. The reasoning behind the time periods considered was related to the availability of data.

Table 5. Overview of the studied weather variables for Papers I and II.
Paper II considered 2011–2019 and Paper III considered 2006–2020.

Weather variable	Number of data points in Paper I	Number of data points in Paper II	Number of weather stations in Paper I	Number of weather stations in Paper II
Daily average temperature (°C)	692,773	1,031,675	241	258
Daily average precipitation (mm)	778,131	1,178,347	312	282
Daily average snow depth (m or cm)	505,317	528,050	217	222
Hourly maximum wind speed (m/s)	10,938,298	N/A	153	N/A
Daily maximum wind speed (m/s)	N/A	506,394	N/A	134

Table 6 gives an overview of descriptive statistics of the weather data used between 2006 and 2020, including mean, maximum, minimum, the 25th quartile, and the 75th quartile.

Table 6. Descriptive statistics of weather data from 2006–2020.

Weather variable	Mean	Maximum	Minimum	Q1	Q3
Temperature (°C)	6.12	27	-40	0	13
Precipitation (mm)	1.88	134	0	0	2
Snow depth (cm)	7.34	229	0	0	0
Wind speed (m/s)	9.37	54	0	7	11

Paper I utilised temperature, precipitation, and snow-depth data observed daily, and wind-speed data observed hourly; however, all weather variables were aggregated to a weekly level for analysis. In contrast, Paper II used daily observations for all weather variables without aggregation. Another difference is that snow depth was recorded in meters in Paper I, and in centimetres in Paper II¸ this was done because in Paper I the data were aggregated on a weekly level to determine disruption shares (see *Section 7.2*), whereas Paper II required data with finer granularity in order to conduct a fault-rate analysis (see *Section 7.3*).

Finally, in both studies, average values were used for temperature, precipitation, and snow depth, as these variables tend to exert their effects cumulatively over time. In contrast, maximum wind speed was used to capture the peak intensity of wind events, which are typically short-lived but potentially highly disruptive.

Köppen-Geiger Climate Data

In Paper II, Köppen–Geiger climate data from Beck et al. (2018) was used to reflect how weather exposure varies across Sweden, given the country's diverse geography and climate zones. In Sweden, there are four climate zones: Cfb, Dfb, Dfc, and ET. Cfb is a temperate climate, Dfb a humid-continental climate, Dfc a sub-Arctic climate, and ET a polar, tundra climate. Table 7 presents the number of railway stations in each climate zone.

Table 7. Number of railway stations in each climate zone (adapted from Paper II).
Climate zones based on Beck et al. (2018).

Climate zone	Full name	Number of stations
Cfb	Temperate climate	2
Dfb	Humid continental climate	567
Dfc	Sub-Arctic climate	326
ET	Polar tundra climate	0

Due to the limited number of data points (n=2) in the Cfb climate zone, these stations were reassigned to the Dfb category. The subsequent analysis is described in *Section 7.3*.

6.2.2 Operations and Infrastructure-Fault Data

Paper I made use of operations data, while Paper II made use of infrastructure-fault data; these were obtained from the Swedish Transport Administration, which is the owner and infrastructure manager for the majority of railway infrastructure in Sweden.

Operations Data

In Paper I, railway operations data from the Swedish Transport Administration database, covering both passenger and freight trains from 2011 to 2019, were utilised (Swedish Transport Administration, 2025a). This contains detailed information derived from the signalling system, including scheduled and actual arrival and departure times at each station. Additional variables include train identification number, route, and train type. For more details on how the data are collected via the signalling system, refer to Kuipers (2024) and Palmqvist (2019). Over the study period, the dataset comprises approximately 100 million registered station arrivals. For the purposes of this thesis, a disruption is defined as any arrival that was either cancelled or delayed by more than 60 minutes. The reasoning behind this is that larger delays were of more interest in this paper than the impacts of weather on a micro scale.

Infrastructure-Fault Data

Paper II uses infrastructure-fault data from the Swedish Transport Administration, covering the period of 2006 to 2020. Faults are recorded in a database known as Ofelia (Swedish Transport Administration, 2025b), which includes information such as the date a fault was reported, when it was resolved, and its location.

Each fault report consists of two parts. The first is the initial report, referred to as the *symptom*, which is entered by a technician at the Traffic Control Centre. This technician is responsible for documenting the fault until it is resolved, with the aim of guiding maintenance and informing traffic operations. The second part is the *real* *error*, reported by the on-site technician who rectifies the fault. This technician provides an assessment of the *real cause*, identifying what they believe to be the underlying reason for the fault. Finally, they report the *action*, describing how the fault was resolved.

Over the study period, a total of 945,329 faults were recorded. For the purposes of this study, the analysis focused on faults related to switches, tracks, catenaries, and signals. Applying this inclusion criterion resulted in a dataset of 126,364 relevant fault reports. In this context, faults are any unexpected or abnormal infrastructure condition, not only those that result in service delays (which are typically classified as failures).

6.2.3 Data Preprocessing, Dataset Matching, and Data Limitations for Quantitative Data Used

The weather data, operations data, and infrastructure-fault data had already been pre-processed in Microsoft SQL Server Management Studio prior to conducting this research. For the specifics of the pre-processing of the data, see Palmqvist (2019).

As weather stations are not typically located at or near train stations, each station was linked to its nearest weather station, and the corresponding daily weather observations for the study period were retrieved (for more detail, see Palmqvist, (2019)). In Paper II, a sensitivity analysis was conducted to determine the distance threshold between the weather and railway stations. This approach enabled the linkage of weather data with both railway operations and infrastructure-fault datasets using the common railway station field. In addition, in Paper II, the Köppen-Geiger climate zones were used to map each station in its respective climate zone using QGIS[5], assigning each railway station to a climate zone.

In addition to the caveats regarding weather stations not being located near railway infrastructure, there were also limitations associated with the infrastructure-fault data. Specifically, the reporting of weather-related faults is subjective and influenced by the knowledge and experience of the person reporting the fault, as well as the constraints of the reporting system itself. Faults can be reported by various actors, including train drivers and maintenance inspectors (Mirzanamadi et al., 2024). The technician who enters a fault into the database may associate it with a specific weather-related hazard, such as flooding or fire, but this classification is subjective and not typically applied in a systematic manner. A report may indicate flooding, but it can be unclear whether the cause was heavy rainfall or a burst pipe at a station. Additionally, some weather-related faults may be miscategorised under other categories, such as switch faults, where the underlying cause is not specified.

[5] QGIS is a free and open-source geographic information system (GIS) software.

Although the reporting system includes a free-text field for further elaboration, it is heavily underutilised.

Initially, in a previous version of this work, I attempted to use predefined fault codes under the *symptom, real error,* and *cause* fields used in the system – specifically, flood, buckling, slippery rails, landslide, lightning, fire, snow or ice, storm, and tree fall – to quantify the impacts of weather on railway infrastructure. However, the subjectivity of the reporting made it difficult to draw reliable conclusions about causation. This challenge led to the approach taken in Paper II, where I correlated weather data with infrastructure faults without excluding or focusing on specific fault types.

6.3 Qualitative Data

The qualitative data collected and used in this thesis were derived from workshops, interviews, and literature. These were used to understand the impacts of flooding on railway infrastructure in previous research (Paper III), the barriers and opportunities to dynamic adaptation of coastal railways (Paper IV), and the barriers to climate adaptation in Sweden (Paper V), as well as to review climate adaptation and practices relating to disaster risk reduction in Japan (Paper VI).

6.3.1 Workshops

While the quantitative data described above were useful in determining the impacts of weather on railway operations and infrastructure, they did not provide insights into the minds of practitioners who work with weather impacts and climate adaptation. Ørngreen & Levinsen (2017) define workshops as structured settings in which a group of participants collaboratively engage in learning, knowledge exchange, creative problem-solving, or innovation related to a domain-specific issue. Therefore, workshops were chosen to collaboratively engage in and integrate knowledge from various disciplines.

Paper IV is based on data gathered through three actor workshops held in Trelleborg, Sweden, which were designed to apply a DAPP-light approach. The participants collaboratively engaged in the steps of a DAPP-light framework to explore adaptation pathways for coastal railway infrastructure. Workshops were selected over other methods, such as interviews, because they enabled the participants to collectively walk through the steps of the DAPP-light approach, ultimately co-developing an adaptation pathways map. This format was well-suited to the DAPP-light framework, which relies on collaborative decision-making and the integration of diverse perspectives. The workshops also facilitated dialogue between municipal and national actors, revealing governance challenges that may not have emerged through individual interviews.

Key actors invited to participate included representatives from the Swedish Transport Administration, Trelleborg Municipality, and the County Administrative Board of Skåne. Although the Swedish Transport Administration holds primary responsibility for adapting railway infrastructure to climate change, the railway crosses land owned by other actors, necessitating the inclusion of other organisational perspectives. Participants were invited via email and encouraged to forward the invitation to relevant colleagues, thereby employing a snowball sampling technique (Bryman et al., 2022). An overview of workshop participants is presented in Table 8.

Table 8. Overview of participants in each of the three workshops (adapted from Paper IV.

Organisation	Number of participants
Workshop 1	
The Swedish Transport Administration	2
Trelleborg Municipality	4
The Country Administration Board of Skåne	1
Lund University	1
The Port of Trelleborg	1
Workshop 2	
The Swedish Transport Administration	1
Trelleborg Municipality	5
The County Administration Board of Skåne	1
Workshop 3	
The Swedish Transport Administration	1
Trelleborg Municipality	4

Each of the three workshops focused on one of the three elements of the DAPP-light approach: i) establishing the vulnerabilities, climate adaptation goals, and uncertainties of the current system; ii) identifying potential climate adaptation approaches; and iii) developing an adaptation pathways map. Each workshop included facilitators who guided the discussions, and notetakers who documented the conversations using provided templates with guiding questions. The discussion in Workshop 2 was also recorded. Further details on the structure and content of each workshop are available in Paper IV.

Data Preprocessing

Prior to analysis, the data were cleaned and processed to enable coding in NVivo, a CAQDAS (computer-assisted qualitative data analysis software). First, all written material was translated from Swedish to English using DeepL and then proofread by the native Swedish-speaking co-authors. The discussion from the second workshop, which was recorded, was transcribed verbatim by one of the native Swedish-speaking co-authors.

6.3.2 Interviews

Similar to workshops, interviews are useful for understanding the decision-making processes and identifying the barriers related to climate adaptation. Interviews were chosen to gain a more nuanced understanding of complex issues such as climate adaptation (Beyers et al., 2014). In Paper V, semi-structured interviews were utilised, while in Paper VI the interviews were unstructured. A total of four unstructured (three in-person and one virtual) interviews were conducted in Japan, and a total of 19 semi-structured interviews (one in person, and 18 virtual) were conducted in Sweden. In some cases, more than one participant was present at the interview. Table 9 provides an overview of all of the interview participants. As the majority of railway companies in Japan are private, the names of the organisation are not disclosed.

Table 9. Overview of interview participants.

Type of actor	Organisation	Number of interviewees	Type of interview	Format of interview
Japanese practitioners		4	Unstructured	In person
Japanese practitioners		2	Unstructured	Virtual
Public agency	The Swedish Transport Administration	3	Semi-structured	Virtual
	The Swedish Transport Agency	2	Semi-structured	Virtual
	The Swedish Civil Contingencies Agency[6]	1	Semi-structured	Virtual
	The Swedish National Board of Housing, Building, and Planning	1	Semi-structured	Virtual
	The Swedish Civil Contingencies Agency	1	Semi-structured	Virtual
	The Swedish Meteorological and Hydrological Institute	1	Semi-structured	Virtual
County administration board	County Administration Board Gävleborg	1	Semi-structured	Virtual
	County Administration Board Skåne	1	Semi-structured	Virtual
Region councils/PTAs[7]	Region Västra Götaland	1	Semi-structured	In person
	Region Värmland	1	Semi-structured	Virtual
	Region Stockholm	1	Semi-structured	Virtual
	Region Skåne	1	Semi-structured	Virtual
Municipality	Trelleborg Municipality	1	Semi-structured	Virtual
	Stockholm Municipality	1	Semi-structured	Virtual
	Norrköping Municipality	1	Semi-structured	Virtual
	Lund Municipality	2	Semi-structured	Virtual
Research council	Swedish Expert Council on Climate Adaptation	1	Semi-structured	Virtual

[6] See Note 3, p. 61

[7] Public Transport Authorities.

Unstructured Interviews

The unstructured interviews utilised in Paper VI were conducted between July and August 2024 in Tokyo, Japan, and were held in English. Three of the interviews were conducted in person, and one was held virtually via Zoom. Each interview lasted approximately 60 minutes. Four interviews were conducted with representatives from four organisations involved in railway operations and research. In two of the interviews, more than one person from the organisation participated.

These interviews served as a complementary data source to the selected grey literature (*Section 6.3.3*), helping to elicit expert experience and knowledge. Unstructured interviews allow for more flexible discussions and deeper exploration of social contexts (Myers & Newman, 2007). In Japan, the majority of railway companies are privately owned. Additionally, the language barrier played a role. These factors collectively influenced the decision to use unstructured interviews. Their informal nature can help build rapport, making interviewees more comfortable in sharing their insights (Chauhan, 2022). However, a main question of how the company handles extreme weather and views climate adaptation was still asked prior to the interview, so that the interviewees could prepare. In this sense, the interviews were not entirely unstructured.

The interviewees were selected based on contacts held by me and my co-authors, with expertise ranging from climate adaptation and risk management to transportation planning. The interviews were not recorded; instead, notes were taken for later analysis. During each interview, the participants were first asked to describe how they manage meteorological hazards such as landslides or typhoons. During and following this initial presentation, further questions were posed to the participants.

Semi-Structured Interviews

Paper V utilised semi-structured interviews, which were chosen because I was already familiar with the case of Sweden, and therefore the approach was less exploratory than that of Paper VI. In addition, semi-structured interviews were used to identify barriers to climate adaptation that might not be evident in policy documents (Williamson et al., 2019) or via other methods. Furthermore, semi-structured interviews facilitated a more conversational exchange with the interviewees, while maintaining enough structure to ensure that all of the selected topics were addressed, allowing flexibility to adapt questions and include follow-up prompts based on the interviewee's expertise and familiarity with the subject matter (Bryman et al., 2022; Brinkmann & Kvale, 2015).

The 19 semi-structured interviews were conducted between February and March 2025, and in English; 18 were conducted online via Microsoft Teams or Zoom, and one took place in person. In three of the interviews, more than one person from the organisation participated. Because railway climate adaptation is a multidimensional issue, a range of actors were interviewed to capture diverse perspectives and gain a deeper insight into the complexities of climate adaptation across different levels of governance. The identification of relevant organisations to interview was guided by the Swedish Expert Council for Climate Adaptation (2022) report, and the interviewees themselves were selected using a combination of purposive and snowball sampling (Bryman et al., 2022).

Each interview was supported by an interview guide, which touched upon the following three topics: i) climate adaptation knowledge; ii) responsibilities regarding climate adaptation; and iii) collaboration. The guide consisted of a series of questions that were neutrally worded in order to avoid being leading, and was inspired by barriers identified in previous research on climate adaptation. Each guide was also slightly tailored to reflect each actor's specific role and organisational context, given their varying degrees of involvement in climate adaptation, transport, or both. Each interview began with introductory questions about the organisation and the interviewee's role to help establish trust (Bryman et al., 2022).

Data Preprocessing

As with the workshop data, before the interview data were analysed they were cleaned and processed to enable coding in NVivo. In the case of the unstructured interviews this was minimal, as the notes taken during the interviews were uploaded directly into NVivo for coding.

The semi-structured interviews were recorded and transcribed verbatim. On occasion, interviewees used Swedish terms, which were translated using DeepL and verified with a native Swedish-speaking co-author; the translations were added in brackets following the original word. However, the grammar was left unchanged to preserve the interviewees' intended meaning and avoid misinterpretation (Haapnen, 2016).

6.3.3 Reviewed Literature

The empirical material used for the systematic literature review conducted in Paper III consisted of literature obtained from the Scopus database directly through the Lund University library portal in March 2022. In addition, a process called mapping the field (Denyer & Pilbeam, 2013) was used to identify literature for the study and helped to define its scope. The keywords chosen for the search string included *rail** and *train*, and were combined with flooding- and disruption-related keywords: *flood, delay, cancel*,* and *disruption*[8]. The literature collected was limited to the

[8] The asterisk (*) is used as a truncation symbol to capture multiple word endings. For example, *rail** retrieves *railway, railways, rail,* etc.

English language, and to peer-reviewed journal articles, reviews, and conference papers; there were no restrictions on publication year.

The literature reviewed in Paper VI consisted primarily of grey literature, including news articles, annual reports from railway companies, national climate adaptation plans, climate change assessments, and operational guidelines for various natural hazards. The search took place between June and August 2024. The decision to utilise grey literature was based on two key considerations. First, the study aimed to examine climate adaptation and practices relating to disaster risk reduction in Japanese railway organisations. Second, there is limited research on climate adaptation in Japan's railway sector, making grey literature an accessible source of information. Grey literature also serves to address actor concerns and provide practical insights that may not be captured in academic publications (Mahood et al., 2014). The literature was obtained through searches of railway company and government websites, news outlets, and documents shared by the interview participants.

6.3.4 Limitations of the Qualitative Data Used

Language Biases

The literature review in Paper III was limited to English-language publications. This introduced a set of potential biases, as it restricted the scope to research produced by scholars who do not conduct research in English-speaking environments. While there are caveats associated with translating literature, I believe it is important to acknowledge the researchers whose work may have been excluded from this study due to language constraints.

Language-related biases were present in both Papers IV and VI, though in different ways. In Paper VI, the use of translated Japanese literature introduced risks of mistranslation, which were mitigated through careful judgement and consultation with a native Japanese speaker. In Paper IV, workshops were conducted in Swedish, which reduced some biases but introduced others due to my limited fluency. Workshop materials were translated into English; this may have led to minor misinterpretations, but this risk was mitigated by my native Swedish-speaking co-authors, who supported planning, facilitation, and proofreading to ensure accuracy.

Several potential biases in the interview data (Papers V & VI) stem from language barriers, as English was used despite many participants being native Swedish or Japanese speakers. This may have affected the depth and openness of responses, although efforts were made to build trust and accommodate language needs, such as encouraging Swedish when necessary, using translation tools, and involving a native Japanese speaker in some of the interviews.

Data Generation and the Art of Workshops and Interviewing

The process for selecting workshop participants and interviewees is described in *Sections 6.3.1* and 6*.3.2*, respectively. In the case of the workshops, the participants were encouraged to attend all of the workshops. However, due to their availability, the number of participants and actors represented varied in each workshop. While this variation provided a range of insights, it may also have limited the comparability across workshops, and the representativeness of perspectives.

In the case of the interviews in Paper VI, 46 interview requests were sent out, and 19 positive responses were received. Despite this relatively small number, a saturation point was evident after these 19 interviews. In contrast, Paper V likely did not reach saturation, as the number of interviews conducted was influenced by time constraints and participant willingness.

The majority of the interviews were conducted online rather than in person, which may have introduced certain biases in the data. For instance, participants may perceive higher levels of attentiveness, trust, and respect in face-to-face interviews (Anthony et al., 2025). However, the online interviews were conducted via video, which can still foster a good level of rapport and empathy (Ibid.).

One advantage of conducting interviews online in the Swedish case was the ability to reach a wide range of organisations across the country. Interviewees located in Skåne and near Göteborg could choose between in-person and online interviews. Of the 19 interviews conducted in Sweden, only one was held in person. This is likely because, since the COVID-19 pandemic, Sweden has continued to promote hybrid working arrangements, which may have made interviewees more comfortable with participating online.

7 Methods of Analysis

Four main methods of analysis were utilised in this thesis. Table 10 gives an overview of the methods used to analyse the data collected (which was presented in *Section 6*).

Table 10. Overview of the method of analysis used in this research.

Method of analysis	Paper number
Literature review	Papers III & IV
Visual graphical analysis	Papers I & II
Fault-rate analysis	Paper II
Thematic analysis	Papers IV–VI

7.1 Literature Review

Paper III utilised a systematic literature review to examine the current state of knowledge on the relationship between flooding and railway infrastructure. This method was chosen as it enables a comprehensive mapping of the field, and helps to identify research gaps and future directions (Page et al., 2021). The selection process was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021).

Following the initial identification of records (described in *Section 6.3.3*), the systematic literature review, inspired by the PRISMA framework (Page et al., 2021), included the following screening and quality-assessment steps: i) title screening, ii) abstract screening, and iii) full-text screening. Ninety records were initially identified via Scopus, with an additional three identified by mapping the field. After applying the screening and quality criteria, 24 articles remained. Studies were included if they addressed railways and some aspect of flooding impact, assessment, or prevention. Exclusion criteria included lack of full-text access, absence of a railway focus, or a primary emphasis on other natural hazards, such as hurricanes or earthquakes.

Paper VI also utilised a literature reviewed, but this was triangulated through interviews. This study employed a narrative review to explore climate adaptation and practices relating to disaster risk reduction in Japanese railways. The benefit of a narrative review over a systematic review is that the former is more flexible and draws on multiple sources to enhance contextual understanding (Motevalli, 2025). Motevalli (Ibid.) describes a process that typically begins with a broad research question, and relies on the author's expertise to select and interpret relevant sources. Rather than applying strict inclusion criteria, studies are chosen for their relevance and contribution to the topic. The review process involves summarising and integrating key findings and perspectives into a coherent narrative. In this case, narrative review was felt to be suitable as Japan was a new case to explore. This approach enabled me to explore relevant grey literature; this, combined with insights from unstructured interviews, supported the investigation of broader research questions and a more exploratory research approach.

7.2 Visual Graphical Analysis

Papers I and II both make use of visual graphical analysis. This technique is an explorative method that can be used for visualising trends in analyses (Keim et al., 2006; Wainer & Thissen, 1981). Weather datasets typically contain a large proportion of observations that reflect "normal" conditions, while events of greater interest – such as storms, heatwaves, and heavy precipitation – are rarer and more extreme. This imbalance poses analytical challenges, particularly when attempting to understand the impacts of weather on railway operations and infrastructure.

In Paper I, data relating to the weather and railway operations were aggregated on a weekly basis in order to determine the share of disruptions causally linked to each of the studied weather variables. This was then plotted to visually analyse trends. In Paper II, a fault-rate analysis was conducted, and each of the studied weather variables was plotted against the fault rate to visually analyse trends against the results of the fault-rate analysis. This approach, used in both papers, allowed trends to be visually observed, which is useful for revealing patterns, clusters, outliers, and other trends that statistical models may miss (Correll et al., 2018; Kim et al., 2025). This approach served as an important first step in exploring the relationship between weather and railway operations and infrastructure, while more advanced statistical techniques, such as extreme value theory (Montes-Pajuelo et al., 2024) could be applied in the future to model the tail behaviour of rare but disruptive events. However, this was outside the scope of this thesis.

In Paper II, visual graphical analysis was used alongside fault-rate analysis to support interpretation of weather-related infrastructure faults.

7.3 Fault-Rate Analysis

In Paper II, a fault-rate analysis was conducted. This method was chosen as it enabled the calculation of thresholds, which are key mechanisms that are used to inform preparatory and preventative asset management ahead of adverse or extreme weather events (Network Rail, 2021). In addition, the fault-rate analysis enabled greater comparison across geographies and infrastructure-asset densities than typical methodologies, which consider only the total incidence of faults regardless of relative exposure (Fisher, 2021; Greenham, 2023).

The fault-rate analysis conducted in Paper II involved a two-step normalisation: first by the number of assets at each station, and second by the weather conditions experienced at that station on a given day. Infrastructure-fault data were aggregated at the station level on a daily basis over a 14-year period, including days without faults. To account for differences in station complexity, fault rates for switches and signals were normalised by asset quantity, while track and catenary faults were calculated per kilometre using station length as a proxy. Fault rates were then grouped by weather variable and weighted to reflect asset exposure. A lower bound was applied to exclude unreliable fault rates associated with infrequent weather conditions, following Fisher (2021). Thresholds were defined as the weighted average fault rate plus one standard deviation, with the fault-rate analysis repeated across the two dominant climate zones (Table 7 in *Section 6.2.1*). Visual graphical analysis was subsequently used as a complementary tool to illustrate threshold exceedance and to support interpretation by highlighting the most prominent trends in the data.

7.4 Thematic Analysis

Papers IV–VI all employed thematic analysis. Although each paper used different types of data, all of the material was coded in NVivo following Braun and Clarke (2006), with slight variations in application across the studies. Thematic analysis is a flexible and accessible method for qualitative data analysis; it can identify, analyse, and report on various themes in data, and be applied using either an inductive (data-driven) or deductive (theory-driven) approach (Ibid.). The six steps are: i) familiarisation with the data; ii) generating initial codes; iii) searching for themes; iv) reviewing themes; v) defining and naming themes; and vi) producing the report.

In Papers IV–VI, the first step entailed collection, transcription, and initial reading of the data before uploading this into NVivo.

The second step was generating initial codes. In Paper IV this was undertaken deductively, using predetermined codes. In this paper a Windows of Opportunity Framework – a framework used to analyse moments or events that can catalyse transformative change (Abunnasr et al., 2015; Brown et al., 2017; Göransson et al., 2023) – that was particularly inspired by Brown et al. (2017) was used. Paper IV investigated the barriers and opportunities to dynamic adaptation, and therefore the empirical material collected during the workshops was coded using codes predetermined by Brown et al. (2017) for i) open windows, ii) closed windows, iii) reframed windows, and iv) transformed windows. In Paper V, the codes were generated inductively, which allowed for more familiarity with the empirical material and a deeper understanding of the complexities surrounding climate adaptation to be developed (Bingham, 2024). Since the aim of the paper was to investigate the barriers to climate adaptation in the railway sector, the material was initially coded for challenges. In Paper VI the initial codes were driven by the research questions and more inductive approach. These codes included: i) climate change in Japan; ii) approaches to mitigating meteorological hazards; iii) framings of disaster risk reduction and climate adaptation.

Steps iii–v of the thematic-analysis process occurred together, in a relatively iterative process. For Paper IV the material was coded under each of the Windows of Opportunity, and during this process a fifth window emerged: half-open windows. The material was further coded and condensed into similar themes, which led to the identifying of windows under each opportunity class. In Paper V the initial code of challenges was also further grouped and refined into four main barriers. Finally, in Paper VI, various themes emerged under each initial code related to the research questions and were refined throughout the process.

To provide insight into how the thematic analysis was conducted, I briefly illustrate how raw data were coded and developed into themes. The following example is a short excerpt from Paper V: "So, the responsibility for climate adaptation is a bit scattered in the organisation."

During the initial inductive coding, this excerpt was coded under the broad category of "challenges." As the analysis progressed and similar codes accumulated, this was refined into a more specific theme of "responsibilities." Through an iterative process of comparing coded segments and examining emerging patterns across the dataset, this theme was eventually integrated into the broader theme "legislation," with the subtheme "decentralised governance." This final categorisation captured how fragmented governance structures and unclear organisational responsibilities were experienced as barriers within existing legislative frameworks.

8 Summary of Included Papers

Paper I: Weather and Train Disruptions in Sweden 2011–2019

This paper makes use of data on the weather and railway operations from 2011–2019 in order to understand the relationship between weather and train disruptions. In this case, disruptions were defined as cancellations or delays of more than 60 minutes, and the weather variables used were snow depth, temperature, precipitation, and wind speed.

The data on weather and railway operations were aggregated on a weekly basis to determine disruption shares for each weather variable using visual graphical analysis. Additionally, since weather stations are not located at train stations, an algorithm was created to match the coordinates of the train stations to the nearest weather station on a day-by-day basis.[9]

The results showed that disruption shares increased with increasing snowfall, precipitation, and wind speeds. Disruption shares also increased dramatically with both below-freezing temperatures and high wind speeds, but less dramatically with high temperatures and high levels of precipitation. Due to climate change, Sweden is projected to experience increased temperatures and precipitation, and potentially an increase in the frequency and severity of storms. This indicates that Sweden may experience more disruptions related to high temperatures, wind speeds, and levels of precipitation due to climate change. On the other hand, the number of disruptions related to winter conditions, low temperatures, and high snow depth may decrease over time. The results of this study serve as useful inputs for decision-making in order to increase resilience to adverse weather conditions and implement appropriate climate adaptation approaches. They offer empirical evidence on weather impacts on railway operations, establish a baseline for operational vulnerability, and relate this baseline to future climate-change projections.

[9] Here I acknowledge a typo in the publication, which states that each weather station was matched to the nearest train station; it should state that each train station was matched to the nearest weather station.

Paper II: The Impacts of Weather on Railway Infrastructure in Sweden

Paper II uses data on railway infrastructure faults, specifically switches, signals, tracks, and catenaries; and on weather, temperature, precipitation, snow depth, and wind speed. This was used to quantify the vulnerability of the Swedish railway network to weather between 2006 and 2020. This study quantified the fault rate in order to establish thresholds that can be useful for identifying areas of concern for operations. In addition, in order to account for geographical differences within Sweden, climate-zone data were used to split the network into two main climate zones. The fault-rate analysis was then conducted again in order to determine any differences in fault rates and thresholds between the two climate zones.

The results indicate that high and low temperatures have a noticeable impact on the fault rates of switches, tracks, and catenaries. Additionally, high levels of precipitation are associated with higher fault rates across tracks and catenaries; snow depth has an impact on the fault rates for switches and tracks; and high wind speeds are associated with higher fault rates for tracks and catenaries. Finally, signals were found to be the most resilient asset. When comparing the two climate zones, notable differences were only found for track asset vulnerability.

These findings indicate that differences in preparedness and asset management across Sweden's railways influence the resilience of assets to weather variables, and that this vulnerability is likely to be further exacerbated by climate change. The results of this study are useful for decision-making and future climate adaptation approaches, as understanding the impacts of weather on railway infrastructure is an important prerequisite for increasing the resilience of railway infrastructure to today's climate and future climate change.

Paper III: The Effects of Flooding on Railway Infrastructure: A Literature Review

Paper III presents a systematic literature review of research that investigated the effects of flooding on railway infrastructure, and discusses how future climate adaptation approaches are addressed. A systematic search of the Scopus database, conducted in March 2022, identified 90 records, with three additional records found through field mapping. After screening and quality assessment, 24 studies were included in the paper.

The studies were categorised into three groups, based on their focus: past effects, future effects, and climate adaptation. The results indicate that most research is focused on understanding the past effects of flooding on railway infrastructure. These studies mainly use specific case studies to quantify the past and present impacts of flooding on railway infrastructure, before considering future impacts. Studies that focus on future effects often combine estimates of past effects with projections of future climate change to predict the future impacts of flooding on railway infrastructure. Finally, some studies also discussed future climate adaptation approaches with regard to increasing the resilience of railway infrastructure to flood events. Of the 24 studies analysed in this work, only five highlighted climate adaptation or resilience approaches. These include policies, frameworks, and structural measures such as proper drainage systems or early-warning systems.

The results of this study can serve as useful inputs for future decision-making, as many of the studies analysed in this literature review highlight the importance of quantifying and understanding past events in order to predict and prepare for the effects of future flooding on railway infrastructure. Many of the studies indicate that they are a base for future climate adaptation studies and resiliency planning, highlighting the importance of climate adaptation in future research. Moving forwards, more emphasis should be placed on developing appropriate climate adaptation approaches that are suitable to local geography and infrastructure. As railway infrastructure has a long life-span, it is important to both adapt current infrastructure and build new infrastructure with resilience in mind. Overall, this paper identifies gaps in climate adaptation-focused research, and positions flooding as a key climate risk.

Paper IV: Barriers and Opportunities for Dynamic Adaptation of Coastal Railways

Paper IV explores the potential of applying dynamic adaptation approaches to coastal railway infrastructure in Sweden, using Trelleborg as a case. Climate adaptation approaches and pathways were developed through three actor workshops, inspired by a DAPP-light approach, which supports long-term decision-making under uncertainty. To evaluate the feasibility of these pathways, a Windows of Opportunity framework (Brown et al., 2017) was used to identify institutional and governance-related barriers and opportunities.

Three workshops were conducted between September 2023 and March 2024 in Trelleborg, Sweden with participants from Trelleborg Municipality, The County Administrative Board of Skåne, and the Swedish Transport Administration. Following the workshops, the data generated were analysed using a Windows of Opportunity Approach to understand the barriers and opportunities related to utilising more dynamic adaptation approaches such as DAPP.

Five Windows of Opportunity were identified: open, closed, reframed, transformed, and half-open. The open windows identified were: i) allows for reflection on current development plans; and ii) highlights dependencies and reduces the risk of lock-in. The closed windows identified include: i) political arena; ii) funding; iii) scientific understanding; iv) land use and ownership; v) interconnectedness of sectors; vi) place attachment; and vii) resistance to change**.** The reframed windows identified were: i) land use; and ii) legislation. The transformed window identified was thinking on long-term horizons, and the half-open windows identified were: (i) creates an arena to discuss the problems and goals; (ii) collaboration.

Open windows such as Trelleborg Municipality’s willingness to monitor climate adaptation plans and reserve land for future climate adaptation approaches highlights the potential for more flexible planning processes and legislation at a national level. However, closed windows, such as the current political arena, reluctance to engage in flexible long-term planning, and rigid land-use restrictions continue to act as barriers to dynamic adaptation.

Throughout the process of conducting the study, it was evident that Trelleborg’s urban-development and coastal-protection plans incorporate elements of dynamic adaptation; however, the climate adaptation of railway infrastructure is disconnected and siloed by sector. Moving forwards, DAPP offers opportunities for more flexible adaptation decision-making, despite the identified barriers. Climate adaptation of coastal railways cannot be undertaken in isolation and without consideration of other elements of the built environment, but barriers such as allocation of responsibilities, resources, and planning legislation remain.

Paper V: Barriers to Climate Change Adaptation in Swedish Railway Infrastructure

The aim of Paper V was to identify the barriers to climate adaptation of railway infrastructure in Sweden. This study utilised 19 semi-structured interviews, conducted in Spring 2025 with representatives from 17 organisations across multiple levels of governance in Sweden.

The four key barriers identified are: legislation, resources, prioritisation, and knowledge. Legislation refers to the decentralised governance in Sweden and the effects of this on climate adaptation, and policy misalignments. Limited resources refers to the uneven distribution of competencies and funding restraints. Low prioritisation refers to inconsistent priorities and inflexible investment cycles. Knowledge gaps act as an overarching barrier that drives the other barriers. There is still a lack of knowledge regarding what climate adaptation means in Sweden, what it entails, and how railway infrastructure will be impacted by extreme weather and climate change.

These findings reveal that Sweden's decentralised governance structure, with responsibilities across different organisations, often leads to fragmented responsibilities and unclear mandates, particularly in urban areas where multiple actors manage interconnected transport infrastructure. Financial constraints further hinder effective implementation. Additionally, climate adaptation is often deprioritised in favour of short-term goals. This study highlights the need for increased knowledge, clearer mandates, and long-term planning in order to strengthen climate resilience of railway infrastructure.

Paper VI: On Track to Climate Resilience? Insights from Japanese Railways

In Paper VI, an exploratory approach was utilised to review climate adaptation and practices relating to disaster risk reduction in Japan. Unstructured interviews with representatives of three railway organisations and one research institute in Greater Tokyo, conducted in Summer 2024, and a literature review of grey literature contributed to understanding how the climate is changing in Japan, what approaches are used by Japanese railway companies, and how Japanese railway companies have acknowledged climate adaptation alongside disaster risk reduction.

The results indicate that Japan is expected to experience an increase in both precipitation and temperature due to climate change. An increase in localised torrential rain events has already led to operational and infrastructural challenges in Greater Tokyo. Disaster risk reduction is deeply rooted in the organisation culture of infrastructure management in Japan, including railway infrastructure. The history of natural hazards across Japan has led to prioritisation of safety in business culture, and efficient engineering efforts to "engineer" hazards out of the system.

Today in Japan, disaster risk reduction tends to operate with relatively short planning horizons, in contrast to the longer-term perspectives associated with climate adaptation. However, as the national government introduces more climate-adaptation strategies and guidance documents, these practices may gradually shift toward longer-term planning. Barriers to climate adaptation in the railway sector in Japan are still prevalent, as a majority of railway companies in Japan are private and therefore face limited profits and investment; moreover, knowledge gaps persist.

9 Answering the Research Questions

Research Question 1

How does weather impact railway operations and infrastructure in Sweden?

Papers I, II, & III

The first research question of this thesis investigated how weather impacts railway operations and infrastructure in Sweden. As outlined in *Sections 1.1* and *3.1*, adverse weather can lead to service disruptions, infrastructure faults, and increased maintenance costs. These impacts occur in two primary ways: behavioural changes in operations due to weather-related stresses, and physical damage to infrastructure caused by extreme conditions (Jaroszweski et al., 2014).

Snow

Snow is a significant driver of both operational disruptions and infrastructure faults. The share of disruptions increased with snow depth. In weeks when the average weekly snow depth reached around 0.7 metres, approximately 30% of services were disrupted between 2011 and 2019, compared with a baseline value of 11%. Snow-related delays and cancellations were especially common during the winter months, particularly in northern Sweden.

Regarding infrastructure, switches are highly sensitive to snow accumulation, with fault rates increasing when snow depths exceeded 10 centimetres. Tracks also showed increased vulnerability, especially above 70 centimetres. Catenaries and signals were less affected.

When comparing climate zones, tracks in Dfb (southern Sweden) were more vulnerable to snow depth than those in Dfc. Where the threshold (see *Section 7.*2) is crossed at 50 centimetres for Dfb and 90 centimetres for Dfc. This is likely due to the fact that Dfc (northern Sweden) is exposed to higher volumes of snow than Dfb, and therefore the maintenance approaches may vary. Regarding other assets, there is no notable difference in the fault rates.

Temperature

Temperature extremes, both high and low, are linked to increased disruptions and infrastructure faults, with impacts more notable at low temperatures. When average weekly temperatures reached around –30°C, disruptions reached 60%, compared to an 11% baseline. High temperatures (>20°C) also raised disruption rates (up to 15%), though the effect was less than that of low temperatures.

In regard to infrastructure, switches are particularly vulnerable to freezing conditions, with fault rates rising below 0°C. There was also some impact when temperatures exceed 25°C. Tracks showed increased fault rates at both low and high temperatures, with thresholds identified at around –20°C and +10°C, increasing sharply at +20°C. Catenaries were affected by low temperatures, especially below –10°C, and to a lesser extent by heat. Finally, signals were found to be relatively resilient to temperature fluctuations. When comparing the climate zones, Dfb showed higher fault rates in warmer conditions, while Dfc showed vulnerability at both extremes.

Wind Speed

Wind plays a critical role in both service reliability and infrastructure resilience during storm events. Disruptions rose sharply when weekly maximum wind speeds exceeded 20 metres per second, reaching up to 70% compared to an 11% baseline.

Regarding infrastructural impact, tracks and catenaries were most impacted, with fault rates rising as wind speed exceeded 10 metres per second. Switches and signals showed minimal sensitivity. When comparing climate zones, Dfb was found to be more exposed to windstorms, leading to greater overall vulnerability.

Precipitation

Precipitation had a more modest but still notable impact on railways systems in Sweden than the other studied weather variables, particularly during extreme rainfall events that led to flooding. Disruption rates increased with precipitation, though the relationship was weaker compared to other variables. At around 20 mm of daily average precipitation over one week, disruption shares reached approximately 15%, compared to an 11% baseline.

Infrastructure was impacted by precipitation in various ways. Tracks and catenaries were the most affected, with fault rates rising significantly for both types of assets when rainfall exceeded 20 millimetres. Switches and signals showed limited sensitivity to precipitation, though drought conditions may also have impacted fault rates. When climate zones were compared, the track fault rate for Dfb was slightly higher than that of Dfc, signifying that tracks were more vulnerable to precipitation in southern Sweden compared to northern Sweden. This contrasts with recent flooding events in northern Sweden in 2023 and 2025. However, this difference can potentially be explained by the number of data points for Dfb exceeding Dfc due to there being more railway stations in Dfb.

Flooding[10]

Flooding is highlighted as a major hazard in the literature, and can lead to significant infrastructural damage, including damage to embankments, tracks, electrical systems, and bridges (specifically through scour). Such damage not only leads to high repair costs for infrastructure managers but also can trigger large-scale disruptions across railway networks, including rerouting and prolonged service suspensions. These operational impacts can be equally expensive as infrastructure repairs, with some lines remaining closed for several months due to expended repair times.

Flooding is expected to increase in severity and frequency due to climate change, leading to the aforementioned impacts if no approaches are made to adapt. The impacts will vary based on geography, catchment size, and quality of infrastructure and maintenance, with low-lying areas such as plains, valleys, and coastal zones particularly vulnerable. Sea-level rise may also impact coastal railways through erosion or when combined with tidal surges and storms, which can increase wave heights and lead to coastal flooding.

Previous research on the impact of flooding on railways has mainly focused on quantifying damage from past events and combining these findings with climate projections to estimate future impacts. Research which has focused on these aspects have done so by quantifying the costs of flooding-related damage, estimating disruptions, identifying links that are most vulnerable to flooding and lead to increased disruptions, and quantifying impacts on specific railway infrastructure assets. The literature positions flooding as a leading cause of infrastructure damage, and a hazard that is likely to occur with increasing frequency due to climate change.

Concluding Remarks

Table 11 summarises the snow depth, temperature, wind speed, and precipitation levels at which operational disruptions and infrastructure faults began to increase. These thresholds were derived visually for the operational disruptions (Paper I) and from the fault-rate analysis conducted in Paper II for the infrastructure assets.

[10] I note that flooding is not a type of weather in itself, but a result of increased precipitation.

Table 11. Thresholds of operations and fault rates for snow depth (cm), temperature (°C), wind speed (m/s), and precipitation (mm).
Adapted from Papers I & II.

	Operations	Switches	Signals	Tracks	Catenaries
Snow depth	70 cm	>10 cm	>110 cm	>70 cm	>40 cm
Temperature	<–30 °C, >20 °C	<0°C, >+25°C	>+15°C	<–20°C, >+10°C	<–10°C, >+5°C
Wind speed	20 m/s	>25 m/s	>10 m/s	>10 m/s	>15 m/s
Precipitation	20 mm	<0 mm	>10 mm	>20 mm	> 20 mm

Table 12 summarises the susceptibilities identified in the Swedish railway system. Snow depth, temperature, precipitation, and wind speed all impacted railway operations, but to varying degrees. The most prominent relationships were between disruptions and snow depth, disruptions and low temperatures, and disruptions and wind speed. In regard to infrastructure, track assets were found to be the most vulnerable to all types of weather, while signals were the most resilient.

Table 12 presents both the threshold values defined in Table 11, and the visual patterns evident in the figures from Papers I and II. Although a numerical threshold can be calculated for signals, for example, the visual graphical analysis of the distributions showed that signal faults do not meaningfully increase with most weather conditions.

When comparing two climate zones, notable differences were observed only for track assets, despite northern Sweden being more exposed to low temperatures and higher snow depths.

Table 12. Overview of weather-related vulnerabilities in Swedish railway operations and infrastructure. 'X' indicates a determined relationship.
Adapted from Papers I & II.

	Operations	Switches	Signals	Tracks	Catenaries
Snow depth	X	X		X	
Temperature	X	X		X	X
Precipitation	X			X	X
Wind speed	X			X	X

Overall, in the Swedish context, railway operations and infrastructure were found to be primarily impacted by winter-related weather conditions (i.e., increased snow depth, low temperatures, and high wind speeds).

These findings are in line with previous research that shows that snow and freezing temperatures are major drivers of railway disruptions and infrastructure faults (Garmabaki et al., 2022; Kasraei & Garmabaki, 2024; Palmqvist et al., 2017; Soleimani-Chamkhorami et al., 2024; Stenström et al., 2012; Zakeri & Olsson; 2018), while heat-related risks such as track buckling are projected to increase under climate change (Dobney et al., 2009; Ferranti et al., 2016; Greenham et al., 2020). Heavy precipitation and flooding pose severe hazards, causing embankment failures and long service suspensions, and windstorms disrupt operations mainly through treefall and debris (Fabella & Szymczak, 2021; Palmqvist et al., 2017; Schriewer et al., 2025; Thaduri et al., 2021; Kasraei et al., 2024; Xia et al., 2013).

This thesis confirms these patterns for Sweden, and adds new insights by quantifying weather-impact thresholds, both nationally and by comparing two climate zones. In addition, these results provide a baseline for the current impacts of weather on Swedish railway operations and infrastructure, which can assist in implementing appropriate climate adaptation approaches.

Research Question 2

What are the challenges involved in adapting the railway sector to climate change within current governance structures in Sweden?

Papers IV & V

The second research question aimed to disentangle the challenges involved in adapting the railway sector to climate change. These are mainly related to legislation, resources, prioritisation, and knowledge. A summary of the challenges and how they manifest in Sweden is presented in Table 13.

Table 13. Identified challenges to climate adaptation and examples of how they manifest.
Adapted from Papers IV & V.

Challenge area	Swedish manifestation
Legislation	Fragmented governance; unclear mandates; misaligned policies; siloed responsibilities; contested funding; complex land-use laws
Resources	Uneven funding; limited staff in smaller municipalities; generalised risk maps; regional variation in capacity
Prioritisation	Climate adaptation seen as a future issue; slow investment processes; political cycles; rigid planning
Knowledge	Varying understanding of climate adaptation; gaps in climate modelling and risk assessment; confusion between climate adaptation and climate mitigation

Legislation

Climate adaptation in the Swedish railway sector is challenged by a fragmented governance structure, unclear mandates, and misaligned legal and policy frameworks. The current governance structure places primary responsibility for climate adaptation on property owners, which creates complications for linear infrastructure such as railways, which cross multiple jurisdictions and intersect with assets owned by various actors. This is particularly complex in urban areas; for example, there exist situations where mainline railway infrastructure is owned by the Swedish Transport Administration, a railway station by another actor, tram-track infrastructure by municipalities, and tram rolling stock by regional authorities. Such fragmentation leads to unclear risk ownership and complicates coordinated climate adaptation efforts.

This issue was especially evident in the case of Trelleborg, where the Swedish Transport Administration is responsible for mainline railway infrastructure, while the municipality has its own climate adaptation strategy. The lack of synergy between actors, who are each responsible for their own property, hinders long-term planning and integrated climate adaptation efforts. The interviewees and workshop participants in Papers IV and V emphasised that climate adaptation approaches, particularly those related to water management, often require cross-boundary collaboration. However, current legislation does not always support this. For example, the Swedish Transport Administration noted the challenges with the implementation of flood protection measures when neighbouring landowners are affected.

The risk of maladaptation was also raised, where protective approaches (typically structural measures) by one actor could inadvertently increase vulnerability for adjacent properties. This highlights the need for integrated planning and clear legal mandates. Within organisations, climate adaptation responsibilities are often siloed across departments, which can hinder timely action and strategic alignment. One municipality described waiting several years to secure internal support for assessing railway vulnerabilities to sea-level rise due to lack of coordination between planning and maintenance units.

Funding responsibilities can also be unclear. In some cases, municipalities invest in protective infrastructure, such as flood defences, that also benefit railway assets owned by other actors, especially the Swedish Transport Administration. This has raised concerns about fairness, especially when municipalities bear the cost of approaches that also happen to support infrastructure beyond their own responsibilities. There are currently no clear systems in place for sharing these costs or coordinating funding between different levels of government, which makes it harder to plan and implement joint climate adaptation efforts.

At the regional level, climate adaptation engagement is inconsistent. While the regions of Skåne, Stockholm, and Halland have planning responsibilities under the Planning and Building Act (PBL), climate adaptation is not explicitly mandated in regional development plans. Some regions have begun integrating climate adaptation into their approaches, but legislative ambiguity continues to limit their involvement. Moreover, regions often own infrastructure (e.g., metro lines or tram depots), which technically makes them responsible for climate adaptation, yet this is not reflected in current policy frameworks.

Several legal instruments further complicate climate adaptation planning. Ordinance 2018:1428 requires 32 governmental agencies to produce climate risk and vulnerability assessments, but interpretations vary. Some organisations already conduct general risk assessments and are unsure how climate-specific assessments should be integrated. Discussions are ongoing about merging these processes to reduce overlap and improve coordination. A key issue is that some agencies, such as the Swedish Transport Agency, are required to assess climate risks despite not owning infrastructure, making their role in climate adaptation unclear.

Differences in regulation between national railways and urban railways add another layer of complexity. National railways are subject to EU rules, while trams and metros are governed nationally, making alignment across systems difficult. Planning laws such as the PBL and the Environmental Code also pose challenges. Municipalities are responsible for identifying climate risks in land-use plans but can only act on land they own, limiting their ability to address risks affecting shared infrastructure. Detailed plans are costly and difficult to revise, which hinders responsiveness to evolving climate risks. In conservation areas, strict environmental regulations may restrict climate adaptation approaches, even when railway infrastructure is at risk, particularly for older assets built before current laws were enacted.

In summary, Sweden's decentralised and fragmented climate adaptation governance, combined with unclear mandates, siloed responsibilities, and contested funding arrangements, presents substantial barriers to implementing coherent and effective climate adaptation approaches for railway infrastructure.

Resources

Limited financial resources and personnel availability pose major challenges to climate adaptation in the railway sector. Larger municipalities often have dedicated teams working on climate adaptation, while smaller ones may rely on a single staff member managing multiple responsibilities. Within the Swedish Transport Administration, regional climate adaptation efforts also vary, with some regions assigning only one person to handle climate adaptation alongside other duties.

Access to data is another constraint. National agencies such as The Swedish Civil Defence and Resilience Agency and the Swedish Geotechnical Institute (SGI) produce risk maps to support local planning, but these are often too general for urban contexts. Larger organisations can conduct detailed assessments and collaborate directly with the Swedish Transport Administration, whereas smaller organisations may lack the expertise and tools needed to identify and respond to local risks due to lack of resources.

Funding disparities further complicate climate adaptation. County Administrative Boards have lost financial support to assist municipalities, despite retaining coordination responsibilities. This makes it harder for municipalities, especially those that own railway infrastructure, to access necessary support. Although the Swedish Transport Administration receives national climate adaptation funding, each region can decide how it is used, which can lead to mismatches between local needs and national priorities.

Prioritisation

Climate adaptation in the railway sector is often deprioritised due to competing interests, political uncertainty, and rigid planning processes. While national and EU-level goals promote increased railway use, investment in both new projects and maintenance has lagged in Sweden. Climate adaptation competes with priorities such as urban growth and is frequently viewed as a future concern, making it more challenging to justify funding, especially when climate risks are perceived as uncertain or abstract.

Political cycles and slow decision-making further complicate long-term planning. Railways, given their long lifespan, require forward-looking approaches, yet climate change and socioeconomic uncertainties, such as sea-level rise and future land use, make planning difficult, particularly when knowledge and capacity vary across organisations.

Within the Swedish Transport Administration, climate risk assessments are conducted nationally, but regional implementation varies. Some Swedish Transport Administration regions face greater challenges, especially when the number of required approaches exceeds the funding available, leading to difficult trade-offs and misalignment between local needs and national priorities.

The investment process itself is slow, and not in line with emerging climate risks. Decisions made today shape infrastructure for decades to come, yet current systems often lack the flexibility to incorporate climate adaptation. Several actors noted during interviews that by the time funding becomes available, the opportunity to act may have passed.

The Swedish Transport Administration handles climate adaptation differently for new construction and for maintenance. While future scenarios are considered in new builds, maintaining existing infrastructure is more complex, especially when dealing with water management and drainage. Lessons from past events, such as the 2018 heatwave and wildfires, prompted changes in maintenance practices, such as shifting work to cooler evening hours. These examples show that climate adaptation is slowly being integrated, but progress remains uneven.

In the case of Trelleborg, place attachment and resistance to change add another layer of complexity. The coast is central to the town's identity, and relocation is seen as a loss of status as a coastal city. Preferences for open landscapes and spacious living environments also make it difficult to consider building on agricultural land, which is valuable and important. As a result, relocation is viewed as a last resort, particularly by the Swedish Transport Administration, who would be responsible for moving the railway. The long-planned *Kuststad* development project has created a fixed vision for the area, making it difficult to consider alternative, long-term climate adaptation approaches such as retreat.

Knowledge

Knowledge is a cross-cutting challenge. Gaps or inconsistencies in knowledge can affect both the interpretation and implementation of legislation, be exacerbated by limited resources, and hinder understanding and prioritisation of climate adaptation. For instance, the definition of climate adaptation is often misunderstood, or varies between organisations. Moreover, there may be limited understanding of climate change projection models or risk assessments that could support climate adaptation decision-making. How an actor understands climate change and climate adaptation can shape their interpretation of legislation, and influence the way they choose to adapt. Additionally, organisations with fewer resources may find it more difficult to address these challenges. These gaps are compounded by fragmented knowledge sharing and limited coordination between actors, which restricts opportunities for learning and joint problem-solving. Uncertainty in climate projections and risk assessments further complicates decision-making, as actors face challenges with translating potentially complex data from many different sources into actionable approaches.

Concluding Remarks

The challenges identified are consistent with previous research, both in Sweden and internationally. In the Swedish context, fragmented governance and unclear responsibility for climate adaptation have been highlighted as major barriers (Knaggård et al., 2020; Rylenius & Hamza, 2024; Swedish Expert Council on Climate Adaptation, 2022). This fragmentation occurs both between and within organisations, where climate adaptation responsibilities are dispersed across departments, limiting coordination and strategic alignment – in line with the conclusions of recent studies (Barquet et al., 2024a, 2024b; Englund & Barquet, 2023; Rhinard et al., 2023).

Globally, similar patterns emerge: Persson et al. (2021) stress the need for clearly defined responsibilities, Malik and Ford (2024) highlight insufficient financing, Egdami et al. (2023) emphasise stronger actor coordination, and McClure and Baker (2018) note how competing priorities obstruct climate adaptation efforts.

Although the challenges identified are in line with previous research, few previous studies have been conducted for the railway sector. The results of this thesis indicate that the railway sector struggles with similar challenges to other sectors, and that in the Swedish context fragmentation manifests both internally, within organisations, and externally, between organisations. The results also highlight that climate adaptation of railway infrastructure cannot be looked at in isolation, and that it is entangled with other actors, such as local governments and other property owners.

Research Question 3

What lessons can be drawn from different climate adaptation approaches to inform climate resilience in Swedish railways?

Papers III, IV & VI

Different climate adaptation approaches can offer valuable insights for enhancing climate resilience in Swedish railways. *Research Questions 1* and *2* established a baseline understanding of weather-related impacts and current climate adaptation governance, providing a foundation for evaluating the relevance of various approaches. Based on this, several conclusions can be drawn that can inform more resilient planning and decision-making in the Swedish railway context.

Adopting Dynamic Planning Approaches

A key lesson for strengthening climate resilience in Swedish railways is the adoption of dynamic planning approaches, such as DAPP (see *Section 3.2.1*). Unlike traditional static methods, DAPP enables flexible, long-term decision-making by identifying climate adaptation tipping points and outlining multiple pathways that can be adjusted as new information emerges.

This approach was applied in Paper IV through a DAPP-light process in workshops held in Trelleborg, where participants explored different approaches, land-use constraints, and interdependencies between railway infrastructure and urban development. The workshops revealed several opportunities for dynamic adaptation. First, they created an arena for dialogue across governance levels, fostering a shared understanding of risks, goals, and trade-offs between actors. The workshops helped to visualise adaptation tipping points and pathways, enabling the participants to reflect on the timing and sequencing of approaches such as coastal protection phases and potential relocation of infrastructure. Such processes encourage long-term thinking beyond traditional planning horizons and support integrated approaches that align railway climate adaptation with broader urban development.

Second, the workshops also highlighted opportunities to reframe existing policies to enable incremental and flexible planning. For instance, Trelleborg's urban development plan already incorporates dynamic elements by planning incrementally. This includes reserving land for future coastal protection, and designing dykes with room for elevation. Although these incremental approaches align with DAPP principles and demonstrate how some municipalities in Sweden can work with dynamic planning, current legislation and rigid planning structures often hinder such flexibility.

Third, the DAPP-light process revealed windows for transformative change, such as integrating climate adaptation in comprehensive and detailed planning stages, and securing land early for future climate adaptation approaches. These opportunities highlight the potential for dynamic approaches to influence planning practices even within current governance structures, provided national legislation and intersectoral collaboration are strengthened.

These findings are in line with previous research that suggests that frameworks such as DAPP foster a shared understanding of risks, climate adaptation goals, and trade-offs (Bloemen et al., 2018; Carstens et al., 2019; Haasnoot et al., 2013; Kool et al., 2020; Lawrence et al., 2025). The application of the DAPP-light approach revealed that climate adaptation efforts are often fragmented across sectors, highlighting the challenges of siloed decision-making. This aligns with findings by Zorita et al. (2025), who emphasise the difficulties that arise when decisions are made within siloed sectoral boundaries, rather than through integrated planning.

Overall, while dynamic adaptation approaches such as DAPP or DAPP-light can effectively support long-term resilience planning, their success depends heavily on current governance structures. Climate adaptation must be integrated into broader urban and regional approaches, rather than being planned in isolation. This may help to avoid lock-ins and enhance flexibility in responding to evolving climate risks.

Real-Time Monitoring and Early-Warning Systems

Japanese railway companies use extensive networks of sensors and radar systems to monitor weather conditions. These include rainfall gauges, wind anemometers, river-level monitors, track thermometers, and snow-depth gauges. If a company does not have one of these sensors, they rely on forecasting information from the Japan Meteorological Agency. These systems support proactive decision-making, such as planned service suspensions and the activation of structural measures such as floodgates. The Greater Tokyo area has experienced more localised heavy rainfall events due to climate change, increasing the number of suspended services. While rainfall gauges are not perfect at detecting such localised extremes, they still provide valuable insights into conditions at specific railway assets, helping account for aspects such as microclimate.

The resilience of Swedish railways could be enhanced through investment in similar real-time monitoring technologies and developing protocols for early warnings. However, it is also important to recognise the differences in railway governance structures between Japan and Sweden. Japan’s vertically integrated structure means that most operators are private companies, which are responsible for managing infrastructure and operations. This potentially gives private companies greater flexibility in managing infrastructure and allocating resources. Operators in and around Tokyo typically manage fewer lines than the Swedish Transport

Administration, allowing them to concentrate revenue on maintenance and invest in weather-monitoring technology.

Paper III identified early-warning systems as one of the few non-structural measures discussed in the literature, underscoring the need for proactive monitoring and forecasting to complement structural interventions like drainage. In the Austrian context, Kellermann et al. (2016b) discussed the importance of early-warning systems, which are utilised by the ÖBB,[11] for risk management; similarly, Doll et al. (2014) note their role in reducing vulnerability. In Canada, efforts have been made to monitor slopes and wind using sensors (Kostianaia & Kostianoy, 2023).

Lessons from Practices Relating to Disaster Risk Reduction

Japan's long history of managing natural hazards has embedded strong practices relating to disaster risk reduction, which typically focus on short-term risk mitigation and aim to "engineer" hazards out of the system. Structural measures such as windbreak fences, floodgates, switch heaters, and slope-protection structures are widely used. This has also fostered a culture of learning from past events; for example, Typhoon 19 in 2019 prompted greater emphasis on protecting infrastructure assets after flooding damaged the Nagano train depot and decommissioned many Shinkansen[12] rolling stock wagons.

Although hazard impacts have declined in recent decades, climate change is reversing this trend, introducing uncertainties that traditional approaches may not fully address. Increasingly intense rainfall and typhoons require more flexible, long-term planning. Disaster risk reduction offers a foundation for climate adaptation, which must account for evolving and compound risks.

Governance also shapes resilience approaches. In Greater Tokyo, private railway companies prioritise safety and customer service, with planned suspensions have become more accepted, supported by the increase in remote working practices since COVID-19. Clear communication and strong research capacity underpin these efforts. Yet climate adaptation remains a relatively new concept, with limited awareness of long-term risks. The interviewees noted that companies focus on coping with current hazards rather than future climate change, reflecting short business horizons. Recent initiatives, such as the 2018 Climate Change Adaptation Act, signal a shift towards longer-term planning, though progress is slow.

Sweden can draw valuable conclusions from Japan's experience with disaster risk reduction to strengthen its own climate resilience. Disaster risk reduction provides a foundation for managing infrastructure risks; combining disaster risk reduction

[11] Österreichische Bundesbahnen (Austrian Federal Railways).

[12] High-speed rail.

with climate adaptation, and aligning these with governance frameworks, can support more holistic and forward-looking resilience approaches. As Europe moves towards increased securitisation, integrating climate risks into planning is essential to avoid overshadowing climate adaptation priorities.

Previous research highlights the benefits of linking disaster risk reduction and climate adaptation (Schipper, 2009; Becker et al., 2013; Majlingova & Kádár, 2025), although institutional silos and fragmented funding remain challenges (Dias et al., 2021). Aligning climate adaptation with broader frameworks, such as securitisation and risk governance (Barquet et al., 2024a; Rhinard et al., 2023), can help to ensure climate risks are not overlooked in resilience planning.

Integrate Structural and Non-Structural Approaches

Most climate adaptation approaches in the railway sector can be broadly categorised as either structural or non-structural. Structural measures include physical interventions such as seawalls, floodgates, wind fences, and slope-protection systems. Non-structural measures involve planning and operational changes, such as the use of DAPP, planned retreat, cancelling outdated building rights in flood-prone areas, and rescheduling maintenance to avoid heatwaves.

Research on climate adaptation approaches for flood risks remains limited, with only five out of 24 studies investigated in Paper III addressing approaches. Those five studies discussed structural measures, including drainage improvements and embankment protection, and non-structural measures, including risk mapping, reliable early-weather warning systems, and updating infrastructure codes. Doll et al. (2014) suggest that preventative maintenance could be a cost-effective adaptation strategy for alpine railways, while Cheetham et al. (2016) demonstrate the effectiveness of lower-cost approaches such as vegetation for embankment protection. Other approaches include prioritising vulnerable links (Hong et al., 2015) and protecting critical components to reduce delay propagation (Gonzva et al., 2017). Kellermann et al. (2016b) emphasise the importance of combining structural and non-structural measures within a risk-management cycle, as implemented by ÖBB in Austria. However, in Sweden, preventative maintenance faces challenges due to a persistent maintenance backlog (Rambøll, 2023) and scheduling conflicts with increasing operational demands (Ivina, 2024), making integrated planning even more challenging, yet critical.

In both the Swedish and Japanese contexts, climate adaptation discussions have largely centred on structural measures. For instance, Trelleborg's coastal climate adaptation plan relies on a seawall that is designed to be incrementally raised as sea-level projections change. While this introduces a dynamic element, it remains a contested solution due to the ecological impacts associated with hard infrastructure (Piggott-McKellar et al., 2020; Schoonees et al., 2019). Such measures are typically justified based on cost-efficiency grounds but often overlook local perspectives, which can increase the risk of maladaptation (Puig et al., 2025). Relocation, as a non-structural measure, was more difficult to discuss with actors as it is not widely accepted in Sweden (Göransson et al., 2023). In Japan, most climate adaptation efforts were found to be structural, with limited reference to non-structural measures. This reflects broader concerns raised by Eriksen et al. (2011), who argue that climate adaptation responses that are overly focused on technical or infrastructural fixes may overlook social justice and environmental integrity, and risk reinforcing existing vulnerabilities rather than addressing root causes. Similar concerns are raised by Puig et al. (2025), who advocate for a shift towards local perspectives and knowledge when deciding on climate adaptation approaches.

Overall, while structural measures like seawalls and floodgates are effective in the short term, their long-term viability is uncertain as climate risks intensify. For instance, a flood that is currently considered to be a 1-in-100-year event may become a 1-in-50-year event within a decade. This highlights the importance of non-structural approaches like DAPP, which support planning under uncertainty and allow for flexible adaptation pathways. Framing less conventional approaches, such as relocation, within long-term approaches may also increase their acceptability. Integrating both structural and non-structural measures can help to guide decisions about Sweden's future landscape, balancing physical protection with ecological and social considerations.

Concluding Remarks

Lessons drawn from different climate adaptation approaches highlight that climate resilience in Swedish railways requires a shift away from static approaches and towards more dynamic and integrated ones. Frameworks such as DAPP offer structured methods for sequencing actions over time and avoiding lock-ins, while real-time monitoring and early-warning systems provide crucial signals for operational decisions.

Lessons from other fields, such as disaster risk reduction, highlight the importance of adopting long-term perspectives in climate adaptation planning. In Japan, the strong foundation in disaster risk reduction reflects the value attached to a strong safety culture. Yet, railway operators often focus on coping with current conditions rather than planning for the future. Since disaster risk reduction predates climate adaptation and the two frequently operate on parallel, separate tracks, there is value in underpinning climate adaptation efforts within this field to ensure that no risks are overlooked. This need for integration is evident in Sweden as well, where other fields, such as crisis management and preparedness, remain siloed from climate adaptation work. Greater alignment between these streams can ensure greater collaboration, reduce duplication in work efforts, and ensure that climate risks are accounted for.

Finally, the integration of structural and non-structural measures is also important. While structural measures help to maintain and protect existing infrastructure, non-structural measures provide flexibility and support long-term planning, enabling climate adaptation to take evolving climate conditions and socio-economic dynamics into account. Additionally, they can help to identify locations for new infrastructure that avoid dependence on structural measures for protection.

Taken together, these insights emphasise that climate adaptation for railways cannot rely solely on engineering approaches or isolated planning efforts. It must be embedded within broader governance frameworks, supported by collaboration across sectors. This integration is important for ensuring that Swedish railways remain reliable and resilient under evolving climate risks.

10 Discussion

10.1 From Present Risks to Future Resilience

The findings of this thesis reveal that the Swedish railway sector is currently most impacted by winter conditions, i.e. low temperatures, high snow depths, and strong winds. These results highlight the operational and infrastructural impacts of weather today, but it is equally important to consider how these impacts may shift in response to climate change.

Climate projections suggest that Sweden will experience increased precipitation, especially during the winter months (Sjökvist et al., 2025). In some regions, this may result in greater snowfall, while in others, rising temperatures could lead to more rainfall instead. Overall, higher precipitation levels may cause more frequent disruptions, particularly during extreme events that could trigger flooding. For infrastructure, snow cover persisting for less time in some areas may reduce snow-related faults, whereas increased rainfall in other regions could lead to more flooding-related damage (Thaduri et al., 2021).

Mean annual temperatures are also expected to rise, with the most significant increases occurring in winter (Sjökvist et al., 2025). Consequently, disruptions and faults associated with cold conditions are likely to decrease. However, warmer summer temperatures may lead to more heat-related disruptions and infrastructure failures, especially in southern Sweden.

Future wind patterns are more difficult to predict. Thaduri et al. (2021) suggest that rising sea surface temperatures could increase storm frequency and intensity due to higher levels of water vapour. At the same time, warming seas may reduce the formation of low-pressure systems in the northern hemisphere. If storm intensity and frequency do increase, both operational disruptions and infrastructure faults are likely to become more severe. This will be particularly the case in coastal and southern regions, where exposure to high wind speeds is greater.

Sjökvist et al. (2025) identify sea-level rise as a major concern for southern Sweden. This may lead to increased disruptions and infrastructure faults, both during coastal flooding events and through slower processes such as gradual sea-level rise and erosion. Railway infrastructure located near coastlines is particularly vulnerable. These risks highlight the need for long-term climate adaptation approaches that account for both sudden and incremental changes in coastal conditions.

Overall, the findings highlight that climate change is likely to shift the current impacts of weather on the Swedish railway system. While winter-related hazards such as snow, low temperatures, and strong winds are the current main problems, future risks are expected to stem increasingly from high temperatures, heavy precipitation, and coastal flooding. These evolving risks highlight the importance of transitioning from static, short-term climate adaptation to more dynamic adaptation with long-term perspectives. This transition also requires recognising that climate adaptation of railway infrastructure cannot be planned in isolation, and must be embedded within broader frameworks of urban development and governance in order to avoid maladaptation and ensure long-term climate adaptation.

Adapting to climate change will not only help to cope with future risks, but also enhance the overall resilience of the railway system. This resilience should be understood as dynamic and adaptive, where the definition of "normal" shifts over time in response to changing climate conditions (Amekudzi-Kennedy et al., 2023; Markolf et al., 2019; Norström et al., 2025). Rather than aiming to maintain a fixed state of infrastructure or operation, climate adaptation should support the system's ability to evolve, absorb shocks, and recover from disruptions. This perspective encourages flexible planning, iterative learning, and the integration of anticipatory approaches that reflect the changing nature of climate risks.

This transition also requires drawing on broader lessons, such as the integration of structural and non-structural measures, the value of real-time monitoring systems, and the incorporation of practices such as disaster risk reduction. One important insight is that climate adaptation planning must also consider operational consequences, particularly the potential need to suspend train services in anticipation of extreme weather. While such suspensions carry significant implications for service continuity and passenger mobility, they may become a necessary safety measure. In Japan, planned service suspensions are increasingly used as a proactive strategy in response to climate change, reflecting a shift towards anticipatory risk management (Paper VI). However, such transitions must also take into account the challenges within current governance structures identified; these include fragmented responsibilities, limited resources, knowledge gaps, and competing priorities, and can hinder the implementation of climate adaptation approaches.

10.2 Contributions of the Thesis

This thesis makes several contributions to both research and practice. Specifically, I have: i) provided empirical evidence on the impacts of weather on both railway operations and infrastructure in Sweden, establishing a baseline for current impacts; ii) offered insights for asset managers to support resilience planning and inform climate adaptation approaches, including the identification of weather-related thresholds and infrastructure-specific risks; iii) explored a range of climate adaptation approaches, such as DAPP, and assessed their opportunities and limitations in the railway context; iv) disentangled the current challenges to climate adaptation within current governance structures; and v) used international perspectives, primarily the case study of Japan, to highlight potential transferable practices for increasing the climate resilience of Swedish railways.

This thesis addresses a notable gap in the literature: while there is growing research on the impacts of weather and climate change on railway operations and infrastructure, there remains a lack of systematic understanding of climate risks (European Union Agency for Railways, 2024). Moreover, existing studies often overlook the influence of governance structures on the capacity to adapt, and few explore various climate adaptation approaches and how they can be applied in the railway sector.

To address this, I adopted a holistic approach that combined quantitative and qualitative methods, and drew on plural epistemologies to examine both the biophysical impacts and governance processes surrounding climate adaptation. The thesis highlights the complexity of adapting the Swedish railway sector to climate change. Once a baseline of current climate risks is established, it is essential to understand not only which climate adaptation approaches are feasible, but also the barriers to their implementation.

Even if global efforts to reduce greenhouse gas emissions succeed, societal climate adaptation to current and future climate risks remains urgent. This is particularly true for the railway sector, which plays a key role in decarbonising transport and enabling a modal shift. Ensuring that railway services are safe, reliable, and resilient to climate change is essential to supporting this transition, but also to guaranteeing equitable access to sustainable transportation.

10.3 Limitations and Future Research

This thesis offers an empirical baseline for understanding how Swedish railways are impacted by present-day weather, how governance structures shape the ability of Swedish railways to adapt to changing climate, and how different climate adaptation approaches could enhance resilience. As discussed in *Section 10.1*, climate risks are expected to shift from winter-related impacts to ones associated with heat and extreme rainfall.

Limitations arise from the methodological and data constraints highlighted in *Sections 6.0* and *7.0,* such as the linkage of weather to railway stations and the general quality of the data. Overall, the mixed-methods approach adopted in this thesis enabled a holistic understanding of climate adaptation in the railway sector to be obtained, but it also required a balance and trade-off of different methods.

Building on the limitations of this thesis and *Section 10.1*, several future research directions can be pointed out. The first of these is to consider weather variables in combination, for instance low precipitation and high temperatures leading to drought, rather than separately. In addition, in order to capture the effects of future climate change, the operational and fault-rate thresholds identified in this thesis could be linked with climate change projection data to understand climate change impacts on railway operations and infrastructure.

This thesis focuses on identifying barriers to climate adaptation and lessons that can be learned from climate adaptation approaches, but it does not evaluate the outcomes nor effectiveness of implemented climate adaptation approaches. Future research should aim to bridge the gap between climate adaptation strategy and implementation, as suggested by frameworks such as RailAdapt (Quinn et al., 2018). In addition, the DAPP approach could support this by enabling the monitoring of adaptation pathways and facilitating longer-term, more flexible planning.

Future research could further explore comparative analyses of climate adaptation approaches across countries, particularly in order to inform maintenance practices and the integration of climate adaptation with related domains such as disaster risk reduction. Investigating the interlinkages between climate adaptation and transport equity or justice would also be valuable, for instance by examining how extreme weather-related railway closures affect accessibility and mobility for different population groups. This also highlights the need to assess and develop more socially inclusive climate adaptation approaches. For example, certain types of early warning systems may be less accessible for people with hearing or visual impairments if not designed inclusively. Ensuring equitable access to reliable public transport is essential, especially in the context of accelerating efforts to reduce carbon emissions; and overall contributes to social, economic, and environmental sustainability.

Finally, future research could examine the roles of culture and values in climate adaptation decision-making, as well as how different adaptation approaches may, in turn, influence or be influenced by cultural practices, societal values, and interactions with elements such as biodiversity.

11 Policy Recommendations

This thesis could inform policy-making, particularly in relation to infrastructure and asset owners such as the Swedish Transport Administration. However, the findings are also relevant for other transport modes, and some insights may be valuable for practitioners who work with climate adaptation from a broader urban-planning perspective, especially regarding the challenges relating to climate adaptation and the potential of dynamic approaches or non-structural measures, such as DAPP. Finally, the findings of this thesis are also relevant for policymakers and politicians who allocate budgets to authorities such as the Swedish Transport Administration and influence political prioritisation. Their decisions play a crucial role in enabling long-term investment in climate adaptation and ensuring that resilience approaches are adequately funded and implemented.

To create clearer and more comprehensive polices, I propose that policymakers should consider the following seven points, each of which relate to enhancing climate adaptation in the railway sector in Sweden.

Improving Data Collection and Monitoring

As mentioned in *Section 6.2.3*, the lack of systematic reporting on infrastructure faults presents challenges for quantifying the impacts of weather on railway infrastructure and understanding the underlying causes of such failures. Similar challenges have been identified in the Swedish context by Mirzanamadi et al. (2024), and at the European level by the European Union Agency for Railways (2024). Systematic reporting would not only improve the identification of weather-related faults but also strengthen infrastructure resilience more broadly, by supporting more targeted and effective maintenance approaches.

As addressed in *Research Question 3*, Swedish railway infrastructure managers could invest in real-time track-level monitoring systems, similar to practices in Japan, or on-board sensors to anticipate weather-related impacts and inform early warnings, decision-making, and operational responses such as planned service suspensions. While such systems may be costly, they can significantly improve preparedness, and should be aligned with national climate adaptation priorities and existing collaborations. For instance, there may be opportunities to collaborate with other authorities, such as SMHI, which has expertise in real-time monitoring and would also benefit from access to such data.

Enhance Knowledge Sharing and Coordination

During the research process for Papers IV and V, it became evident that there are numerous forums and platforms for sharing information on climate adaptation in Sweden. Examples include the Authorities Network for Climate Adaptation (*Myndighetsnätverket för klimatanpassning*) and regional coastal collaborations such as *Regional kustsamverkan* and *Kustmöte*. While these collaborative platforms are valuable, more effort is needed to ensure that the knowledge generated at national and agency levels (such as by SGI, SMHI, and the Swedish Transport Administration) is effectively translated into local action. For instance, both SGI and the Swedish Transport Administration have geotechnical experts, making it important that technical knowledge is not only shared but also implemented in practice. This would also help to ensure that technical experts are included alongside climate adaptation specialists in relevant discussions and decision-making processes.

The Swedish Transport Administration already conducts climate risk and vulnerability assessments for transport infrastructure. There is potential for the administration to play a stronger role in supporting municipalities and regions that own or manage railway infrastructure by sharing tools, methods, and transport-specific expertise that may be lacking at the local and regional level. Similarly, there is potential for increasing data and knowledge sharing between the Swedish Transport Administration and the Swedish Transport Agency in order to increase the safety of railways as the climate changes.

Acknowledge Climate Adaptation as a Prioritised Issue

National agencies, regional authorities, County Administrative Boards, and municipalities are doing the best they can within the constraints of limited resources. However, the national government should place greater emphasis on prioritising not only climate adaptation but also rail transport more broadly.

Sweden is often regarded as a leader in environmental, economic, and social sustainability. However, there is a growing disconnect between its sustainability ambitions and the realities of policy implementation (Ergon et al., 2025; Magnusdottir & Widengård, 2025), particularly in the areas of transport infrastructure and climate adaptation. To support all aspects of sustainability, it is essential to ensure that railways are reliable, safe, and accessible. This requires recognising that climate change is not a distant future issue, but one that is already impacting infrastructure today and demands immediate action.

Foster Synergies Across Related Policy Domains

In a world increasingly focused on securitisation and preparedness, it is important to ensure that climate risks are not overlooked. Greater integration between policy and research domains such as climate adaptation, disaster risk reduction, securitisation, and critical infrastructure resilience is needed. Aligning these agendas under a shared vision of long-term resilience can help to address competing priorities and make more efficient use of limited resources.

Paper V revealed that many organisations are required to produce both climate risk and vulnerability assessments, as well as more general risk assessments, and these processes could be better integrated. Additionally, the European Union's Critical Entities Resilience Directive (Directive EU 2022/2557) emphasises that all hazards (natural, man-made, intentional, or accidental) should be addressed in a comprehensive manner in order to strengthen the resilience of critical infrastructure. This highlights the strong potential for creating shared knowledge and synergies across policy domains, ultimately supporting more coherent and effective climate adaptation approaches.

Promote Non-Structural and Dynamic Adaptation Approaches

Although structural approaches have an important role to play – particularly in the railway sector, where interventions such as sufficient drainage are often necessary – it is equally important to consider non-structural and more dynamic approaches that account for the uncertainties associated with climate change.

There is a need to move away from the mindset that we can "engineer our way out" of climate risks solely through hard infrastructure, such as seawalls, which may also compromise ecological systems. Climate adaptation decisions often involve trade-offs, and it is essential to evaluate which approaches are most appropriate in a given context, including their social implications. In this regard, attention to socially inclusive adaptation approaches is important to ensure that interventions do not disproportionately disadvantage certain population groups.

Non-structural approaches such as planned retreat, adaptive land-use zoning, and early-warning systems should be explored alongside traditional structural interventions.

Dynamic approaches such as DAPP can support this shift by enabling flexible, long-term decision-making under uncertainty, and facilitating the integration of both structural and non-structural measures.

Embedding Railway Climate Adaptation in Broader Urban Development

The findings of this thesis highlight that climate adaptation cannot be treated as an isolated process, and must instead be integrated into broader urban planning. Currently, the responsibility for climate adaptation in Sweden falls on individual property owners. This can be challenging in areas where multiple property owners interact, intersect, and share exposure to climate risks. In such contexts, fragmented actions can lead to conflicting priorities, disputes over who should bear the costs of approaches that may not benefit all parties equally, and even maladaptation.

Therefore, strengthening collaboration between actors is essential. This requires governance arrangements that enable joint planning, clarifying responsibilities, and aligning climate adaptation approaches with long-term development objectives, to ensure that climate resilience and climate adaptation are embedded in overall planning processes rather than treated in isolation.

Climate Adaptation Beyond Water-Related Risks

Today in Sweden, discussions on climate adaptation are largely dominated by water-related risks. For example, municipalities must identify areas at risk of flooding, landslides, and erosion in their comprehensive plans. While flooding will remain a major concern, it is equally important to address other emerging risks. This is particularly relevant for railway infrastructure, which is affected by hazards in ways that differ from other types of infrastructure.

Going forward, risks such as heat, zero-crossing days, and extreme cold should be considered. Although the Swedish Transport Administration includes these in its climate risk and vulnerability assessments, other railway infrastructure owners may find challenges in doing so due to limited resources, competing priorities, and lack of data.

12 Conclusion

Climate change is intensifying extreme weather events such as heatwaves, storms, and floods, posing growing risks to transport infrastructure systems. Trains are an important critical infrastructure, and play a key role in the energy transition by providing a low-carbon, energy-efficient mode of transport. However, railways are particularly vulnerable to the effects of climate change due to their long lifespan and limited options for rerouting. While climate mitigation has received significant attention, it is no longer sufficient. Addressing the risks posed by existing and projected climate impacts requires urgent climate adaptation to ensure the resilience of railway systems.

Despite this urgency, there remains limited understanding of how climate adaptation is approached and implemented in the railway sector. In particular, few studies adopt a holistic perspective that integrates biophysical impacts and the socio-political processes shaping climate adaptation. Research gaps persist regarding how governance structures, climate adaptation approaches, and operational practices enable or constrain climate adaptation.

To address this gap, this thesis advances the understanding of climate adaptation decision-making processes for the railway sector, using the Swedish context as a lens to examine how climate adaptation is approached and implemented in practice. The following research questions have been answered in order to achieve this aim: i) What are the impacts of weather on railway operations and infrastructure? ii) What are the challenges involved in adapting the railway sector to climate change within current governance structures? iii) What lessons can be drawn from different climate adaptation approaches to inform climate resilience in Swedish railways?

Adverse weather conditions can lead to service disruptions, infrastructure faults, and increased maintenance costs. Snow depth, temperature, precipitation, and wind speed all impact railways operations, albeit to varying degrees. The most prominent relationships are between disruptions and snow depth, disruptions and low temperatures, and disruptions and high wind speeds. Regarding infrastructure assets (in this thesis, switches, signals, tracks, and catenaries), track assets are the asset category that is most vulnerable to all types of weather, while signals are the most resilient asset. Overall, in the Swedish context, both railway operations and infrastructure are most influenced by winter-related weather conditions, namely high snow depths, low temperatures, and high wind speeds. However, due to climate change, these are expected to shift towards risks associated with high temperatures and increased rainfall, raising the likelihood of flooding and heat-related failures.

The main challenges to adapting railway infrastructure to climate change within current governance structures relate to legislation, resources, prioritisation, and knowledge. Fragmented responsibilities and unclear mandates create coordination gaps, while funding constraints and uneven organisational capacity limit implementation. Climate adaptation is often deprioritised in favour of short-term objectives, and persistent knowledge gaps – such as confusion regarding the difference between climate adaptation and climate mitigation – further complicate decision-making. These barriers highlight the need for clearer governance frameworks, improved resource allocation, and stronger knowledge-sharing. The identified barriers also mean that climate adaptation efforts are fragmented, with railway climate adaptation rarely integrated into broader infrastructure and land-use planning despite shared climate risks across interconnected systems.

Lessons drawn from different climate adaptation approaches include the value of adopting dynamic planning approaches, investing in real-time monitoring and early-warning systems, learning from practices relating to disaster risk reduction, and integrating structural and non-structural approaches. Dynamic approaches such as DAPP can support long-term decision-making under uncertainty, which is particularly relevant for railway infrastructure with a long lifespan. Real-time monitoring is essential for short-term operational decisions, while disaster risk reduction offers a foundation for embedding climate adaptation into planning. Although structural approaches remain important, non-structural approaches, such as planned retreat and cancelling of building rights on floodplains, should be considered and integrated.

Overall, adapting railways to climate change calls for a shift in mindset, improved coordination across governance levels, and a commitment to both short-term preparedness and long-term climate resilience. By embracing these changes, railways can continue to play a central role in the transition to sustainable transport, offering a resilient and accessible network for future generations while advancing environmental, economic, and social sustainability.

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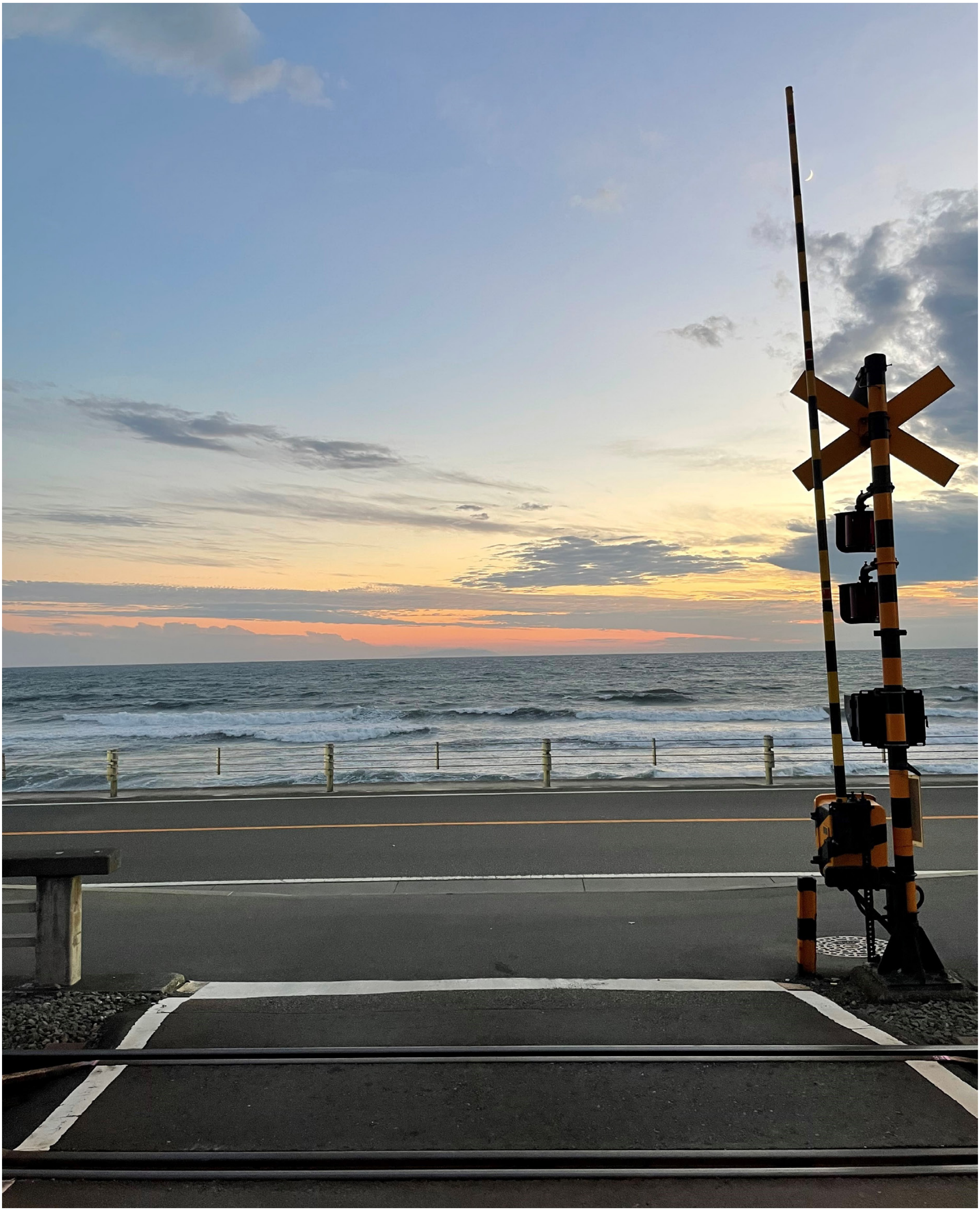

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