ADAPTING TO THE IMPACTS POSED BY CLIMATE CHANGE ON TRANSPORTATION SYSTEMS

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Abstract

With the occurrence of increasingly frequent and severe climate-related events, adapting to the impacts posed by climate change has been a pivotal research topic influencing transport operation, infrastructure, planning and policymaking in recent decades. As most studies on climate change still focus on its short-term impacts, there is insufficient research on how to systematically adapt to the impacts of climate change on transportation, in particular in an integrated inland transport system, e.g., roads and railways. Hence, an assessment of the long-term risks posed by climate change on transportation systems is urgently required.

The primary purpose of this thesis is to explore the general picture of how the impacts of climate change can be adapted in the UK transport systems. A quantitative analysis mainly involves an innovative decision aiding tool: the Fuzzy Bayesian Reasoning (FBR) model. This hybrid model is capable of tackling the existing issues in risks assessment, such as unavailability or incompleteness of climate risk data, synthesis of inconsistent risk and costs expressions and challenges in estimation and selection of risk scenarios. The modelling is followed by a nationwide survey among the road and rail stakeholders in the UK, which not only further confirms the feasibility of the FBR model but also illustrates an overall view of current climate adaptation issues. Afterwards, a comparative study through interviewing five domain experts in the UK transport industry is undertaken, which covers four representative cases. It reveals both opportunities and under-reached issues in climate adaptation planning.

This research re-emphasises the importance of raising the awareness of the community's consideration of the risks of climate change on transport systems and strives for effective risk analysis and adaptation planning to cope with them. The outcomes from this thesis including the critical literature review, advanced FBR model, empirical multi-mode case studies and comparative analyses, have provided transport stakeholders with a pioneer trail in systematically evaluating climate risks and adaptation strategies in the British transport systems. This work has great potential to be tailored for broader applications, offering workable recommendations and global references for climate adaptation on other transportation systems and regions.

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Abbreviations

APF	Adaptation Policy Framework
ARP2	The second round of the Adaptation Reporting Power
BNs	Bayesian Networks
BIM	Building Information Modelling
CEOs	Chief Executive Officers
CIA	Climate Impact Assessment
CIMO	Context, Intervention, Mechanisms and Outcome
CO_2	Carbon dioxide
COP21	The twenty-first session of the Conference of the Parties
CCAPPTIA	Climate Change and Adaptation Planning for Ports, Transportation Infrastructures, and the Arctic
DCC	Devon County Council
DEFRA	Department for Environment, Food & Rural Affairs
DfT	Department for Transport
DoB	Degrees of Belief
EA	Environment Agency
ER	Evidential Reasoning
F-AHP	Fuzzy Analytic Hierarchy Process
FBR	Fuzzy Bayesian Reasoning
FHWA	Federal Highway Administration
FMEA	Failure Mode and Effect Analysis
FRB	Fuzzy Rule-Based
FRB-ER	Fuzzy-Rule-Based Evidential Reasoning
F-TOPSIS	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution
GEM	General Equilibrium Model
GHGs	Greenhouse Gases
GIS	Geographic Information System
HAAFM	Highways Agency's Adaptation Framework Model
HE	Highways England
IDS	Intrusion Detection System

IPCC	Intergovernmental Panel on Climate Change
KPIs	Key Performance Indicators
LCC	Life-Cycle Cost
LCCP	London Climate Change Partnership
MCDM	Multi-Criteria Decision Making
METEX	METeorological data EXplorer
MMR	Mix-Method Research
NGOs	Non-Governmental Organizations
NR	Network Rail
NRCNA	National Research Council of the National Academies
ORR	Office of Road and Rail
QCA	Qualitative Comparative Analysis
RCPs	Representative Concentration Pathways
RFG	Rail Freight Group
RIA	Railway Industry Association
RVW	The Advisory Council for Transport, Public Works and Water Management
TCWR	Tibbitt to Contwoyto Winter Road
TE2100	Thames Estuary 2100
TfGM	Transport for Greater Manchester
TfL	Transport for London
TRB	Transportation Research Board
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UNCTAD	United Nations Conference on Trade and Development
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Program
UNISDR	United Nations Office for Disaster Risk Reduction
UKRLG	UK Roads Liaison Group
WRCC	Weather Resilience & Climate Change
WSI	Winter Severity Index

Chapter 1 Introduction

This chapter briefly introduces the research background, and sets the scene for the thesis through presenting its research questions, research objectives, scope, the context of each chapter, and thesis structure.

1.1 Research Background

Climate change implies alterations in the earth's "pattern of weather, meaning the averages, the extremes, the timing, the spatial distribution not only of hot and cold, but also of cloudy and clear, humid and dry, drizzle and downpours, snowfall, snowpack, snowmelt, blizzards, tornados, and typhoons" (Holdren, 2008). It is evident that the climate has changed considerably especially in the past five to ten decades: the earth has warmer during this period, than at any other time in human history (Asian Development Bank, 2013). From 1906 to 2005, global average surface temperatures have risen by 0.75-0.99 °C (Intergovernmental Panel on Climate Change (IPCC), 2018). The domain scientists from over 100 countries have made a consensus that warming of the climate system and many of these observed changes are "unprecedented over decades to millennia" (IPCC, 2013). The latest report from the Intergovernmental Panel on Climate Change (2014a) also indicated the unequivocal trend that the climate system has been warming since the middle of the twentieth century, which can be observed from the increasingly warmed atmosphere and ocean, the diminished amounts of snow and ice and raised sea level. Global warming causes a series of diversified global effects which include changes in temperature, precipitation and river runoff, sea levels, drought, wind patterns, ecosystem health, species distributions and phenology, food production, and human health (IPCC, 2007a).

With the occurrence of more frequent and severe events related to climate change, adapting to the risks posed by climate change has been a pivotal research topic influencing transport operation, infrastructure, planning and policies in recent years (e.g. Beiler et al., 2016; Moretti & Loprencipe, 2018). As a result, climate change has been an interdisciplinary frontier study. The transport infrastructure and operations are seriously threatened challenged by existing variability in climate. The transport-related activities are vulnerable to heterogeneous weather extremes, which include variations in temperature, precipitation, winds, sea-level/other-water levels, thunderstorms, fog period or visibility, frost and thaw (e.g., Wang *et al*., 2019; Schweikert *et al*., 2014; Love *et al*., 2010). To effectively tackle the risks of climate change on railways, several scholars have proposed corresponding adaptation strategies and applied them to many case studies (e.g. Strauch et al., 2015; Dobney et al., 2009; 2010). It is the time to conduct a rigorous survey on the studies to find the learnt lessons for cross-referencing among different transport modes and explore prominent research challenges to shift the research focus to the most relevant emerging topics.

It is worth mentioning that the strategies to tackle climate change are generally divided into adaptation and mitigation strategies. According to the definition from the IPCC Fourth Assessment Report (IPCC, 2007a), adaptation to climate change is *an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*. Compared with the mitigation strategies which aim to minimise emissions of greenhouse gases (GHGs), adaptation strategies accept the status quo of climate change and strive to strengthen resilience of transport systems to protect infrastructure and operations from severe damages (United Nations Environment Program (UNEP), 2010; Ng et al., 2018). Predominant interests in the early studies of climate change and transportation were on how to reduce the effects of transportation systems on climate change, including the reduction of GHGs from the transport sector to the air (e.g., Patterson et al., 2008; Geels, 2012; Schwanen et al., 2012; Kishimoto et al., 2017; Hendricks et al., 2018). Accordingly, a majority of research emphasis was on the development of the mitigation strategies (e.g., alternative fuels, congestion pricing, and transportation demand management techniques), and paid less attention to the adaptation strategies (e.g., altering land use, infrastructure and development patterns, etc.), as well as the actual rate of climate change and its impacts (e.g., Oswald, 2011).

Given that climate change is an irreversible process which could pose catastrophic risks to human welfare (Keohane & Victor, 2010), the study of climate change is gradually moving away from pure mitigation towards a strategy of addressing mitigation and adaptation simultaneously (Ng et al., 2016). Climate change studies in the context of transportation are not exceptional from such a tendency. This has widespread implications, for transport design, planning, operations and maintenance, materials specifications, network and vehicle function, liability and insurance, user behaviour, and emergency evacuation, with several studies in the public domain concerned with the impacts of climate change on transportation systems (Taylor & Philp, 2010; Hooper, 2013; Meyer et al., 2014; Chinowsky et al., 2015; Olmsted et al., 2017). Most of them study certain regions and transport modes, typically on the road, rail and port; the actual impacts of climate change on transport infrastructure vary on the modes of transportation, geographic location and conditions of events occurrence (Suarez et al. 2005).

Prior literature concerning the impacts on transportation systems reports studies that have been developed at both a national and multi-regional scale. In developed countries, such as the UK, the US and Canada, a considerable number of studies have been carried out to investigate or assess the impacts of climate change on transportation (e.g., Pant et al., 2016; Wang et al., 2016; National Research Council of the National Academies (NRCNA), 2008; Regmi & Hanaoka, 2011). These studies were not limited to the assessment and prediction of the impacts of climate change, but also the costs of mitigation and adaptation when corresponding measures are involved. However, most studies on climate change focused on short-term impacts. Furthermore, few of the studies deal with transport adaptation to climate change in developing countries (e.g. Koetse & Rietveld, 2009). Existing studies focusing on climate adaptation of the transport sector are still piecemeal (e.g., Eisenack et al., 2012). Considering that the phenomena of climate change might be complex and diverse enough to be expressed differently across different geographies, it is necessary to undertake country-specific assessments and quantifications for climate change impacts, and climate adaptation strategies to improve the resilience of a transportation system.

A critical early step in establishing a comprehensive climate adaptation framework is to assess climate risks, including the types and levels, so as to strengthen the resilience and robustness of transport infrastructure and operations to these risks (Meyer et al., 2014). Many traditional risk assessment approaches have been extensively applied to perform a risk assessment in different sectors. Current research on climate-related risk analysis has focussed on interpreting and identifying the existing and future threats, estimating the level of risk as well as determining the level of uncertainties (Yang et al., 2015). Nevertheless, in assessing the threat of landslides, for example, only a limited number of studies have been undertaken to investigate the cost of damage or quantitative analysis of the effects of adaptation, probably because of the difficulties of collecting reliable data and of evaluating the effect of adaptation using an objective approach (Kim et al., 2018). In the meantime, when the expressions of risk and costs are inconsistent, it is challenging to combine risk and cost results to make rational decisions (Yang et al., 2015). Owing to the inadequacy of historical or statistical data on climate risks assessment, the high-level uncertainties in data (United Nations Conference on Trade and Development (UNCTAD), 2012) make traditional probabilistic risk analysis methods, such as Quantitative Risk Assessment (Nicolet-Monnier & Ghenorghe, 1996; Urciuoli, 2011) unsuited for climate adaptation study at this stage (Yang et al., 2018).

Some efforts have been put to address these challenges through combining fuzzy logic and Bayesian networks (BNs) approaches to model subjective input data (Bott & Eisenhawer, 2002; Baksh et al., 2018), as well as combining fuzzy set modelling and evidential reasoning (ER) (e.g., Wang et al., 2018a) to realise climate risk and adaptation cost synthesis to minimise information loss (Wang et al., 1996).

Hitherto, fuzzy set and BNs methods have been applied to climate risk assessment on ports in several pioneering studies (e.g., Greater China (Yang et al., 2015; 2016)), by a group of scholars. For instance, they exerted a 'discrete fuzzy set approach' and a 'fuzzy set manipulation' to accommodate subjective data in climate risk analysis (Ng et al., 2013; Yang et al., 2015; 2016; 2018a). Through modelling subjective linguistic variables extracting from the stakeholders' opinions, climate risks were evaluated and projected based on their occurrence frequencies, the severity of consequences and timeframes of climate threats.

Although these studies have shown much initial promise, practitioners have raised concerns, including the difficulty of accurately evaluating the severity of consequence of climate change, and a lack of empirical evidence on the feasibility of the fuzzy Bayesian modelling in adopting it from seaports to another transport context. More specifically, in previous studies (e.g., Yang et al., 2018a), risk variables were defined in a high level, at which domain experts in some cases felt insufficiently confident to carry out their evaluations. For instance, the consequences of climate change on many occasions need to be further interpreted from three perspectives, including economic loss, human injuries/deaths, and environmental damage. With reference to risk parameters, previous studies have mainly investigated the impacts of risky external events to infrastructure (e.g., the likelihood and severity of consequence) but barely taken into account the resilience of the infrastructure itself. Also, previous fuzzy Bayesian modelling studies have only been applied in the port area; a systematic climate adaptation framework for the road and railway systems has not been established.

Furthermore, another research challenge is the uncertain nature of climate change itself, making it challenging to select and develop appropriate risk (low-risk, medium-risk or high-risk) scenarios in which the analysis of diverse scenarios has been proven to enhance the resilience for unexpected changes (such as in a city (Mikovits et al., 2018)). This issue can be addressed by collecting real survey data from transport experts to calibrate and assign the weights of the defined risk parameters so that the proposed model can be tailored and applied in different circumstances (Wu et al., 2013). It suggests that more complex decision models should be tested to strengthen the robustness of the risk model. Meanwhile, transport planners should take account of diverse climate threats and make a customised risk assessment based on ongoing climate trend observations in a specific region, which needs the input from continuous data collection and innovation of advanced models based on local conditions (Walker et al., 2011).

From the perspective of adaptation planning, it is noticed that many adaptation plans (e.g., in the UK) are not explicitly designed for responding to impacts of climate change but for the co-benefits of other activities such as demands of infrastructure investment and cost savings (Tompkins et al., 2010). A pressing issue on adaptation is that current transportation investment and planning could not address climate change impacts adequately. Firstly, the relatively irreversible investments in infrastructure might fail to reach their expected effects and profits with the accelerating pace of climate change, where predicted short lifetimes of transportation infrastructure might be problematic as more frequent and severe climate events occur (Reilly & Schimmelpfennig, 2000). Secondly, relatively short planning cycles (typically 5-10 years) do not match infrastructure lifespans (typically more than 50 years), which leads to malfunctioning of transport networks (ICF International, 2008; Kintisch, 2008; Koetse & Rietveld, 2012).

The above analysis indicates that transport planners urgently require a general, harmonised procedure for developing long-term climate change adaptation planning in transportation systems. This thesis proposes such a procedure through undertaking both quantitative and qualitative analyses on climate risks and adaptation plans to offer a significant contribution to innovations in climate adaptation methods, in facilitating economic development and investment within the context of transportation planning.

To achieve this, a hybrid of Fuzzy Bayesian Reasoning (FBR) and ER approaches is applied, to quantify the risks posed by climate change with the introduction of new risk parameters to better incorporate raw data for rational results. Furthermore, the developed FBR model is validated by the UK road and rail transport systems, through conducting a nationwide survey amongst 20 rail and 19 road stakeholders. This application reveals the current and predicted future climate risks facing the sector in the UK. Finally, by combining a review of the literature and national reports as well as in-depth interviews in four case studies with relevant transport stakeholders, this research discloses the existing and potential adaptation planning issues and provides useful recommendations for the UK transportation systems. The outcomes of this thesis can help fulfil the research need of transport planners, decision-makers and industrial professionals on how to rationally design adaptation plans and implement adaptation measures and practices.

1.2 Primary Research Questions and Objectives

This thesis was driven by three research questions, based on the literature review of existing knowledge:

1) What are the primary risks on the UK rail and road networks posed by climate change?

2) What are the potential challenges in adapting to climate change in the UK rail and road systems?

3) What are the most cost-effectiveness measures for the UK rail and road stakeholders to adapt to climate change?

Starting with an overview of the above research questions, this thesis aims to achieve the following four objectives:

(1) To stress the significance of the impacts that climate change poses to rail and road planning and to call for more attention from transport stakeholders to these impacts.

(2) To investigate the general situation of climate change and adaptation planning in UK inland transport systems.

(3) To construct a systematic adaptation procedure on risk assessment and development of adaptation strategies for rail and road stakeholders by integrating mathematical modelling and qualitative consultation into decision making.

(4) To provide practical suggestions of climate adaptation planning for both rail and road systems by drawing from the experiences of British inland transport.

1.3 Scope of Research

The research scope includes an extensive literature review and both quantitative and qualitative research methods, including nationwide surveys and multiple case studies (e.g., Highways England and Network Rail).

Although this thesis looks at the global impacts of climate change and adaptations, considering the complexity of climate change across different geographies, most of literature and data (e.g., in survey and interviews) are UK-based with the support of academic and industrial domain experts. This should not be taken as a limitation but a practical approach to fill the gaps among regional studies focused on the UK and the under-researched areas, including the utilisation of an FBR modelling method in inland transport and multi-case comparative study of climate risks and adaptation on roads and railways. The novelty of this study includes:

- Developing an innovative thinking pattern (Climate Adaptation Planning Procedure), for guiding transportation planning for climate change.
- An innovative tool for aiding climate risk assessment and decision making (FBR model) which is capable of mathematically analysing risks and adaptation measures relating to transportation. The risk assessment of the severity of consequence is expanded into three components: economic loss, damage to the environment, and injuries and loss of life. It advances the state-of-the-art technique in the relevant mathematical literature from a single to multiple tier structure.
- A nationwide survey investigating the impacts of climate change and adaptation issues on the road and rail systems in the UK.
- A comparative study involving four in-depth case studies of climate adaptation in the UK road and railway networks, identifying the hidden practical issues (e.g., planning process), and offering useful recommendations and global references for adapting to the climate change on other transportation systems and regions.

1.4 Structure of the Thesis

The thesis contains ten chapters. Following the introduction of the research background, primary research questions, objectives and scope in Chapter 1, Chapter 2 undertakes a systematic analysis by comprehensively analysing current research, including the most up-to-date and innovative studies. The extensive review divides the literature context into five main research themes regarding: 1) the impacts of climate change on road/rail transportation; 2) climate risk assessment; 3) transport asset management; 4) climate planning and policy; 5) adaptation of transport infrastructure to climate change. The resulting analysis, particularly the research challenges, provides helpful insights and a future research agenda for climate change risk analysis, adaptation planning and implementation in transportation. Chapter 3 illustrates a general procedure of how this research is designed and justifies the research philosophy (pragmatism) and method (mix-method research (MMR)) for developing long-term climate change adaptation planning in transportation systems. The step-by-step construction procedure of the FBR model is elaborated in Chapter 4. Afterwards, Chapter 5 narrows this topic down to the UK transport sector by introducing the background of climate risks and adaptations on the British roads and railways. In Chapters 6 and 7, the FBR model is applied to climate risks assessment and adaptation prioritisation through surveys on the British rail and road transport systems, respectively. Following this, Chapter 8 dissects the different adaptation measures and policies used in different entities by conducting four case studies in order to reveal 'hidden' issues in the existing climate adaption planning of the UK transport systems. The analysis of literature review, modelling results of two modes and in-depth interviews with associated domain experts, are then compared and contrasted for discussion in Chapter 9, to response the three primary research questions. Finally, Chapter 10 recaps the research procedure and research questions and concludes with the key findings from this study. The outcomes of the study are stressed by demonstrating their academic and practical contributions to realise the more effective design and implementation of adaptation plans. It also contains the research limitations and recommendations for future research directions. The structure of the thesis is summarised in Figure 1.1.

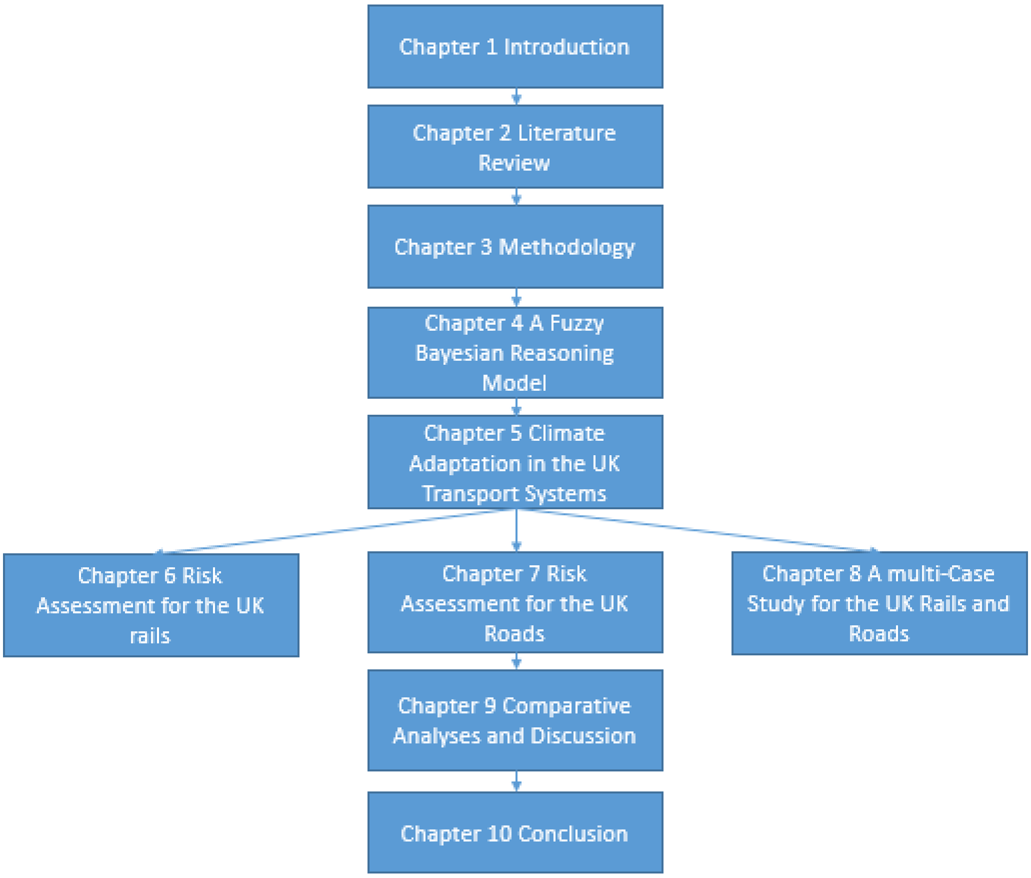


Figure 1.1 Thesis structure

Chapter 2 Literature Review

This chapter presents a systematic review recapping on climate risks, adaptation strategies and planning in the context of road and rail transportation systems. It aims to conduct a rigours survey, to highlight any significant research gaps not addressed in past studies and to analyse current emerging topics. After introducing the overall pattern of climate change and impacts well as climate adaptation strategies, the investigated research papers are evaluated in terms of the geographic location of research, leading authors and co-authorships, domain methodologies, as well as key research themes. More importantly, it critically dissects the selected papers by categorising them into several dimensions to reveal the status quo and potential challenges. These themes cover the impacts of climate change on road/rail transportation, climate risk assessment, transport asset management, climate planning and policy, and adaptation of transport infrastructure to climate change. The survey work and newly proposed climate adaptation framework will provide the domain researchers with valuable references for future research and industrial practitioners and planners with constructive insights and empirical guidance on climate adaptation, risk analysis, transport planning and other important relevant topics.

2.1 Introduction

2.1.1 Climate change and impacts

Climate change implies alterations in the earth's "pattern of weather, meaning the averages, the extremes, the timing, the spatial distribution not only of hot and cold, but of cloudy and clear, humid and dry, drizzles and downpours, snowfall, snowpack, snowmelt, blizzards, tornados, and typhoons" (Holdren, 2008). It is evident that the climate has changed considerably. Global warming has shown a more significant change in the past five to ten decades than any other climate period in human history (Change, 2001). The report from IPCC also indicated unequivocally that the climate system has been warming since the middle of the 20th century, based on observations of a warming atmosphere and oceans, diminishing amounts of snow and ice, and the rise of sea levels (IPCC, 2014a).

The causes of climate change are complicated. IPCC's investigations indicate that the increase of greenhouse gases (GHGs) concentrations is a main cause accelerating global warming since the 1950s (IPCC, 2007b). These GHGs include carbon dioxide, methane, nitrous oxide, halocarbons, and ozone (National Academies, 2008). Owing to the fast population and economic growth, we are currently facing the highest atmospheric concentrations of GHG in the historical record (IPCC, 2014b). Atmospheric concentration of carbon dioxide (CO_2) emission in 2013 was 395ppm, an increase of 5.33% compared to the level in 2005 (375 ppm) (Stocker et al., 2013).

Global warming causes a series of diverse global effects which include changes in precipitation, temperature, river runoff, sea levels and water levels, drought, wind patterns, species distributions and phenology, food production, ecosystems and human health (IPCC, 2007a). Natural systems will be exposed to the most significant and widest impacts of climate change. There is “high confidence” that many species will be forced to change their habitat, seasonal activities and other interactions. The hydrological environment including water quantity and quality will also be affected due to the change of precipitation or snow/ice in some areas. In human systems, there will be more harmful than positive influences posed by climate change, such as on crop yields, which may indirectly pose risks to other biological systems (IPCC, 2014a).

To cope with the impacts of climate change, the first step is to make climate estimation. IPCC (2014b) implied that the observed climate change had posed various impacts on physical, biological and human systems, crossing all the oceans and continents to varying degrees of sensitivity in the past decades. A few projections of potential changes in the climate system were also released, with confidence levels indicating the likelihood of existing and future climate trends, as well as human influences on these trends (IPCC, 2014a). It is “virtually certain” that the majority of inland areas will have fewer cold but more frequent hot days and nights. More frequent and intense heat waves and precipitation incidences are “very likely” to occur. Global earth surface temperature is estimated to increase under all assessed emission scenarios over the 21st century.

The Fifth Assessment Report of IPCC helps predict the potential effects of future climate change under different scenarios known as the Representative Concentration Pathways (RCPs) by a series of climate model experiments (Moss et al., 2010). Compared to the period of 1850–1900, there is “high confidence” that temperature change for the end of this century is projected to likely exceed 1.5°C for the RCP4.5, RCP6.0 and RCP8.5, and the warming is likely to exceed 2°C for RCP6.0 and RCP8.5. It is "very likely" that increased temperature will happen more frequently and last longer. As for precipitation, in an RCP8.5 scenario, the annual mean precipitation was expected to increase in the high latitudes and the equatorial Pacific, but the decrease in many mid-latitude and dry subtropical regions. Extreme precipitation events would become more intense and frequent, and the ocean will continue to warm and acidify for many regions (IPCC, 2014b).

It is also noticeable that the impacts of climate change are various. The costs and severity of the impacts vary based on regional circumstances, and may include latitude and longitude, coastal and inland areas, islands, sea level, and terrain (Oswald, 2011). These variations may attribute to the regional climate effects (changes in atmospheric circulation) and other regional environmental changes (lower aerosol concentrations) (e.g. Meyer et al., 2009). From the 'Special Report on Emission Scenarios' for GHG emissions, temperature projections for the end of the 21st-century range from 1.1 to 6.4 °C higher in comparison to the level at end of the 20th century (Nakicenovic et al., 2000; 2007a). The impacts of these changes also diverse in different regions, which can be exemplified by the higher than average temperature changing of the Western European region over the past decades. In Polar Regions, the impacts of climate change are more significant on a biological system than the other areas (IPCC, 2014a).

Simultaneously, regional diversities in extreme weather and climate events are witnessed. It is possible that large parts of Europe, Asia and Australia will experience more and frequent heat waves. More land regions are likely to experience an increase in the number of massive precipitation events than where it has decreased (IPCC, 2014b). The diversities of climate change, therefore, enlighten us to consider the specific historical period and regional uniqueness in observing climate trends and making the projection of future climate change.

In 2015, the twenty-first session of the Conference of the Parties (COP21), as one of the most significant diplomatic conferences ever organised, attracted nearly 200 countries to make a legally binding global climate deal for seeking the 'last chance' for protecting environment. The main discussions were focused on how to avoid dangerous climate change by lowering global warming to below 2°C through reaching a series of agreements on mitigation and adaptation (Paris Agreement, 2016). Nevertheless, climate change is the real fact and it is only going to get worse if there is no adequate measure adopted. Several vulnerabilities attributed to climate change were identified. For instance, with the number of people exposed to flooding each year tripling to 54 million by 2030 and economic losses caused by flooding would rise up to £340 billion (WIRED, 2015). In the US, research shows that the temperature annually increased by 1.5 degrees Fahrenheit from year 2014 to 2015. Drivers, pedestrians and bikers who are more likely to go out in warmer weather accounted for over 20% of the increase in road deaths in 2015 (Robertson, 2018). Based on the prediction by the UK Hadley Centre for Climate Change Prediction Research that there is a 4°C rise in global temperature by end the of this century, it is expected that temperature-related accidents would cause approximately 600 additional deaths annually equating to a cost of £46 billion from 2010 to 2099 (Leard & Roth, 2015).

2.1.2 Adaptations for climate change

Careful planning and practical actions are urgently required, in order to deal with the impacts posed by climate change. Climate change strategy can be divided into adaptation and mitigation strategies. According to the definition from IPCC Fourth Assessment Report (IPCC, 2007a), adaptation to climate change is *"adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities"*, while mitigation is *"an anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and to enhance greenhouse gas sinks"*. As United Nations Environment Program (UNEP) stated, adaptation aims to build resilience to response to the impacts of climate change (UNEP, 2010). However, even if GHG emissions can be minimised by 2100, the risks of abrupt or irreversible changes will still remain, with the increase in magnitude of global warming (IPCC, 2014a). Owing to the potential uncertainties of climate change, mitigation strategies have clearly failed to address all the deleterious risks in the past decades (Applegate, 2010). With current knowledge it is already too late to avoid all deleterious impacts (Pew Center on Global Climate Change, 2009) so adaptation strategies have been put forward to prepare and protect the environment, societies and economies.

Numerous studies have put forward adaptation concepts and frameworks, indicating conceptual approaches and desired characteristics of a systematic approach (Wardekker, 2011). Smit et al. (1999; 2000) stated that the construction of a systematic adaptation framework is based on three dimensions: the system of interest (who or what adapts?), the climate-related stimulus (adaptation to what?), and the processes and forms involved (how does adaptation occur?). They further identified some aspects in categorising diverse adaptation approaches, such as time horizon (long-term and short-time), form (informational, financial, technological, behavioural and institutional), motivation (planned and autonomous adaptation), timing (anticipatory and reactive adaptation), spatial and/or institutional extent (localized and widespread), function and effects (retreat, accommodate, protect, prevent, tolerate, spread, change and restore). The United Nations Development Programme proposed a novel idea by incorporating future climate risk into policy-making (Lim et al., 2005). It developed the Adaptation Policy Framework (APF) to guide adaptation policy-making with a necessary roadmap to support adaptation processes and enhance the human well-being in response to climate change. The implementation of APF starts with scoping and designing an adaptation project, assessing current vulnerability, evaluating future climate risks, formulating an adaptation strategy and reviewing the adaptation process. Stern (2006) stated in his study that adaptation is a systematic process involving planning improvement, climate-resilient infrastructure development, as well as the overall provision of better information to individual participants. According to the Pew Centre on Global Climate Change (changed to Centre for Climate and Energy Solutions in 2011) (2008), the essential components in the adaptation process include assessing risks, prioritising projects, developing implementing solutions, sharing information, selecting decision-support tools, collaborating with multiple agencies, sectors and geographic boundaries, creating design, managing funding and allocating both financial and human resources. Nevertheless, there is currently no comprehensive theory in the field for adequately guiding the design and implementation practices of adaptation strategies, when considering the needs of any individual sector.

Oswald (2011) provided a detailed discussion of the following perspectives of adaptation strategies: adaptive capacity, adaptation activities, adaptive management, barriers to adaptation as well as the comparison of adaptation and mitigation strategies. From the perspective of adaptive capacity, high adaptive capacity does not directly increase resilience or decrease vulnerability, and this inconsistency can be attributed to the critical drivers including economic resources, technology, information and awareness, skills and human resources, infrastructure, and institutional support and governance (Pew Centre on Global Climate Change, 2009). In order to strengthen adaptive capacity, on ecosystems for example, methods were taken to minimise the adverse effects of urbanisation, decrease barriers to migration paths, and avoid habitat fragmentation. In the meantime, it is crucial to establish supportive governance, social structures and scientific information to minimise the impacts of climate change (EPA, 2009). Snover et al. (2007) categorised the impact of an adaptation activity into three types: 1) no regret, namely, benefits occur even if climate change does not occur; 2) low regret, namely, provide benefits at relatively little cost or risk; and 3) win-win, namely, reduce impact of climate change while providing other social or economic benefits.

Barriers existing in contemporary adaptation for climate changes are diverse, depending upon the uniqueness of diverse regions and sectors. For example, in the adaptation management of forests in British Columbia, Canada, a lack of mandate and resources was identified as the most significant barrier for adaptation at the regional level, followed by the restrictive legislation and policy as well as planning capacity (Daust, 2012). Through vulnerability assessment, it was found that the transformation from ideas to practice is restricted by a lack of resources and clarification of responsibility for forest management. In South Africa, the Institute for Global Dialogue in 2011 coordinated research based on the dialogue between multiple stakeholders (Masters & Duff, 2011). This research revealed the adaptation barriers in the fields of political and economic governance, social and culture development, finance, law and technology. Although climate adaptation actions were diverse in the exemplified case studies, the literature generally encourages the sharing of best practice, to overcome barriers and support 'implementation' initiatives and negotiations.

Afterwards, Moser & Ekstrom (2010) introduced a framework to detect and manage barriers in adaptation. The provision of a holistic and systematic method identifying barriers in each stage (understanding, planning and managing phase) of an established adaptation process provides a context within which stakeholders could deal with the existing barriers. Despite all the regional efforts, the detection and management of the barriers in adaptation are still a tough challenge in itself. As Oswald (2011) suggested, a successful adaptation is based on establishing a stronger adaptive capacity, which could be strengthened by the improvement of understanding of climate change, evaluation of associated risks and vulnerabilities, and innovation of legal and institutional frameworks.

The introductory section (Chapter 2.1) illustrates the increased tendency of global warming and its trigged climate change threats, which may only get worse if no adaptation measures are adopted. Although a great number of studies have been undertaken, such as adaptation concepts, frameworks, categorisation and policy making, research barriers still exist and varies in diverse disciplines and regions. To further investigate the impacts of climate change and adaptation strategies in the context of transportation systems, this chapter systematically reviews the latest published articles in the following sections.

2.2 Methodology and Scope of Review

A comprehensive review on the research papers associated with climate change and adaptation of transportation systems, in particular roads and railways, published in internationally recognised scholarly journals from Web of Science and Emerald Management Plus databases was undertaken in December 2018. Referring to the Systematic Literature Network Analysis by Colicchia & Strozzi (2012), this review work is twofold: the Systematic Literature Review approach (Rousseau et al., 2008) to select, screen and refine the representative articles, and the Co-authorship Analysis (Newman, 2004) to investigate the process of knowledge generation, transfer and development.

The Systematic Literature Review consists of three steps: *1) Question formulation, 2) Locating studies and 3) Study selection and evaluation* (Rousseau et al., 2008). First of all, the author defined the scope of the study in compliance with the objectives by applying the CIMO (Context, Intervention, Mechanisms, and Outcome) logic (Denyer & Tranfield, 2009). Accordingly, the main themes of interest in this research are climate change, adaptation and transportation. Initially, a total of 12 keywords were identified by the authors using a brainstorming process, including climate change, impacts, risks, adaptation, planning, policy, transportation, road, rail, asset management, risk analysis and risk assessment. A team of three academics and two industrial experts refined these keywords to provide sound validity. To avoid too generic and extensive results (e.g. the string “climate change” searches for documents which contain the exact phrase), the author combined the keywords employing simple Boolean logic operators so that intricate searches could be constructed through a simple list (Colicchia & Strozzi, 2012). During the selection and evaluation procedure, the author identified the relevant papers by utilising the Web of Science (Core Collection) database as one of the foremost comprehensive multidisciplinary content search platforms for academia (Clarivate Analytics, n.d.), and Emerald Management Plus database comprising the world's best management and business journals (Emerald Group Publishing, n.d.). Search strings such as ‘climate change’, ‘transportation’, ‘adaptation’, ‘planning’ ‘road’ and ‘rail’ (together with substrings of these terms) were selected as ‘keywords'. All the searching results generated from the above strings were then combined by an ‘OR’ function. The results revealed that there were only 17 most relevant articles found between the years 1970 and 2004, and since then, the number of papers increases significantly (175). Hence, the author took year 2005 as a threshold and surveyed the published articles from 2005 to 2018. The 192 articles in total were retrieved from 75 academic journals in subjects of business, management, transportation, economics and engineering, etc. Only papers written in English were collected and reviewed.

First of all, the author thoroughly reviewed all the 192 articles and some cross referencing which could be traced back to 1990s. To guarantee the quality and relevance of the reviewed articles, the author carefully screened the papers using two strict constraints: 1) only peer-reviewed academic journals as the peer-review process is the most respected in the scientific community (Bergström et al., 2015); 2) only relevant titles, keywords, and abstracts were retained, improving the screening efficiency by ruling out irrelevant papers. Conference proceedings, technical reports, book chapters and editorial materials were deliberately excluded from the screening. Other articles where climate change or adaptation was regarded only as subtopics or just as a label were eliminated. Furthermore, the papers relating to air and water transportation were excluded. This is because they rely less on man-made infrastructures than rail and road, and their critical mass is too small (12 water-related and 4 air-related papers) to generate sensible conclusions at this stage. Consequently, the database for this thesis has been reduced to 100 peer-reviewed journal papers.

At the second stage, the author utilised a Co-authorship Analysis (Newman, 2004) approach to categorise these journal papers regarding affiliation of the author(s), as well as years of publication, top journals, and geographic location of researchers. The main themes and research methods are discussed in Section 2.3. By examining the research papers in this systematic approach, the author seek to investigate the evolving pattern during the period of 1970-2018 to reveal the research gaps and stimulate new exploration.

2.3 Trends in Climate Change and Adaptation Research on Transportation Systems

2.3.1 Evolution of paper numbers and top journals

A critical review of 100 papers, addressing a variety of aspects such as climate change risks and adaptation, and transportation policy and planning, featured in 65 internationally recognised academic journals in a timespan between January 2005 and December 2018. Analysis of the publications over the past 14 years allows us to identify the changing pattern and themes in this field, and how the research themes have evolved over time.

The distribution of the reviewed papers is presented in Figure 2.1. Among the 100 papers, 76 (76 %) were published during the latest 7-year (2012-2018) period, with 24% were published during the period between 2005 and 2011The paper generation rate was about 3.4 papers per year before 2012 compared to 12.6 papers per year between 2012-2018. The number of papers peaked in 2015 when 16 were published. There is a great potential in developing this research topic in terms of the increased number and better quality of publications.

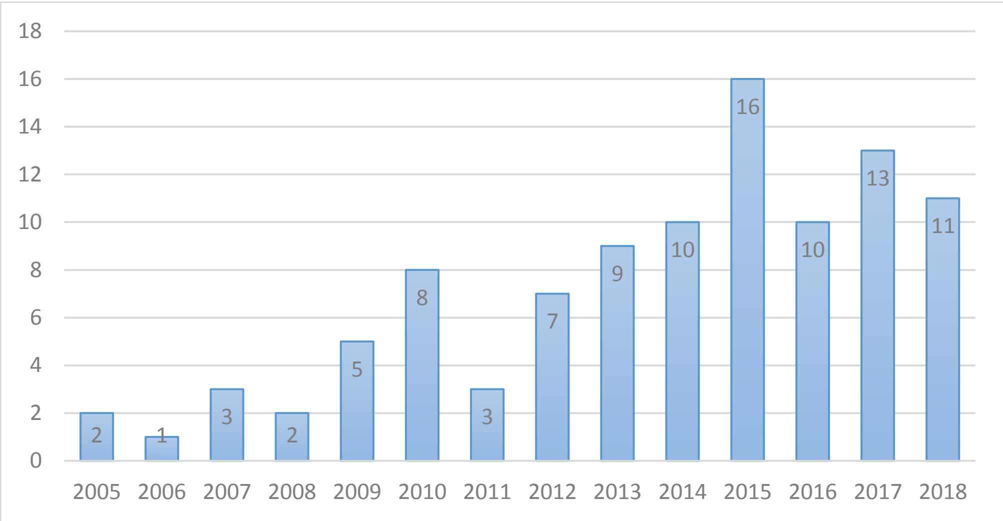


Figure 2.1 Distribution of articles by year of publication (January 2005 - December 2018)

The top 5 journals that contribute to the most articles in the literature review are listed in Table 2.1. Among them, Transportation Research Record is the pivotal source of articles, accounting for 11 articles alone. Transportation Research-Part D, Climatic Change, European Journal of Transport and Infrastructure Research and Natural Hazards are the followers. Other related journals include the Journal of Transport Geography and Transport Policy. All the aforementioned journals together account for approximately two-thirds of the reviewed articles. It is noticeable that the top journals are multifaceted, involving the subjects of transportation, climate change, risks, policy and geography.

Table 2.1 Top journal sources of climate change and adaptation in the transportation field (January 2005 to December 2018)

No.	Journal Title	No. of Articles
1	Transportation Research Record	11
2	Transport Research Part D	8

3	Climatic Change	6
4	European Journal of Transport and Infrastructure Research	5
4	Natural Hazards	5
5	Journal of Transport Geography	4
5	Transport Policy	4

2.3.2 Evolution of the geographic location & co-authorship

The popularity of climate change and adaptation research on transportation in a particular country can be interpreted by the number of researchers (i.e. authors) in that country. In the reviewed articles, the researchers were mainly from 13 countries according to the locations of their institutions. Figure 2.2 presents the regional distribution of the researcher numbers in each continent over the past decade. Overall, the North American (27%) and European（25%）researchers were the main force on climate change and adaptation research in the transportation field. The unknown category implies some international collaboration or work without geographic features. In particular, before 2012, the relevant research was only carried out in a few countries in Europe and North America, and the number of researchers was meagre. Since then, more papers were generated in North America and Europe and geographically extended to Australia, South America, Asia and Africa. It has been observed that North American and European researchers dominated this research area in the period between January 2005 and December 2018. However, South American, African and Asian researchers have become gradually involved in the global research team over the last 7 years.

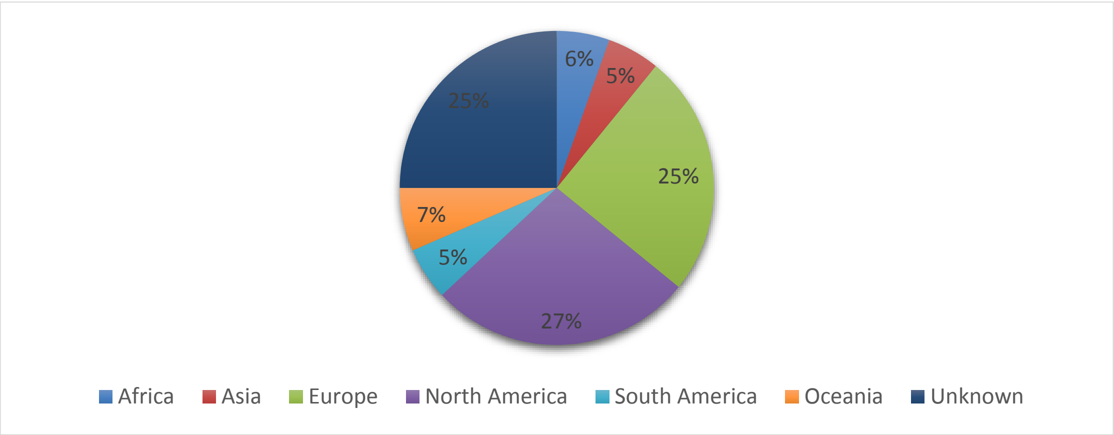


Figure 2.2 Distribution of articles by geographic location (January 2005 to December 2018)

Furthermore, the co-authorship analysis of scientific collaborations was applied in this paper. It served to extract meaningful information about the existence of communities (clusters) of different types in a co-authorship network and identify their emerging factors, e.g., linguistics, geography, and/or disciplinary proximity (Newman, 2004), as well as to reveal the overall structure of the collaboration pattern from fragmentation to cohesion (Newman, 2010). Indeed, the author measured the scientific collaborations of not only the individual authors but also the authors who write together, regardless of the order of the authors or their specific role such as first author or corresponding author, in order to capture the linkages among the researchers. By doing so, the results of co-authorship analysis within and across papers are illustrated by a mapping graph, in which graph nodes (vertices) are as authors, and links (edges) are as the co-occurrence of at least two authors in the same paper.

Figure 2.3(a)

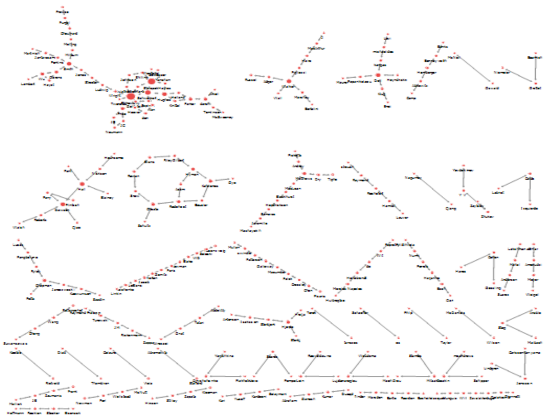


Figure 2.3(b)

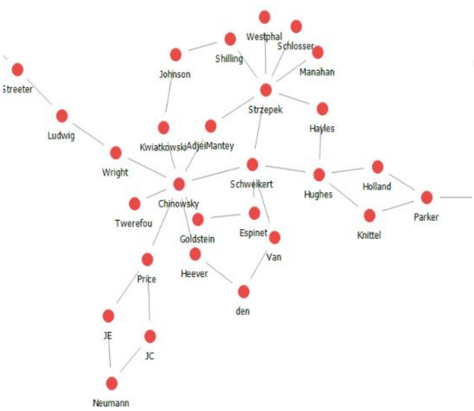


Figure 2.3(c)

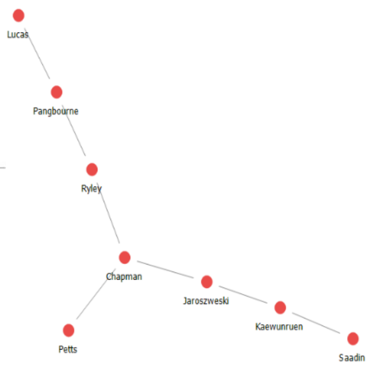


Figure 2.3(d)

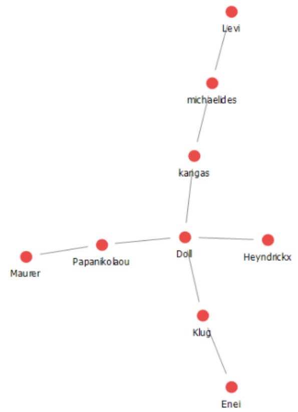


Figure 2.3(e)

Figure 2.3(a-e) Key network of the co-authorship in published articles (January 2005 to December 2018)

Figure 2.3 visualises the network of the co-authorship across the research of climate change and adaptation in the transportation field since 2005. It can be seen that there were two main communities including Chinowsky, P., Schweiker, A., Strzepek, N. and Strzepek, K. in one and Chapman, L. and Doll, C. in the other. In particular, all these publications were generated since 2010, except from the only one published by Chapman, L. alone in 2007, implying that the co-authorship network had been formed since 2010 with the markedly increased number of research papers. Among the two communities, the collaborative networks involved researchers from different geographical regions. Specifically, co-authored papers led by Chinowsky, P., together with Schweiker, A., Strzepek, N. and Strzepek, K. had background related to North America, Africa and Asia, such as United States, South Africa, Vietnam and Korea. Meanwhile, the group represented by Chapman, L. and Doll, C. consisted of researchers from European countries such as the United Kingdom. It therefore explains why the overall geographic distribution of the publications is heavily weighted towards European and North American counties and gradually extended to other regions.

2.3.3 Evaluation of primary research methods and themes

The primary research methods exerted in the selected studies fall into seven categories, including review articles, conceptual work, survey, case studies, mathematical modelling, simulation and others (e.g. Wacker, 1998; Sachan & Datta, 2005). The category of 'others' encompassing descriptive research and perspectives from industries, mainly refers to qualitative methods. Figure 2.4 illustrates the published papers distributed against different research methods during this review period. In accordance with the result of categorisation, 'case studies' and 'conceptual work' were the two pivotal methods, accounting, in combination, for 41% of the total publications. Together with the review articles, survey and others, the papers using the qualitative research methods made up 76% of the total, while those using the quantitative research methods, including simulation and mathematical modelling, only accounted for 24% of the total publications. It is also noted that some of the studies utilised mix-methods, for instance, the combination of 'conceptual work' and 'case studies' (Wilson & McDaniels, 2007; Espinet. et al., 2017), and the hybrid of 'modelling' and 'case studies' (e.g. Walker et al., 2011). Under such circumstance, the author counted twice each categorised method.

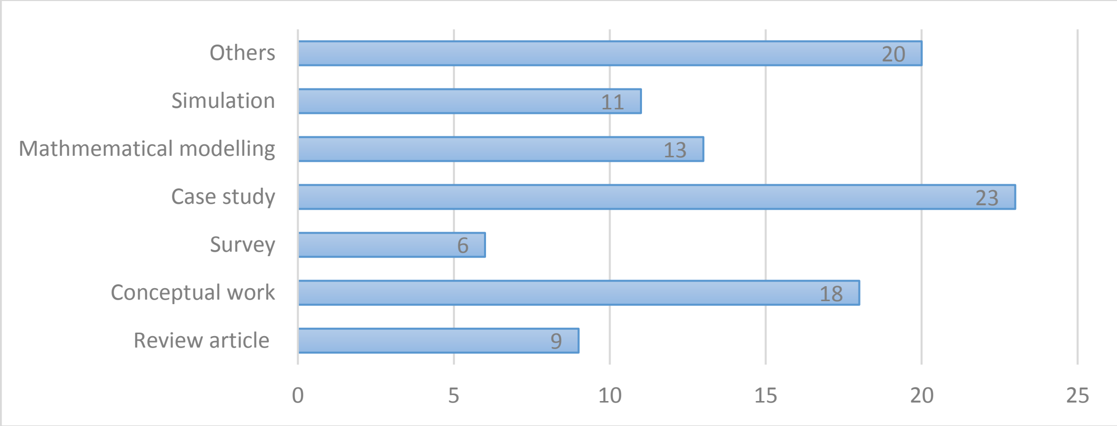


Figure 2.4 A categorisation of papers based on research methods (January 2005 to December 2018)

The semantics analysis was then applied to categorise the selected work based on different themes, by which scholars were searched for the emergence of ideas and trends in large corpuses (Knuth, 1993; Ferrer et al., 2001). This thesis started analysing the titles and abstracts of the selected papers, as they best summarise the main themes of the articles; this is the first information viewed by readers before they reach the rest of the work (Lau et al., 2017). After that, the author examined the corpuses through a full-text review. Accordingly, the selected papers were categorised into six dimensions regarding diverse subjects of the research: impacts of climate change on road/rail transportation, climate change risk assessment, climate change and asset management, climate planning and policy, transportation adaptation to climate change, and others. Figure 2.5 depicts the number of papers in each dimension. A summary of context analysis by research themes can be found in Table 2.2.

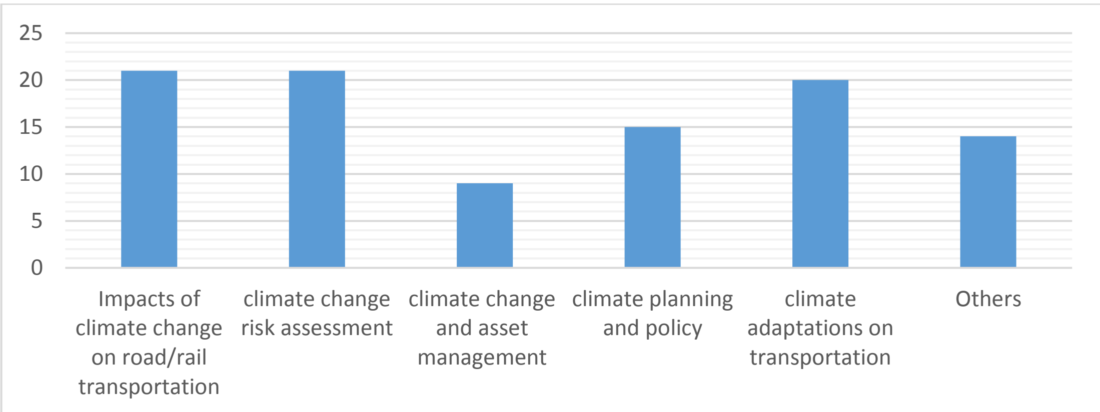


Figure 2.5 A categorisation of papers based on research themes (January 2005 to December 2018)

Table 2.2 Critical review results by research themes

Themes	Context	Gaps
Impacts of climate change on road/rail transportation	Some research has maturely developed at a national and multi-regional scale (i.e., some developing countries).	Little research conducted in the public domain concerned with the impact of climate change on transportation systems; the majority of research is primarily focusing on the specific regions and transport modes.
	The US road system -climate stressors, climate change impacts and adaptation cost analysis	Climate change is not in all phases of transportation decision making; lacking in secondary impacts and indirect economic losses; requiring wider scope of climate stressors and alternative adaptation approaches.
	The UK road and rail: predicted climate change impacts on transport infrastructure	Only recently that more attention has been attracted to the impacts of climate change on transportation; mainly focusing on road freight
	Asia: Climate change impacts on road infrastructure in Vietnam; potential impacts on road and building infrastructure in four Asian countries	Research mainly focuses on railway infrastructure; how climate will change in the future, especially at a local level is uncertain; requiring country-specific assessments and quantifications of impacts and diagnostic frameworks.
Climate change risk assessment	Geographic Information System (GIS); Climate Impact Assessment (CIA); scenario-based risks/vulnerabilities analysis; environmental assessment index; General Equilibrium Model (GEM); Life-Cycle Cost (LCC) analysis; multiple decision models; resilience of transportation systems in climate risk evaluation	A few uncertainties in decision making (e.g., nature of climate change itself and changing social, economic and political dimensions) have not been well addressed; insufficient attention on a particular type of climate change event or transportation assets
Climate change and asset management	Risk-based methodology and adaptation framework; asset management system; a sustainability framework with its associated modelling and	Data limitations; inadequate treatment of risk; lack of sufficient financial resources; uncertain demands in in future system

	visualisation techniques; Sensitivity Matrix; Building Information Modelling (BIM)	
Climate planning and policy	Mitigation-related policies: pricing, land use and tax-related policy, the roles of policy capacity and spatial planning in climate change transitions. Planning: structure decision-making and its tools	The expected goals and capacity of policy in response to climate change have not sufficiently translated into actions; focusing on the 'proofing' of infrastructure against future climate change whilst ignoring other important factors in the short-medium terms.
Transportation adaptation to climate change	Trade-offs between mitigation and adaptation; research is still at a stage of infancy: primarily focused on physical infrastructure, roadways and waterways, a medium-sized set of case studies; a top-down policy pattern	Existing literature is too vague or focuses on general principles and overly detailed technical adaptation measures; relatively scattered, lacking in dominant journals, research and theories; much knowledge on adaptation remains unclear in the peer-reviewed arena; current transportation investment and planning could not address climate change impacts adequately; lacking of access to financial resources.

2.4 Critical Review Results by Research Themes

2.4.1 The impacts of climate change on transportation

The related activities of transport systems, in general, are sensitive to diverse weather extremes, including, but not limited to, variations in precipitation, temperature, winds, thunderstorms, frost, thaw, and fog/visibility, sea level and water level (e.g., Love et al., 2010; Schweikert et al., 2014). The impacts of climate change can be further magnified as the impacts posed at one location could pass to all sorts of aspects of transportation networks in other regions directly or indirectly especially in the cases of international trade and multimodal transport. Some significant weather parameters which lead to the disruptions to transportation infrastructure and operations are summarised in Table 2.3.

Table 2.3 The impacts of climate change on transportation

Weather parameters	Categories	Impacts
Precipitation elements	Freezing precipitation, snow accumulation, liquid precipitation, perceptible water vapour, soil moisture, flooding, and water body depths	Loss of traction and control, delays, reduced speeds, stresses on vehicle components and tyres; flooding induced road and highway closures; re-routing; wet road surface; road spray; weak and uneven braking; softened railroad beds; roadbed scouring; drought-induced risk of dust and smoke to reduce visibility; intermodal impacts from barge shutdowns as lower water levels
Temperature related	Air and surface temperature, including maximum and minimum, the first occurrence of season, heat index, and cooling or heating degree days	Stresses on vehicle components, infrastructure, perishable cargoes, and rail buckling; reduced speeds on rails; new surface and air routes in northern regions, including road transportation in non-permafrost regions; cost reduction and safety improvement due to the milder winter; less lift due to high temperatures affecting take-offs and landings at airports
Sea Level Related	Tropical cyclones including tracks and elements affecting evacuation routes, open-water sea ice, high surf, storm surge, abnormal high or low tides, freezing spray, hurricane winds, sea state, flooding, wind wave height, and sea wave height	Supply chain disruptions; road, port and airport closures; extensive damage to infrastructure and vehicles; obstructions blocked rails; sea level rise-induced extreme water levels; risk and damage to infrastructure; changes in agricultural and manufacturing production and shipments; disruption of supply chains; opening of a possible commercial pathway
Thunderstorm related	Severe storm cell tracks, lightning, and hail,	Rapidly changing conditions with multiple risks of collisions and damage due to loss of control; impaired visibility; rock slides causing risk of collisions and delays; damage to infrastructure; blocked railroads
Winds	Wind speed	Vehicle instability, loss of control and re-routing; blow-overs; damage to ships and airlines
Visibility	Restrictions from fog, haze, dust, smog and sun glare, and upper atmosphere restrictions from volcanic	Reduced speed; risk of collisions and damage due to rapid change; re-routing; schedule delays; airport closure

	and desert dust	

(Source: adopted and processed from the articles of Peterson et al., 2008; McGuirk et al., 2009; Love et al., 2010)

Climate impacts have widespread implications for transport design, planning, operations, materials specifications, maintenance, network and vehicle function, liability and insurance, user behaviour and emergency evacuation, with several studies in the public domain (i.e., Taylor & Philp, 2010; Hooper, 2013; Meyer et al., 2014; Chinowsky et al., 2015b; Olmsted et al., 2017). The majority of research papers about the impacts of climate change on transportation are primarily focusing on the specific transport modes, typically on the road, rail and ports. In reality, the impacts of climate change on transport infrastructure vary on the particular modes of transportation, geographic locations and conditions of event occurrence (Suarez et al. 2005).

The relevant research has been maturely developed at a national and multi-regional scale. In developed countries, such as the US, the UK, Australia and Canada, there have been a few studies assessing and documenting the impacts of climate change on transport (e.g., Pant et al., 2016; Wang et al., 2016; NRCNA, 2008). These studies were not limited to the assessment and prediction of the impacts of climate change, but also the costs of mitigation and adaptation when the corresponding measures are involved. To further demonstrate that climate impacts on transport infrastructure are sensitive to geographical locations, the author conducted case analysis and compared the primary relevant research in the United States with that from a few developing countries in Asia.

2.4.1.1 United States

As one of the nation's foremost capital assets, the road network plays a vital role in supporting the US economy. Some potential climate change impacts on highway systems and possible strategies had been identified (e.g., Meyer et al., 2014). The climate stressors impeding the highway system were summarised into changes in temperature, precipitation, sea level rise and hurricanes, with their different impacts on transport infrastructure, operations and maintenance. Several studies regarding the cost analysis of the impacts of climate change had been undertaken in recent decades. The Transportation Research Board (TRB) (2008) carried out a detailed analysis of the potential impacts of climate change on North American roads, bridges, ports, and other transportation infrastructure. Chinowsky et al. (2013) quantified the adaptation costs of climate change with regards to the maintenance and construction of the US road networks. More recently, Chinowsky et al. (2017) investigated the impacts of climate change on operations of the US rail networks in response to the rise in delayed costs owing to temperature increases.

Despite all the preceding efforts, the potential impacts of climate change on transport systems are wide-ranging, which emphasises the importance of considering climate change in all phases of transportation decision-making where vulnerability is estimated (National Research Council, 2012). These changes may pose significant secondary impacts and indirect economic losses in the transportation sector that need to be considered as part of the planning process in the long term. It demands a broader scope of climate stressors and alternative adaptation approaches to tackle the impacts in the future (Meyer et al., 2014; Chinowsky et al., 2013). Having shown some research achievements, there is still inadequate work concerning the quantitative analysis of the impacts of climate change and the associated costs (Chinowsky et al., 2013).

2.4.1.2 Asia

In Asia, extreme climate events pose significant impacts on road transport with substantial economic losses. The effects of climate change on road infrastructure and operations are attributed to the increases in temperature and precipitation, flooding, frequent freeze-thaw phenomena, storm surges, and sea level rise in most climate change studies. Whilst all of the investigated Asian countries experience these effects, the scale of impacts varies depending on the natural conditions of regional topography and terrain (Regmi & Hanaoka, 2011).

Chinowsky et al. (2015a) focused on the physical asset of road infrastructure in Vietnam through assessing the potential impact posed by climate change including sea level rise, increased temperature and flooding. Regmi & Hanaoka (2011) surveyed the impacts of climate change on road transport infrastructure and adaptation strategies from June to July 2009 to assess the awareness of climate change and adaptation among policymakers and public, climate-related emergency preparedness, existing design standards and practices and other issues. The results implied that although adaptation has been realised in disaster management, Asia still lags behind in formulation and implementation of adaptation strategies for climate change within the road transport sector. In Northern Asia, including the three countries of China, South Korea and Mongolia, a study was conducted by Chinowsky et al (2015b) to examine the potential threats posed by climate change on built environment, including the impact on roads and building infrastructure within the given timeframes of

2030, 2050 and 2090 based on the Global Circulation Model scenarios (Larsen et al., 2008). The results indicated that Mongolia was vulnerable under most of the scenarios and faced the greatest opportunistic cost in terms of potential loss to its road networks. China was also vulnerable, but with varied vulnerability depending upon the climate scenarios whilst South Korea had the least vulnerability but could still face annual costs of billion dollars due to the impacts of climate change.

Flooding was considered as a significant threat to the rail systems in Asia (i.e., Binti Sa'adin et al., 2016; Berg, 2017). In India, many bridges were damaged by severe floods which caused dramatic damage to lives and properties over the past decades with the changes in hydrological conditions and river regime (Berg, 2017). A destructive flood occurred in the Machak River when heavy rainfall washed off the Machak rail culvert in summer 2015. The flash flood resulted in the severe derailments of two passenger trains on the flooded bridges within 6 hours (Durga Rao et al., 2017). Meanwhile, Asia has experienced more landslide occurrences than any other regions in the world, which might be attributed to the changes in water level, slope geometry, intensity and loading of rainfall (Regmi & Hanaoka, 2009). Even if the smallest landslide occurs on a railway line, trains cannot deflect or go around the detritus, leading to high risks for rail infrastructure and potential injuries from incidents (Kaewunruen et al., 2016). Although climate change threatens asset systems, degrades operations and delays train services, unfortunately the impacts on railway infrastructure have not been adequately addressed in the existing literature due to the complexity and variety of local environments (e.g., in Malaysia (Binti Sa'adin et al., 2016)).

As most studies on climate change tend to focus on short-term impacts (Koetse & Rietveld, 2009), insufficient attention has been given to the transport sectors and especially in Asian counties. Country-specific assessments and quantifications of impacts and adaptation strategies to improve the resilience of transport infrastructure are needed. Proactive policy planning with a better understanding of the projected climate change impacts on the built environment was suggested to avoid high costs in the future (Chinowsky et al., 2015). To adapt to the impacts posed by climate change, as Meyer et al. (2014) stated, one of the crucial early steps in the diagnostic frameworks was to determine the types and projected levels of climate change in order to increase the resilience and robustness of transport infrastructure and operations against these risks. However, the climate will continue to change but exactly how it will change in the future, especially at the local scale, is uncertain, creating a dilemma for transportation decision makers, planners and related stakeholders engaged in the transportation systems exposed to climate risks. Therefore, it is imperative to look at the risk assessment of climate change to detect the relevant threats and uncertainties and for transport planners to tailor their risk assessment, adaptation planning and policy for climate change to a specific region.

2.4.2 The risk assessment for climate change

A considerable number of approaches and practices have been developed in recent years to identify the vulnerabilities of transportation systems when facing the risks of climate change. These studies include not only the assessment of environmental impacts (i.e., Neumann et al., 2015; Tonmoy & El-Zein, 2018; Matthews et al., 2017), but also economic analysis of climate risks and the associated adaptation costs (i.e., Qiao et al., 2015; Schweikert et al., 2014; Twerefou et al., 2015).

In recent years, some regional studies have been developed via the establishment of multiple decision models. In the United States, Neumann et al. (2015) investigated the potential impact of climate change (temperature, precipitation, sea level, and coastal storms) on roads, bridges and coastal development as well as urban drainage infrastructure. Four models were synthesised to assess vulnerability impacts as well as the efficiency of mitigation and adaptation measures. A regional travel demand model was proposed by Kim et al (2017) to evaluate the risks of flooding affecting the transportation system in urban Honolulu in America, by using travel demand data to forecast potential evacuation and sheltering requirements. Tonmoy and El-Zein (2018) created an indicator-based vulnerability assessment method to evaluate the impacts of sea level rise on the eight beaches in Shoalhaven, New South Wales Australia. Alirezaei et al. (2017) focused on road safety, using a system dynamics method modelled the climate change-road safety-economy nexus, and investigated the complex interactions amongst these essential areas. Five sub-models were generated to test each aspect of the overall nexus and their interactions to simulate the overall system effectively.

Two recent studies conducted by Mullan et al. (2016) and Matthews et al. (2017) respectively, looked at the impacts of climate change on winter roads. Mullan et al. (2016) found out that as a result of global warming, there was a trend towards thinner lake ice and a reduced time window when lake ice was at sufficient thickness to support trucks on the Tibbitt to Contwoyto Winter Road (TCWR), the world's busiest massive haul ice road. Assessed by three climate models, a clear trend towards winter warming effects on TCWR required decision-makers to consider future changes in climate when planning annual haulage. A new method to create a Winter Severity Index (WSI) model was developed and applied to central British Columbia, Canada (Matthews et al., 2017). Supported by the data from the maintenance records and meteorological stations, the WSI model allowed users to better understand how winter weather translated into inter-annual variations in winter road maintenance activities and to assist a northern community in climate adaptation.

Regarding the economic consequences of climate change, a Life-Cycle Cost (LCC) analysis was applied to assess its potential impacts on road pavement performance by Qiao et al. (2015). They used binary non-linear programming to optimise intervention strategies so as to minimise the associated costs (i.e. agency costs/total costs). Accordingly, the differences in road maintenance planning and LCC under current and future climate scenarios were derived. A stressor-response methodology was proposed to analyse the costs "with adapted" and "without adapted" strategies to climate change (Schweikert et al., 2014; Twerefou et al., 2015). Combining 54 potential climate futures using general circulation models approved by the IPCC, Schweikert et al. (2014) assessed the national-level climate change cost impact in South Africa and drew the conclusion that the expected costs were between US$116.8million and US$228.7million annually in the 2050 decade for the median and maximum climate scenarios without adaptation strategies, while these costs could be reduced to US$55.7million with adaptation strategies. Similarly, Twerefou et al. (2015) estimated the economic impact of climate change on road infrastructure in Ghana. It was found that the total cumulative costs of maintaining and repairing damage caused to existing roads due to climate change were $473 million, while the costs could increase to $678.47 million if taking into account the higher initial investment for incorporating adaptation measures in the design and building of new road infrastructure. Hence, the question as to whether lowering decadal costs in the future or increasing initial costs as a priority remains unanswered. Reasonable adaptation investment and decision making are significant in an initial planning stage.

Some recent articles have taken transport resilience into climate-related risk evaluation. In the context of the transportation system, resilience was defined as the ability of the system to *"absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions"* (Wan et al., 2018). Beheshtian et al (2018), for example, proposed a stochastic optimisation model for strengthening the long-term resilience of the motor fuel supply chain in response to the impacts of sea level rise and flooding in Manhattan, New York. The modelling results emphasised the importance of immediate risk management as well as investments of the vulnerable infrastructure at both early and late stages of the planning, retrofitting, and reconstruction for developing a successful climate adaptation framework.

Indeed, some recent studies have acknowledged the issues of supply chain and logistics uncertainty in risk management. For example, to determine of transport and logistics uncertainties threating on the UK road sector, Sanchez Rodrigues et al. (2010) put forward a logistics triad uncertainty model to identify and analyse the diverse sources leading to an unsustainable supply chain. The factors impacting transport operations were barely found, and further mitigation measures were called for reducing these uncertainties. Furthermore, Kwak et al. (2018) highlighted that port selection could influence the choice of rail routes available for distributing imports into the UK from a supply chain perspective, as risk interactions plays a vital role in risk events' evaluation. By doing so, a new interpretive structural model was established to assess the risk event interactivity, including specifically investigated the interactions between international logistics risks and explained how these risks could be interconnected and amplified.

Nevertheless, an apparent problem is that the existing models utilised in climate risk case studies could only provide partial information to guide adaptation planning of specific infrastructure and sectors. Hence, it is expected to adjust the sectoral model and climate scope when extending the research to rail, port and other intermodal transport networks. Considering the interdependency of different climate change impacts on infrastructure, macroeconomic models are suggested that will include the investigation of indirect effects, including business and transportation interruption, as well as the economic failure of capital investments due to damaged infrastructure (Neumann et al., 2015).

2.4.3 Climate change planning and policy

Planning principles and practice play an essential role in adapting to climate change complementary to the design, maintenance and operations of transport infrastructure (Taylor & Philp, 2010). The issues of climate change have been considered from the perspective of national and regional transportation planning and policy-making. However, the existing references are relatively scattered and tend to focus on GHG mitigation, such as on the pricing, land use and tax-related policy (Boarnet, 2010; Solaymani et al., 2015), the roles of policy capacity and spatial planning in climate change transitions (Newman et al., 2013; Hrelja et al, 2015), as well as structured decision making tools to link adaptation, mitigation and sustainable development decisions in transport infrastructure (Wilson & McDaniels., 2007). Some climate-related long-range planning documents, literature and policies have been reviewed, revealing institutional barriers in several case studies (e.g., Taylor & Philp, 2010; Bache et al., 2015; Hrelja et al., 2015).

One of the most critical aspects of transportation policy is the pressure to reduce GHG emissions in the forthcoming decades, together with the consideration of a variety of measures to subsidise low carbon fuels (Boarnet, 2010). Holland et al. (2015) simulated four transportation sector policies: cap and trade, ethanol subsidies, a low carbon fuel standard and a renewable fuel standard. The simulation included prices, quantities, changes in the private surplus and changes in farming activity. Boarnet (2010) stated that the combination of pricing and land use regulation could effectively minimise the GHG emissions posed by climate change, with relationship between land use and travel behaviour or distance (e.g. vehicle miles of travel) being identified in the past decade (e.g., Crane, 2000; Ewing & Cervero, 2001; Handy, 2005).

Tax policies are considered as a valid measure for reducing GHG emissions. Solaymani et al. (2015) examined the impact of tax policies, including a carbon tax and its alternative energy tax, on both the economy and the transport sector in Malaysia. The simulation results from a Computable General Equilibrium framework illustrated that the carbon tax policy was cheaper and more effective than the energy tax policy concerning reducing carbon emissions. Additionally, the inappropriate climate change policies would cause mitigation on the rebound effect at aggregate and transport level. They therefore recommended the government to consider low rates of carbon reduction targets rather than the high levels (less than 5%) in the implementation of an energy tax policy to minimise the adverse effects on the economy.

Climate change also requires re-orientation of spatial planning and swift systematic attention to potential pathways (Wilson & Piper, 2010). However, existing planning in climate policy seems to play a limited role for climate change transitions in practice. In other words, the expected goals and capacity of policy for climate change have not sufficiently translated into action (e.g., Biesbroek, et al 2009; Preston et al., 2011; Romero-Lankao, 2012). For instance, Bache et al. (2015) examined how the UK government’s headline climate change targets were translated into action at the local level in the transport sector in two English regions. The symbolic meta-policy leading to little action on the ground posed threats to established conceptions of policy implementation and only served as political goals without practical effectiveness. Therefore, to achieve climate change targets across government, it calls for the elaboration of other policies at other levels such as targets for government departments and local authorities. Hrelja et al. (2015) analysed the ability of spatial planning in supporting local climate change transitions by utilising two case studies of climate planning in Swedish municipalities. They suggested planners moderate their expectations on planning so that planning for climate change could be linked to an overall attractive city storyline, whilst recognising that climate transition needs to be generated within the current local implementation structure.

Newman et al. (2013) stressed the concept of policy capacity, which reflected the ability of civil servants to provide useful advice and to deliver the advice to political decision-makers effectively. Policy capacity has received a renewed interest in recent years, as an essential component in the policy cycle and a necessary condition for successful policy output on transportation sectors (e.g., Edwards, 2009; Howlett, 2009). However, there are incompatible matches between the current goals of climate action and the established goals of transportation, leading to a particular administrative constraint called policy layering (Kern & Howlett, 2009). To enhance the policy capacity, they suggested more institutional support be given to politicians to generate viable climate strategies, and appropriate solutions to help counter these institutionalised constraints.

In the context of climate change, planning of transportation infrastructure is always complicated, involving uncertainty and demand for balancing costs and benefits. Therefore, structured decision-making is essential for human development, in particular under limited resources (Hammond et al., 1999). Wilson & McDaniels (2007) highlighted the concept of structure decision-making whose tools had been widely applied in a variety of policy contexts for generating explicit, pluralistic and innovative decision-making processes. During the examination of land-based transport in relation to climate change in Australia, Taylor & Philp (2010) emphasised the necessity of regional rural networks for emergency evacuation planning as one of the research directions in the future. The decision support system could be based on a macroscopic model, which offers planning guidance for the evacuation of people from threatened areas to safe designated shelters. However, the existing policies tend to focus on the 'proofing' of infrastructure against future climate change whilst ignoring other factors that may be more significant in short to medium term (Hearn, 2015). Some management agencies rarely incorporate climate change into decision-making processes, which partially explains the lack of tangible information and tools for climate forecasting and planning

(Espinet et al., 2016). Vulnerability assessment could be a crucial step in adaptation planning as vulnerability can significantly damage the efficiency and capability of the operation of the transport system. Hence, this chapter reviews the management of transportation infrastructure and assets for climate change in the next section.

2.4.4 Asset management for climate change

Transport infrastructure is one of the most significant components of transportation systems. The damage and economic losses on transport infrastructure posed by climate change could be significant in both direct and indirect ways (i.e., Huibregtse et al., 2016). The direct costs include increased maintenance, repair and capital costs and accelerated infrastructure replacement costs. The indirect costs may stem from a loss of infrastructure service and activity disruption (Sawyer, 2014). Asset management has been put forward to offer a structured approach to efficiently maintain property and support decision-making in the transportation sector. A significant amount of works has been undertaken in the past decade, especially in developed countries (i.e., the US, the UK and Australia), including risk-based methodology and adaptation framework (Wall & Meyer, 2013; Huibregtse et al., 2016; The Federal Highway Administration, 2012), economic analysis and asset planning (Chinowsky et al., 2013; Sawyer, 2014).

In the US, risk-based transportation asset management has become a mandatory approach in assisting agencies to understand how risk management could benefit decision making (FHWA, 2012). The second report published by The Federal Highway Administration (FHWA) of the US transportation agencies individually examined risk-based approaches in asset management at multiple levels (the operational, program, project, asset category and individual asset levels) of the transportation sector. Further asset risk management was suggested, to be embedded in relevant institutions, involving policy innovation, assigning responsibilities, documenting processes and training at each risk level (FHWA, 2012). The same method was adopted by Wall & Meyer (2013) who proposed a risk-based adaptation framework for climate change planning in the transportation sector through reviewing two types of adaptation planning: on physical infrastructure and assets, and on operations and maintenance. More recently, Huibregtse et al. (2016) applied the risk-based methodology to quantify the impacts of climate change on a road network, illustrated by a test case, on the frequency and effects of flooding of a tunnel in the Netherlands due to heavy rainfall. This method was based on the philosophy of defining the resilience of the targeted system which indicated the amount of time left before an unacceptable situation arises and can be adopted in climate adaptation planning as an element of asset management. The probabilistic risk assessment was concerned with the overall risk of two factors: the probability of failure and the consequences of failure.

Meyer et al. (2012) stressed the concept of asset management systems, which was utilised as a decision-making framework to integrate climate change into transportation planning. It is evident that the asset management system offered the most convenient approach to develop transportation asset planning in response to climate change, and the system had been widely applied to sizeable local transportation agencies to some extent. Nevertheless, there were few resources helping decision makers to identify critical thresholds and sensitivity indicators to extreme weather events in an asset system (Rowan et al., 2013). To deal with the resource limitation, Rowan et al. (2013) introduced the Sensitivity Matrix for the US Department of Transportation's Gulf Coast Phase adaptation pilot project in Mobile, Alabama. The Sensitivity Matrix allowed transportation planners to screen assets that were particularly sensitive to climate change by setting up critical thresholds in which damage could be observed. Further studies were recommended to identify additional thresholds and sensitivity indicators for specific projects. The matrix synthesised information of empirical studies of damage, historical climate data and engineering analyses so as to link physical assets to climate variables under projected climate scenarios.

Doust (2010) proposed a sustainability framework, together with its associated modelling and visualisation techniques, which provided planners with an approach to balance the trade-offs between governments, businesses and their communities and to address the challenges in climate change adaptation. These techniques in systems engineering, widely used in the delivery of infrastructure in cities, also offered valuable sources in developing a useful sustainability framework in transportation asset management. Afterwards, Sanchez et al. (2014) applied Building Information Modelling (BIM) into a sustainable whole-life transport infrastructure asset management in Australia. BIM was regarded as an essential tool considering sustainability to manage transportation infrastructure throughout its life cycle. It assisted transport agencies to be more cost-effective through better analysis of the impact of alternative designs, as well as monitoring and optimisation of essential performance for the asset (Sanchez et al., 2014). More recently, The Tennessee Department of Transportation in the US conducted an assessment of critical transportation to respond to potential threats posed by extreme weather by 2040 (Abkowitz et al., 2017). A framework of extreme weather vulnerability assessment was formed which included establishing an asset inventory, recognising the types of extreme weather events to which the critical assets may be affected, and making quantitative evaluations for potential asset damage for the selected event types and critical asset combinations.

The analysis of economic losses due to the impacts of climate change is also a key component in asset management. Under the assistance of Transport Canada in partnership with Yukon Research Centre, the International Institute for Sustainable Development developed a guide to help practitioners to better understand the economic implications of both the ongoing damages to transport infrastructure and the benefits of investing to strengthen infrastructure resiliency (Sawyer, 2014). This guidance provided a general framework to conceptualise economic effects posed by climate change, and link climate change, asset vulnerability and economic outcomes together.

However, climate change has only started to be integrated into the management of infrastructure (Huibregtse et al., 2016), and only a limited number of agencies have considered adaptations in their organisational management practices (Wall & Meyer, 2013). Some common barriers have been revealed in Wall and Meyer's research (2013), including data limitations, inadequate treatment of risk, lack of sufficient financial resources, and uncertainty in future system demand. Hence, more professional and resilient asset management is called for to quantify the potential effects of climate change on transportation infrastructure, which could be supported by investigating multiple parameters, reviewing the quick scan model and adding extra functionality (Huibregtse et al., 2016). To better implement asset planning in future climate adaptation, it suggests transportation agencies utilise common, consistent and directive approaches, widely accepted risk standards and in-depth user guides. Broad communicating and information sharing among agencies and climate researchers will allow them to figure out the most effective solution for each case and to enlarge benefits for the entire transportation sector (Wall & Meyer, 2013; Sawyer, 2014).

2.4.5 Adaptation to climate change in transportation systems

2.4.5.1 Climate change strategies

To effectively deal with the impacts of climate on transportation, climate change strategies must be addressed. As mentioned, the strategies to tackle climate change are generally divided into adaptation and mitigation strategies.

There have been numerous research articles concerning measuring, managing and minimising carbon dioxide and GHG emissions (e.g., Patterson et al., 2008), as well as the de-carbonisation of the transportation sector (Geels, 2012; Schwanen et al., 2012; Hendricks et al., 2018). These mitigation measures include reducing the speed of transport vehicles (e.g. ships' slow steaming) and introducing new technologies into engine design that make for more efficient operations (Love et al., 2010). Compared to the mainstream of carbon emission studies in climate change, unfortunately, it is only very recently that adapting to climate change on transport has begun to receive more attention (Hooper & Chapman, 2012). This might partially attribute to the fact that adaptation is far more cost-effective than mitigation or reactive strategies (Pielke, 2007; Stern & Britain, 2006), and there are more anticipated regulations or global attention to GHG issues (Becker et al., 2012). However, even under extreme GHG mitigation efforts, climate change has become an inevitable fact to some extent (IPCC, 2007a; 2007b). There have been a growing number of countries starting to recognise the importance of adaptation and incorporating it to their political and scientific agenda; however, the majority of contributions are at an initial stage of climate risks determination (Arnell, 2010).

Klein & Huq (2007) and Koetse & Rietveld (2012) explained the trade-off between mitigation and adaptation. The optimal investment levels of the two strategies mainly depend upon cost-benefit analysis. The high efficiency of a mix of mitigation and adaptation measures can be achieved in the case of maximum damage reduction and minimal marginal social costs (Koetse & Rietveld., 2012). Mitigation reduces the level of climate change so as to reduce damages and adaptation measures needed. Likewise, neglecting or delaying adaptations in decision-making can not only exacerbate consequences posed by climate change but also degrade the benefits of mitigation (e.g., failed infrastructures due to weak economic investments at the designing stage) (Oswald, 2011). Considering the high interdependence of optimal mitigation and adaptation, a potential question needing to be solved is how to balance the two strategies in policy making as mitigation is usually considered at a global scale, while adaptation mainly takes place at regional and local levels (Koetse & Rietveld, 2012).

2.4.5.2 Adaptation strategies in transportation systems

The majority of current studies related to climate change adaptation primarily focuses on physical infrastructure, such as bridges, pavements and drainage systems (i.e., TRB, 2008; De Bruin et al., 2009). Dobney et al. (2009; 2010) quantified the effects of higher summer temperatures due to climate change on the UK railway network, and suggested that ensuring appropriate maintenance of track and track bed and raising the stress-free rail temperature are two effective adaptation measures. De Bruin et al. (2009) put forward relatively holistic adaptation options for the Netherlands based on a literature review and expert opinions.

In a study in Washington State, the US, Strauch et al. (2015) identified that the temperature changes in hydrological regimes increased flooding in autumn and reduced snowpack in spring, and higher soil moisture in winter led to the reduction of slope stability. Adaptation strategies were proposed to upgrade, change or maintain stream crossing and drainage design, revise funding policies, relocate or close roads and increase public participation. A methodological framework for developing adaptation strategies was developed through exemplifying the management of rural roads in Thailand, where the vast road network was vulnerable to the impacts of flooding and sea level rise (Rattanachot et al., 2015).

Overall, the most crucial adaptation strategies are, but not limited to, designing new vast infrastructure, improving the capacity of locks and weirs, and developing more 'intelligent' infrastructure and water management systems. Some other specific adaptation measures include increasing the height of bridges and elevating road infrastructure in the case of water level rise etc. (e.g., Demirel, 2011). More adaptation tools and frameworks utilised in transportation are elaborated in Table 2.4.

Table 2.4 Climate adaptation tools and framework on transportation

Name	Context	Reference
Blueprinting	A collaborative process by which residents engage in an interactive dialogue about the future urban development of their metropolitan area	Niemeier et al. (2015)
Dynamic Adaptive Planning	Used to overcome the disadvantages of existing methods by dealing with the Level 4 uncertainty which is often called	Wall et al. (2015)

	deep uncertainty	
Roadmaps for Adaptation Measures of Transportation to Climate Change	Review adaptation measures policies for the transport sector and evaluates them through a series of performance indicators.	Stamos et al. (2015)
Three-pillar (Policy-Management-Technology) model	The assessment of potential impacts of each climate change indicator requires sensitivity and risk analysis so as to identify the critical threshold and quantify the risks in response to the requirements in the level of management, policy and physical infrastructure	Mutombo (2014)
New York City Panel on Climate Change - adaptation framework for sea level rise and storm	Map the crucial targeted infrastructure, making state-of-the-art scientific projections and developing a regional risk management approach to adaptation	Rosenzweig et al. (2011); Major & O'Grady (2010); NPCC (2010)
Climate Change Adaptation Tool for Transportation in the Mid-Atlantic areas of the United States	Utilise a decision-theoretic approach to identify uncertainty and appraise climate change scenarios on the long-range transportation planning timeline	Oswald et al., (2012a, 2012b)
Adaptive systems management	Include projecting the potential climate change, identifying vulnerabilities in the transportation system, and assessing different mitigation and adaptation strategies for climate change from the perspective of transportation engineering	Meyer & Weigel (2010)
Spatial planning	Map the coastal inundation along the northern coast of Java, Indonesia via a GIS model, and analyse land use changes with an estimation of damage exposure	Suroso & Firman (2018)

Despite all these pioneering attempts, systematic reviews of literature show that existing research on adapting transport to climate change is still scanty and is either overly general, or considers conceptual adaptations or site-specific technical measures (i.e., Eisenack et al., 2012; Koetse & Rietveld, 2012). Although the transport sector has realised its social and economic vulnerability to climate change, up to now adaptation to climate change in transportation has received insufficient attention, especially on specific adaptation measures. Most studies tend to focus on a medium-size set of case studies rather than systematic strategies. Only a few countries have implemented specific adaptation strategies at a national level, such as the UK (Department for Environment, Food & Rural Affairs (DEFRA), 2006; Committee on Climate Change, 2014; 2017), the US (Environmental Protection Agency, 2009; 2014), Netherland (The Ministry of Infrastructure and the Environment, 2016) and Finland (Marttila et al., 2005; Ministry of Agriculture and Forestry, 2014). Reviewing over 200 adaptation measures from 30 papers in 23 peer-reviewed journals from 2005 to 2009, Eisenack et al. (2012) found that the research was relatively scattered, lack of dominant journals, researchers, and theories, and much knowledge on climate adaptation was not clarified in the peer-reviewed arena. The most institutional adaptation which could help planners make decisions was usually found in the grey literature.

Lack of access to financial resources could pose a massive challenge for the implementation of an adaptation plan (Miao et al., 2018). Deficiency of implementation of adaptation plans may also be caused by the fact that they have a stakeholder-oriented focus, involving multiple participants (public, private and households), actions and agencies (Nelson et al., 2007). It is challenging to develop strategies supported by all participants (Klein et al., 2005; Eisenack et al., 2007). Most importantly, a significant challenge for transportation planners is the shortage of data both in precise climate change prediction and the cost-benefit analysis owing to the high uncertainty posed by climate change (De Bruin et al., 2009; Koetse & Rietveld, 2012). The knowledge gaps regarding direction, magnitude and severity also lead to the failure of adaptation strategies in the transport sector (Koetse & Rietveld, 2012). Accordingly, quantitative analysis and cost-effectiveness evaluation for potential climate change is fundamental for making a specific adaptation plan for transport systems (i.e., Adger et al., 2007).

The factors such as infrastructure age, location, design, use maintenance, limited redundancy, and funding policies and management could influence the sensitivities of transportation systems as well as the implementation of adaptation planning (Strauch et al., 2015). Nevertheless, existing research has barely taken into account how to figure out the factors that might constrict or promote the implementation of adaptation. It requires more detailed knowledge about related actions and stakeholders for adaptation strategies at an advanced stage (Eisenack et al., 2012). It is also noticeable that the literature concerning adaptation possibilities mainly focuses on the global North (i.e., the US and Europe) rather than the global South; the global South might be more vulnerable to climate change in terms of geographical scale and affected population, and has inadequate infrastructure networks to support the implementation of adaptation planning (Koetse & Rietveld, 2012).

Although almost all transportation modes have been covered in the current literature, the primary research emphasis is on roads (e.g. Strauch et al., 2015) and waterways (e.g. Osthorst & Mänz, 2012) compared to railway and air transport (Eisenack et al., 2012). Doll et al. (2014) revealed that the butterfly effects of climate change has influenced not only one mode but also connected modes of its main line or feeder traffic, such as the delay and closure of the channel or transhipment process on account of extreme climate events. This phenomenon might further lead to the disconnection of adaptation in multimodal transportation systems where transport networks are connected by rail stations, road depots, ports and intermodal terminals, and all of the entities are considered to share passenger trips and freight movements. Furthermore, even if all transport modes are involved in the climate adaptation, their level of adaptation could be diverse due to the different degree of disruption and adaptation capacity across all modes.

Generally speaking, most adaptation initiatives have an organisational or planning nature that follows a top-down policy pattern (Eisenack et al., 2012; Koetse & Rietveld, 2012). Koetse & Rietveld (2012) explained that public stakeholders were responsible for enabling or obliging a transport provider to adapt to climate risks for transport users. In transportation adaptation practice, governmental organisations, as an operator, often play the role of commissioners through setting a regulatory framework and offering adaptation guidance, and meanwhile leaving space for receptors to develop their own concrete adaptation measures. However, as private transport could be strictly regulated by the public sector, the top-down pattern has been doubted by some researchers who argue that most of the adaptations could be led by the private sector. To better understand the different sectors and their functions in adaptation planning, bottom-up adaptation strategies will be considered in future research.

Instead of long-term strategies, most of the adaptation policies in Europe, for example, strive to reinforce short-term resilience (Aparicio Mourelo, 2017). As a result, current transportation investment and planning does not address climate change impacts adequately. Firstly, the relatively irreversible investments in infrastructure might fail to reach their expected effects and profits under the new climate parameters with the accelerating pace of climate change, where predicted short lifetimes of transportation infrastructure might not be achieved as more frequent and severe climate events occur (Reilly & Schimmelpfennig, 2000). Secondly, relatively short planning cycles (typically 5-10 years) do not match infrastructure lifespans (typically more than 50 years), which leads to malfunctioning of transport networks (ICF International, 2008; Kintisch, 2008; Koetse & Rietveld, 2012). The first issue is relatively easy to be solved by incorporating climate change into regular monitoring and maintenance, supported by stricter design parameters in response to various extreme climate events (e.g., TRB, 2008). Investors who are involved in long-term and substantial investments are encouraged to integrate climate change with adaptation planning decisions as soon as possible as these investments are more sensitive to changeable climate parameters (Frankhauser et al., 1999). This strategy is also called proactive or ex-ante adaptation, which applies to significant and long-term investments where most elements of transport infrastructure are costly and the mistakes on investments, could cause irreversible negative consequences if the infrastructure lifetimes exceed the climate thresholds (Koetse & Rietveld, 2012). Embedding adaptation in broader investment or adaptation programmes has been exemplified by the adaptive infrastructure design to sea level rise in Canada and coastal zone management in the US and the Netherlands (Adger et al., 2007).

However, the second issue requires more consideration due to its complexity. In port planning, for example, Becker et al. (2012) found that more than half of the responding ports planned for the historic 100-year storm period, but this preparation would not be adequate if the 100-year return period becomes a new 30-year return period due to climate change. As a common port infrastructure is designed with a 50-year lifespan, new infrastructure put in place today should be built with a new climate regime in mind. Hence, balancing the investments in infrastructure with the planning cycle, especially under financial constraints, should be considered in adaptation planning (Wang, 2015). For the climate change predictions in a shorter time horizon where higher uncertainty exists, there is a likelihood that appropriate and profitable adaptation investments become inappropriate, unprofitable, and insufficient ex-post (Dixit & Pindyck, 1994). For irreversible investments, Koetse & Rietveld (2012) suggested an option to address the issue. The decision-making and infrastructure updating can be postponed until key climate change parameters are known with a relatively confident certainty, especially in the case when updating design is a long-lasting procedure and wrong decisions are costly. Also, adaptation measures can be implemented in scheduled updating, and investment or maintenance can be followed with little additional cost, for which the costs of overinvestment are relatively low, and damages are relatively insignificant (e.g. The Advisory Council for Transport, Public Works and Water Management (RVW), 2009). The postponement strategy in adaptation investment has been applied to diverse policy-related planning (Koetse & Rietveld, 2012).

2.5 Implications and Future Research Agenda

Research investigating the impacts of climate change on the transport sectors has developed at a national and multi-regional scale in some developing countries (Pant et al., 2016; Wang et al., 2016; NRCNA, 2008). A few studies identifying the risks of climate change on the transportation system have not been limited to the assessment of environmental impact and have included the quantification of economic consequences of the impacts based on the diverse transport modes and regional studies via multiple decision models. However, literature on Asian studies is relatively underdeveloped, calling for country-specific assessments and quantifications of impacts and adaptation strategies to improve the resilience of transport infrastructure (Chinowsky et al., 2015). Understanding that planning for climate change remains abstract and usually fails to identify the specific vulnerabilities in risk assessment (Walker et al., 2011), it is imperative to consider climate change planning and policy in climate risk assessment.

From the perspective of risk assessment for climate change, a few dilemmas remain in transportation research. Firstly, the kaleidoscopic nature of climate change itself challenges the estimation and selection of risk scenarios in the future, making it difficult to select and develop appropriate risk scenarios (Jaroszweski et al., 2010). The analysis of diverse scenarios has been proven to enhance the resilience for unexpected changes (such as in a city (Mikovits et al., 2018)). This issue can be addressed, for instance, by collecting realistic survey data from experts to calibrate the weights of the defined risk parameters so that the proposed model can be tailored and applied in different circumstances (Wu et al., 2013). The uncertainty in changing social, economic and political dimensions requires planners to comprehensively consider the critical dimensions in the future socioeconomic and macroeconomic environment based on regional and sectoral conditions (Jaroszweski et al., 2010; Bachner, 2017). Secondly, because traditional risk analysis usually pays insufficient attention to a particular type of climate change event or transportation assets, future scenario development is expected to include different climate and weather events, providing region-specific customisation and ongoing trend observation. It suggests that more complex decision models are tested to strengthen robustness of the risk model. Meanwhile, transport planners should take account of diverse climate threats and make a customised risk assessment based on ongoing climate trend observations in a specific region, which needs the input from continuous data collection and innovation of advanced models based on the updated local conditions (Walker et al., 2011).

Although multiple vulnerability studies on climate adaptation have been conducted in the transport sector, the existing research is still at an embryonic stage with inadequate attention on specific transport adaptation planning and nationwide adaptation strategies (Eisenack et al., 2012). A vacuum yet to be bridged in existing adaptation literature is between too vague or general principles and too detailed technical adaptation measures (Eisenack et al., 2012; Koetse & Rietveld, 2012). Koetse & Rietveld (2012) suggested that adaptation instruments should be as generic as possible so as to facilitate the requirement of concrete organisational or technical measures. Typically, the establishment and development of an adaptation framework on the transportation sector are motivated by three factors: 1) government acts and or legislation as adaptation planning requirements; 2) increasing frequency of extreme weather events; 3) self-motivated internal agency initiatives (Wall & Meyer, 2013). These adaptation drivers have also been confirmed by Aguiar et al. (2018) through reviewing over 140 European local adaptation strategies.

However, as the motivation might not be singular or explicit in some cases, it calls for more integrated management of transport systems containing the systemic planning guidance at different stages, such as vulnerability assessment, cost-benefit analysis, and investigation of policy measures, strategies and operational decisions (Leviäkangas & Michaelides, 2014). Additionally, the butterfly effects of climate change implies that an extreme event could trigger substantial potential disaster and directly or indirectly pass to all the stakeholders of its and closely knitted transport systems. This is because climate change affects not only one mode but also interdependent modes and their main line or feeder traffic (Doll et al., 2014). The above cases demonstrate the need for better cooperation among multiple organisations and information sharing in intermodal transportation systems.

The lack of data on current and potential impacts of climate change, as well as cost-benefit analysis for climate change, poses a significant challenge for transportation planners and causes the failure of adaptation strategies in the transport sector (i.e., De Bruin et al., 2009; Koetse & Rietveld, 2012). Owing to the high level of uncertainty related to the future climate, adaptation measures should be robust. Espinet et al. (2015) proposed a robust prioritisation framework for transport infrastructure adaptation investments under the uncertainty of climate change, which offered a new decision-making process and practical guidance on achieving low-regret adaptation options for flexible road infrastructure design. As per Adger et al. (2007), more quantitative analysis and cost-effectiveness evaluations are recommended for dealing with potential impacts of climate change. A practical and robust adaptation framework on climate change is called for to assist with more accurate weather forecasts, innovative applications and information dissemination channels, in order to minimise the vulnerability of the mode for expected shifts in extreme weather patterns due to climate change (Pilli-Sihvola et al., 2016).

From the perspective of adaptation planning, it is noticed that many adaptation plans (i.e., in the UK) are not explicitly designed for responding to impacts of climate change but for the co-benefits of other activities such as demands of infrastructure investment and cost savings (Tompkins et al., 2010). Hence, identifying clear drivers would be the first step in climate adaptation planning regarding entities without plans. A significant portion of existing adaptation planning follows a top-down policy pattern where the public sector plays a more important role (Eisenack et al., 2012; Koetse & Rietveld, 2012). The top-down pattern becomes uncertain as the public sector sometimes strictly regulates the private sector while most of the adaptations could be led by the private sector (i.e., Nordhaus, 1990). Bottom-up adaptation strategies might be considered in accordance with practical requirements. It is more critical for planners to better understand the complicated sector constellations in the transport sector, the receptors and exposure units, in order to select a workable planning pattern (Eisenack et al., 2012). In general, a proper infrastructure planning supported by a useful planning tool (e.g., Infrastructure Planning Support System (Espinet et al., 2016)) should be based on a systematic procedure. It includes recognition of the risks associated with climate change, categorisation of infrastructure most at risk and opportunities for adaptation responses, examination of the current governance structures, as well as identification of regulatory and network constraints related to disruptions or degradation. Additionally, as adaptation strategies are significant and could be costly, infrastructure sectors should be embedded to the future planning optimisation in advance (Neumann and Price, 2009; Larsen et al. 2008). In the European case, the cost analysis based on WEATHER and EVENT projects implies a high uncertainty on the financial burden of European transportation systems, as well as discrepancy cost rates among the transport modes. These uncertainties could be relieved through vertical and horizontal collaboration between the company and government: the company may consider updating cost estimation schemes and making business adaptation plans for climate change; the government should establish better risk and disaster management mechanisms and lead suitable adaptation strategies for climate change (Doll et al., 2014).

Another pressing issue is the inadequacy of current transportation investment and planning for climate change. The pro-active or ex-ante strategy and postponement strategy in adaptation investment might address this issue according to the scale and lifetime of the investment (Koetse & Rietveld, 2012; RVW, 2009). The decision-making of investment also relies on smart policies in climate change adaptation that contain three elements: robustness of transport networks in adapting to current climate conditions, strong linkage of transportation policy with other climate-related policies, and low-cost adaptation measures in supporting massive investment (Koetse & Rietveld, 2012). Though some examples of adaptation in transportation design have been revealed, many communities are incapable of incorporating climate impacts into infrastructure planning and management. Some questions are deferred for future consideration, such as how researchers can engage with local experts to explore adaptation, how to balance the roles of central and local governments, and how to tackle the barriers faced by communities in adapting to climate change vulnerabilities (Picketts et al., 2016). Hence, as echoed by Jude et al. (2017), further research requires a more comprehensive analysis on adaptation planning in terms of identifying the feasibility, deficiency and resilience in key stakeholder organisations as well as motivation and challenges faced by other organisations.

Last but not least, although there has been much effort on developing appropriate adaptation tools for climate change, some issues remain. Firstly, many adaptation tools or framework are not explicitly designed for the transportation sector (e.g., city planning in Niemeier et al., 2015). Secondly, as proposed adaptation measures are either conceptual or lack of concert models, these models could not provide a one-for-all solution for decision makers (Mutombo 2014). Accordingly, this thesis conducts a systematic analysis on climate risks and adaptation planning for the UK transport system through diverse approaches such as FRB model, survey, case studies and interviews which will be introduced in Chapter 3.

2.6 Conclusion

This chapter presents a state-of-the-art survey on climate adaptation of transportation systems based on 100 high quality journal papers featured in 65 internationally recognised Web of Science cited journals in a period between 2005 and 2018. The wide-ranging review dissects significant theories and practise among the publications in the period, to reveal the significant research gaps addressed in the past, analyse the emerging topics today and develop a conceptual framework to guide possible research directions in future.

Among the analysed papers, the majority are published in the most recent 7-year period with a general growing tendency. The top journals that contribute to the most articles are Transportation Research Record, Transportation Research-Part D, and Climatic Change, involving multiple disciplines such as transportation, climate change, risks and geography. North American and European researchers were the main driving force on climate change and adaptation research in the transportation field. However, South American, African and Asian researchers have gradually become more active in the global research team in recent seven years. In particular, case study and conceptual work are the dominant research methods, accounting for 41% of the total publications. Though the existing research was relatively scattered, lacking in dominant journals, researcher and theories (Eisenack et al., 2012), the co-authorship analysis indicates that a multiple-background network with two main communities has been formed since 2010 with an increased number of research papers. Concerning the used methodologies, it is found the existing studies are dominated by qualitative rather than quantitative research methods, with mix-methods used in some cases (Wilson & McDaniels, 2007; Walker et al., 2011; Espinet et al., 2017).

By semantics analysis, the author categorised the corpuses based on different research themes and analysed them in terms of the impacts of climate change on road/rail transportation, climate change risk assessment, climate change and asset management, climate planning and policy and climate adaptations on transportation. It offers significant insights for encouraging innovative climate adaptation methods and economic developments within a uniformed framework addressing transportation planning for climate adaptation.

Through in-depth analysis and discussion, this research pioneers the review work on climate change risk assessment, adaptation planning and other relevant topics in transportation studies, as well as providing transport planners and decision-makers with useful insights and guidance on understanding the status quo and potential challenges.

Chapter 3 Methodology

The selection of an appropriate research methodology is neither an abstract, unnecessary, impractical philosophy nor a simple selection of approach for data collection and analysis. In contrast, it is based on the nature of the phenomenon being studied itself (Ryan et al., 2002), whose reality (ontology) influence the creation of knowledge (epistemology) and the extent and ways that the researcher's values influence the research procedure (axiology or human nature) (Bryman & Bell, 2007; Foster, 2014; Burrell & Morgan, 1979). Indeed, the research philosophy can be directly linked to three primary questions that many researchers need to consider in conducting a study - ‘what to research?', ‘why research?' and ‘how to research?' (Remenyi et al., 1998). Meanwhile, the above three philosophical assumptions are tightly knitted to a ‘methodological nature', namely, how the researcher obtained or investigated the knowledge (‘how to research?') (Burrell & Morgan, 1979; 2017).

Following the explanation of the research background, including the research questions, objectives and structure in Chapter 1 and the literature review in Chapter 2, this chapter illustrates a comprehensive procedure of how this research is designed. This includes the rationalisation associated with fundamental research philosophy, methodology and strategies, as well as justifications of the methods selected for this research and how they are developed. Specifically, Chapter 3 is divided into five sections: 3.1 briefly introduces the main research philosophies in social science and justifies the philosophy utilised in this study. 3.2 discusses the primary research approaches and methodologies. 3.3 further explains the philosophical and methodological stance of the current research. Moreover, the research strategies, research methods, data collection and analytical techniques utilised in this study are elaborated in 3.4. Finally, 3.5 elaborates a mixed method approach for climate adaptation planning in this thesis, including a novel mathematic model, nationwide online surveys, and semi-structured interviews to cope with the impacts of climate change.

3.1 Research Philosophies

Research is to search and gather information to solve a specific problem or question (Gall et al., 2016). Venkataram (2010) interprets it as a systematic process of information collection and analysis to facilitate researchers' understanding of a particular phenomenon. Although in some circumstances, researchers may have (or think they have) an answer for a question they want to address before initiating research, their ‘knowledge' is merely less rigorous ‘guesswork' or ‘intuition' until conducting a scientific examination (Somers, 2008). Given the belief that human's knowledge is always too limited to solve the ever-changing problems in diverse subjects or disciplines, researchers are asked to propose these questions and strive to figure out the best solutions for them. Accordingly, research offers a scientific approach to archive these solutions by consistently and inquiringly collecting evidence (Venkataram, 2010).

Research Philosophy is the foundation for all research design and the basis of how research results will be interpreted. Holden & Lynch (2004) state that the dual effect of a philosophical review can have on researchers. Firstly, it enlightens their mind to explore other possibilities to enrich research abilities. Secondly, it helps to increase researchers' confidence in selecting the most appropriate research methodology to deal with the research problem, which can increase their confidence for research output as well (Holden & Lynch, 2004).

As Saunders et al. (2015) state, before making a sound selection of research philosophy, two key questions need to be in a researcher's mind: 1) understand what kind of research assumptions need to be used in their research, and 2) which research philosophies are suitable. The term research philosophy can be defined as ‘a system of beliefs and assumptions about the development of knowledge' (Saunders et al., 2015, pp.124). At each phase of a study, researchers need to make a series of assumptions, which can vary from reality (ontological assumptions) human knowledge (epistemological assumptions) and the influence of researcher's values on research procedure (axiological assumptions or human nature) (Bryman & Bell, 2007; Saunders et al., 2015). Meanwhile, the three sets of assumptions directly imply a ‘methodological nature' of research, as each of them profoundly influences the way that a researcher explores and achieves the knowledge about the world (Burrell & Morgan, 1979).

3.1.1 Research philosophy assumptions

There are three main types of assumption in research philosophies include ontology, epistemology and axiology (e.g., Saunders et al., 2015). Ontology is the theory about the nature of reality, including objects and their ties. As a theory of ‘being’ or ‘existence’, a key question of ontology is about ‘if there is a real word out of there that is independent of our knowledge of it’ (Goertz & Mahoney, 2012). Concerning with categorical analysis, such as the intention of categorical analysis (‘prima facie’), entities of the world and categories of entities (Poli & Obrst, 2010), ontology can be divided to three types: descriptive, formal, and formalised (e.g., Smith & Burkhardt, 1991; Spear et al., 2016; Poli, 2003).

Descriptive ontology aims to collect data of 'prima facie' (Poli & Obrst, 2010), while formal ontology abstracts, filters, codifies and integrates the findings from descriptive ontology (Husserl, 2001). Formalised ontology seeks formal codification at the third level of theory construction (Poli, 2003). Ontology offers researcher criterion to distinguish a variety of objects, such as existent and non-existent, concrete and abstract, real and ideal, independent and dependent, as well as their relations, estimation and dependencies (Corazzon, 2019). Some fundamental questions to be answered in ontology include: if the reality is objective or influenced by personal cognition and if the reality is external to the people or the consequence of personal consciousness (Burrell & Morgan, 1979).

The other two assumptions tend to concern about external elements in research rather than the object itself. The second assumption, called epistemology refers to knowledge, including its nature, scope, structure (Goldman, 2014), origin and validity (Roos & Von Krogh, 2016). Epistemology is closely related to ontology as it addresses how we come to know the reality. However, instead of a theory about the world (ontology), epistemology investigates the way of acquiring knowledge to construct frame a theory eventually (Poli & Obrst, 2010). Essentially, it is about how an individual start interpreting this world, how to distinguish truth from false, how the created knowledge can be communicated between individuals (Burrell & Morgan, 1979), as well as in which ways an individual should treat knowledge in a 'prescriptive, normative manner' (Goldman, 2014). Essentially, assuming knowledge is something that can be obtained and manipulated by personal experience, epistemologists are concerned with the contribution to the knowledge they can make as a result of their research (Burrell & Morgan, 1979; Saunders et al., 2015).

Last but not least, the third assumption, axiology, is related to the role of values and ethics in the research, or 'human nature' connecting individuals and their environment (Burrell & Morgan, 1979; Saunders et al., 2015). As Heron (1996) stated, the values of human beings are the drivers triggering their action. In other words, axiological researchers have their own judgements on what kind of topics they decide to choose based on the values they hold instead of other's opinions.

In a nutshell, the above three sets of assumptions imply that research philosophies are a reflection of progression in scientific practice based upon human's beliefs and assumptions in term of knowledge and values, so as to facilitate the research move forward (Creswell, 2009). Therefore, these assumptions all lead to resolving the issue about methodology, namely, what procedure researchers can use to obtain the required knowledge.

3.1.2 Research paradigms

One strategy in differentiating research philosophies is to recognise different research paradigms. A research paradigm reflects researchers' 'worldview', the beliefs about the world they live in and want to live in (Lather, 1986; Mackenzie & Knipe, 2006). It can be defined as social constructions, attempting to address the question about where the researcher comes from so as to create meaning embedded in data (Denzin & Lincoln, 2000). A paradigm comprehensively constitutes four elements, namely, ontology, epistemology, axiology and methodology (Lincoln & Guba, 2000). A typical matrix utilised in paradigm analysis is based on the political or ideological orientation to divide paradigms into four major types: radical humanist, radical structuralist, interpretive and functionalist under the subjectivist-objectivist and radical change-regulation two dimensions (See Figure 3.1) (Burrell & Morgan, 1979; 2017).

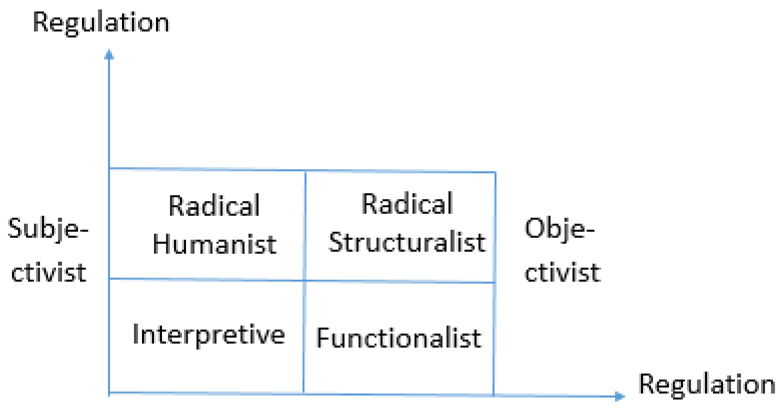


Figure 3.1 A matrix of four paradigms in organisational analysis

Saunders et al. (2015) further explain the four concepts, in particular, when applying to business and management research. Functionalist paradigm is the most popular one in social science research. Functionalists believe objectivist and regulation. For instance, to study the pattern of natural social phenomena or actions, functionalists believe in objective methods, such as observation and experiment to collect data rather than personal experience. In this paradigm, originations are regarded as conscious entities, and researchers are seeking rational explanations and solutions to resolve the rational problem. However, the interpretive paradigm integrates regulation with subjectivist. Hence, interpretivists believe in the human's interpretation that individual engagement, for instance, the interview is the best way to study social regulation. Believing that the world is filled with radical changes, radical structuralists and radical humanists attempt to apply objective and subjective methods to explain these phenomena respectively. However, these two types of paradigm only occupy little portions in social science studies as a majority of researchers take more attention to universal actions, events or phenomena instead of particular or changing social events.

3.1.3 Three major philosophies

Indeed, functionalist and interpretive paradigms represent the two primary research philosophies: positivism and interpretivism/ constructivism. Additionally, another primary one called pragmatism, originated in the late 19th century, highlights that concepts are only relevant when supporting actions (Kelemen & Rumens, 2008). Pragmatists usually begin their research with a problem, and strive to investigate practical solutions to future implication; the proposed research problem and research question are the critical drivers for conducting research strategy and research design. Therefore, it harmonises objectivism and subjectivism, while promotes the use of multiple methods to deal with practical problems (Saunders et al., 2015). Pragmatism is generally viewed as the most popular paradigm for mixed methods of social enquiry (Greene, 2007).

Patel (2015) summaries the core concepts of the three most common philosophies from ontological view (ontology) as below:

Positivism: *there is a single reality, which can be measured and known, and therefore, they are more likely to use quantitative methods to measure this reality.*

Interpretivism/ constructivism: *there is no single reality or truth, and therefore, reality needs to be interpreted, and therefore, they are more likely to use qualitative methods to get those multiple realities.*

Pragmatism: *reality is constantly renegotiated, debated, interpreted, and therefore the best method to use is the one that solves the problem.*

Table 3.1 further explains the other four dimensions of the three research philosophies in terms of their epistemology, axiology, methodology and typical methods according to work by Crotty (1998), Patel (2015) and Saunders et al. (2015).

Table 3.1 Four dimensions of the three research philosophies

Research Philosophies	Epistemology	Axiology	Methodology	Typical methods
Positivism	• Reality is measurable • Use scientific methods and reliable tools to collect data • Contribution: causal explanation and predictions	• Positivism and post-positivism • Research is value-free • Researchers are neutral, independent of the research object, and maintain an objective stance	• Experimental research • Survey research	• Deductive, large samples, measurement, and highly structured methods • Typically quantitative methods, including sampling, statistical analysis, questionnaire, interview, focus group, measurement and scaling
Interpretivism/ Constructivism	• Reality is interpretable • Concepts and theories are simplistic • The concern with stories, narratives, perceptions and interpretations • Investigate the underlying meaning of events, actions and phenomena • Contribution: novel interpretations and worldviews	• Interpretivism, critical inquiry and feminism • Research is value-bound • Researchers are part of the research context, and their interpretation is key to the contribution	• Grounded theory • Ethnography • Phenomenological research • Action research • Discourse analysis • Heuristic inquiry	• Inductive, small samples and in-depth analysis • Typically qualitative methods, including interview, observation, case study, narrative theme identification, life history, participant and non-participant
Pragmatism	• Solving problems is the best approach, change is the aim and finding out is the means • Knowledge's practical meaning in specific contents • Emphasise problems, practices and relevance and only 'true' theories and knowledge lead to fruitful research • Contribution: solving a problem and informing future practice	• Research through design and Deweyan pragmatism • Research is value-driven • Researchers are reflexive, and their beliefs and doubts initiate and maintain the research	• Mix-method • Action research • Design based research	• In accordance with research problems and research questions • Stress on practical solutions and outcomes • Combining different type of methods, including quantitative, qualitative, action research, multiple and mixed methods

As many scholars believe, there is no 'shortcut' or 'the best philosophy' for conducting research (Tsoukas & Knudsen, 2003). Taking business and management research as an example, because a broad discipline emerged from social sciences, applied sciences and organisational practices (Starbuck, 2003), scholars have a long-term debate on its ‘multiplicity' of research philosophies (Saunders et al., 2015).

In contemporary philosophies, as Hughes & Sharrock (1997, pp. 94) state, many realists and empiricists are pragmatics[1], as they

"...do not worry about epistemology and ontology but about the particular problems they confront from their theories and investigations…using methods appropriate to the problems they have to deal with, then philosophical worries about ontology and epistemology are an irrelevance…There is certainly no reason to feel bound by stipulations about a unified method or a unified ontology for science, for on these arguments no such creature exists."

Understanding such, in pragmatic research, what the researcher concerns are the problem itself rather than the selection of methods which have to fit a particular ontology or epistemology. Nevertheless, it does not mean that ontology and epistemology should be treated irrelevant. Alternatively, the problem is urged to be investigated with a method from different philosophical stance (Holden & Lynch, 2004): to use both quantitative and qualitative methodologies for triangulation purpose (e.g., Brannick & Roche, 1997).

3.2 Research Approach and Methodology

There are two primary approaches to reasoning for enriching knowledge in research: inductive and deductive (e.g., Trochim, 2006; Creswell & Plano Clark, 2007). In general, inductive research means theory-generating and is often linked to qualitative analysis, while deductive research is theory-testing, which is often linked to datasets, surveys or quantitative analysis.

As "a theory-building process", inductive research is based on premises (experience and observation), usually moves from observations of a specific instance to broader creation and theories, utilising a ‘bottom-up' approach and accepting a certain degree of uncertainty. On the contrary, deductive research starts with and applies a well-known theory and ends with specifics, in other words, testing the application of general theories, laws, rules or universally

[1] Realists consider that the aim of science is to interpret the truth through informed speculation to the real world, while empiricists argue that aim of science is to afford the truth, so that exclude from science any activity of a hypothetical nature (Dilworth, C., 2007).

accepted principles to a specific instance. It, therefore, utilises a ‘top-down' approach (Burney, 2008). A distinct difference between induction and deduction is that inductive researchers aim to bridge the gap between the observed premises and the conclusion being judged, whereas inductive researchers aim to deduce conclusions based on facts and evidence logically, so that conclusions are deemed to be true when all the premises are true (Ketokivi & Mantere, 2010).

Saunders et al. (2015, pp. 146-147) discussed three critical features of conducting deductive research. First of all, it is an investigating process to "explain causal relationships between concepts and variables". The research might begin with a comprehensive literature review to develop a theory and propositions to link these concepts and variables. Afterwards, gathering quantitative or qualitative data to test the proposed propositions. Secondly, the concepts have to be ‘operationalised' to allow measurement of the facts, usually by quantitative methods. Thirdly, the deduction can be generalised, which requires a sufficient data size and strict procedure in sampling. Thus, it is witnessed that deduction is of the philosophical characteristics of positivism. Despite showing a few advantages, as Saunders et al. (2015) stated, inductive scholars in social science had criticised deduction that the established relationship based on premises does not take account of humans' interpretation (interpretivism).

Meanwhile, deductive research might be restricted by a hidebound methodology, which turns off the voice of what is happening (Saunders et al., 2015). Hence, using an inductive approach allows the researcher to focus on the context where events take place so as to develop a theory as a result of data analysis. Researchers using this approach are more likely to manipulate qualitative data with diverse methods to collect these data to construct different views of phenomena. However, it might be restrained by a small sample of subjects, focusing on the interpretation of the human but does not allow alternative explanations (Alrajeh et al., 2012).

Besides, another standard method for theory development is called abduction. Rather than a ‘top-down' (deduction) or ‘bottom-up' (induction) procedure, abductive research is more flexible by combining deduction with induction (Suddaby 2006). Abductive approach is gradually accepted as an essential part in interpretive research (Lukka & Modell, 2010). It usually starts with a ‘surprising fact' being observed, and which is taken as a conclusion to examine if available premises are ‘sufficient or nearly sufficient' to support this conclusion

(Ketokivi & Mantere, 2010; Saunders et al., 2015). Using both deductive and inductive approaches, it continually moves from the empirical to theoretical aspects of analysis, whose logic is more useful than utilising the inductive or deductive approach alone, in particular for testing plausible theories (Dubois and Gadde, 2002; Van Maanen et al., 2007).

A methodology describes the "general research strategy that outlines how research is to be undertaken" (Howell, 2013). It is the rationale of the research approach, determining the selection of method(s) and data analysis. Research methodologies can be generally dived into qualitative, quantitative and mix-method research.

Qualitative research aims to understand some aspect of social life and its methods which generate words for data analysis (Bricki & Green, 2007). It can be interpreted from constructivist or naturalistic or interpretative view with inductive approaches to investigate a subject when the variables and the theory base are in abundant (Creswell, 2009). There is a considerable number of methodologies available for conducting qualitative research (e.g., Yin, 2009; Creswell, 2009). For instance, participatory regards the participants as part of the researcher team, phenomenology explores the lived experience of a phenomenon, grounding theory aims to create a new theory, ethnography investigates the human behaviours, culture, beliefs in the social world, and ethnomethodology investigates the way that human beings establish their world view through using language or body language.

Quantitative research, such as experiment and survey, on the other hand, is mainly governed by positivist and objectivism philosophy. It is a systematic investigation into a social or human problem by utilisation of mathematical, statistical, or computational techniques, to develop or implement models, theories, and hypotheses related to the phenomena (Given, 2008; Creswell, 2009). As a result, it is objective leading to positivist and deductive reasoning in a research study (Saunders et al., 2009; Yin, 2009). Experimental research, strictly following a scientific research design, usually contain a hypothesis that variables can be manipulated, measured and analysed by researchers. Thus, it is referred to a hypothesis testing or a deductive research method and undertaken under a controlled environment (Baker, 2001). Survey research is more efficient for the researcher to discover features of a relatively large sample of individuals of interest groups. In a quantitative survey, through posing a series of predetermined questions to participants, researchers can quickly obtain required quantitate data so as to lay solid foundations for further more focused, in-depth qualitative research (e.g., in-depth interviews) (Ponto, 2015).

Qualitative and quantitative researchers have different views on studying concepts and measurement regarding their ontology and epistemology (e.g., Goertz & Mahnonet, 2012). Ontologically, qualitative researchers usually attempt to investigate the essences of a concept via semantic approaches, while quantitative researchers intend to establish a causal relationship among variables. Epistemologically, quantitative researchers seek solutions to generate valid data and minimise errors, while qualitative researchers aim to tackle the 'fuzziness' in producing knowledge that partial degrees of membership might exist in conceptual sets. The advantages and disadvantages of using qualitative and quantitative research approaches and methods have been discussed. For example, in language testing and assessment research (Rahman, 2017), the advantages of using qualitative research include a more firm understanding of the behaviour, perception and feeling of participants to realise better designing, interpretation and administration in the assessment. Nevertheless, the disadvantages include time-consuming and unreliability or unrepresentativeness of results owing to the small sample size. This limitation can be made up by quantitative research in which larger size of sample and variables can provide researchers with sound testing results. However, quantitative research might not in-depth and overlook the participants' experiences.

Understanding such, last but not least, Mix-method research (MMR) can be a more efficient research inquiry that employs both qualitative and quantitative approaches in research work for breadth and depth of understanding and partnership (Johnson, Onwuegbuezie, & Turner, 2007). Creswell and Plano Clark (2011) added that the indispensable premise of mixed method design was that the use of qualitative and quantitative, in rapport, would provide a better understanding of the research problem than the use of either one method alone in a study. MMR, based on pragmatism (e.g., Rorty, 1982; Cherryholmes, 1992), allows researchers to draw liberally from both quantitative and qualitative assumptions and leave more freedom to select diverse methods, techniques, procedures as well as form of data collection and analysis to realise the aims of the research (Murphy, 1990; Creswell, 2013). Moreover, the five critical rationales for conducting MMR were summarized by Greene et al. (1989, pp.259): 1) *complementarity* - elaborating, enhancing, illustrating and clarifying the results from one method to other methods; 2) *triangulation* - converging, corroborating and corresponding the results from diverse methods; 3) *development* - using the results from one method to inform or develop the other methods; 4) *initiation* – recasting results from diverse methods to reveal paradox and contradiction of new aspects of the research; 5) *expansion* -

using different methods for different inquiry components to extend the breadth and range of inquiry.

3.3 The Philosophical and Methodological Stance of the Current Research

From an ontological view, this study believes that climate change poses considerable impacts on transportation systems, and appropriate climate adaptation measures can relive these effects. The objects refer to climate change risks, transportation systems, adaptation strategies, etc. This research is to identify the reality of climate change, and relations between the threats posed by climate change and corresponding adaptation strategies, predict future tendency and independencies of diverse parameters on transportation systems. Even though the occurrence of climate change is an objective reality, the impacts on transportation systems are constantly changing and affected by individual actions and mind. For instance, if GHG emissions caused by human beings has increased; if a specific adaptation plan has been implemented in an organisation; if the transport planner has a proper understanding for climate change and long-term planning for it.

Hence, epistemologically, the reality is both measurable and interpretable. One the one hand, the research attempts to utilise scientific methods and efficient tools (e.g., archive data and questionnaire and Fuzzy Bayesian Reasoning model) to collect data to reflect the ‘real' threats of climate change from an objective perspective (positivism). On the other hand, as the deficiency of historical data and significance of personal interaction in climate change studies, the researcher aims to interpret the underlying reasons of climate adaptations strategies and planning of transport stakeholders by qualitative approaches (e.g., interview and case study) from an objective perspective (interpretivism). Axiologically, the researcher is neutral and independent of this research object (positivism). However, the researcher’s interpretations to climate change impacts (e.g., believing the tendency that climate change event is occurring more frequently and severely) as well as adaptation planning (e.g., believing the cost-effectiveness adaptation measures can resolve climate risks) are also vital to the contribution (interpretivism).

Therefore, this study reconciles objectivism and subjectivism while promoting the use of mixed methods to deal with practical problems. The core value of this research is to resolve a practice problem about an investigation of the risks posed by climate change in the transport sector and appropriate adaptation strategies to inform future planning. Conducting this research is therefore closely related to the research questions proposed in Chapter 1 with particular concerns on their operationalisation. Based upon this understanding, the author holds a favourable position in believing the reality of climate change and its impacts posed on the transport system. A few quantitative approaches (FBR modelling and survey) are utilised to prioritise these climate threats and cost-effectiveness of adaptation measures.

Meanwhile, in order to assess how the corresponding adaptation strategies can deal with these climate impacts and understand the procedure, essential elements and other ‘hidden' issues in climate adaptation planning from the perspective of transport stakeholders, interpretive research approaches (interview and case study) are further applied. On the basis of pragmatism, the author adopts mix methods to construct a comprehensive conceptual framework and guarantee reliable and sufficient data collection. A detailed introduction of research method, strategies and design, in particular, the construction of a long-term climate adaptation framework and FBR model is illustrated in the following sections.

Thus, how does a researcher determine which method to use in conducting research? What has been observed is that there is no single research method superior to others (e.g., Kaplan & Duchon, 1988). As cited by Soiferman (2010), Creswell (2005) summarised the following three significant factors: 1) matching the method to the research problem; 2) fitting the method to research audience; 3) relating the method to the researcher's experiences and training.

A dilemma is that the uncertain nature of climate change itself challenges the estimation and selection of risk scenarios in the future. This issue can be addressed mathematically, by collecting real survey data from domain experts to calibrate and assign the weights of the defined risk parameters so that the proposed model can be tailored and applied in different circumstances (Wu et al., 2013). This enables transport planners to consider diverse climate threats, for example, and undertake a more credible risk assessment and longer-term transport planning based on ongoing climate trend observations in a specific region. To do so, it needs continuous data collection and the design of advanced models based on local conditions (Walker et al., 2011). Accordingly, this thesis conducts comprehensive climate risk analysis and adaptation study through constructing a novel mathematic model collecting first-hand survey data in response to the impacts of climate change. The research audiences include both academic scholars and industrial professionals who interested in climate adaptation, transport planning and relevant fields, and therefore the results from both quantitative analysis (e.g., mathematical modelling and survey) and qualitative analysis (e.g., case study) will trigger their interests and suggestions will enlighten their works. Moreover, the author (as the researcher) has rich experience in using multiple methods (e.g., survey and interview) in climate adaptation research (e.g., in ports), which offers a solid foundation to undertake this research by both quantitative and qualitative methods.

Considering all the above factors, overall, this study is designed as an MMR and conducted by abductive approach. In the first part of this research, it follows a deductive process, beginning with a comprehensive literature review to illustrate the status quo of climate adaptation and its relevant themes in the context of transportation systems. Referring to the research questions and gaps revealed by literature review, a series of research design, methods and data collection are followed to examine existing theories and to fill research gaps. Nevertheless, based upon the modelling results, an inductive procedure (case studies) is undertaken as well via reviewing documents and interviewing associated transport experts to develop existing and potential dilemmas, supplemented with statistical results with workable recommendations.

3.4 Research Strategies and Research Methods

A strategy, as described by Andersen (2018, pp.129), "is a formulated plan to achieve one or more goals under changing conditions, and it "is about setting a target and describing the way to reach that target." Although a considerable number of research strategies have been investigated in the past decades (e.g., Bryman, 2016; Bell et al., 2018), the categorisation of diverse methodologies is relatively fragmented in social science research.

Beissel-Durrant (2004) develops a systematic typology of research strategies. In his framework, the research typology has been divided into seven main categories[2]. The three primary categories include *"Frameworks for Research and Research Designs, "Data Collection"*, and *"Data Handling and Data Analysis".* In terms of research design and framework, 20 subcategories have been listed in Beissel-Durrant's typology. Combining with

[2] 1) Frameworks for Research and Research Designs; 2. Data Collection; 3) Data Quality and Data Management; 4) Data Handling and Data Analysis; 5) ICT, Software and Simulation; 6) Research Management and Application of Research; 7) Research Skills, Communication and Dissemination.

other categorisations (e.g., Bryman, 2016; Bell et al., 2018). A few conventional research methods including literature review, survey research, comparative research, conceptual framework, mathematical modelling, action research, field experiments, case study, pilot study, secondary analysis, simulation, forecasting and mix methods have been discussed. Data gathering techniques include sampling, interviewing, questionnaire, observation, measurement, visual method and other advanced technologies. Finally, in data handling and analysis, primary quantitative approaches include survey data analysis and estimation, regression analysis, data mining, structural equation models and time series analysis, etc. Whereas, critical qualitative approaches include documentary analysis, grounded theory, ethnography, content analysis and thematic analysis, etc.

From the perspective of pragmatic researchers, a specific research problem could be solved by either a quantitative or qualitative approach (Hughes & Sharrock, 1997; Creswell, 1994). As Trochim (2006) implies, quantitative and qualitative data are usually not manipulated separately, and therefore, both qualitative and quantitative methods are suggested. Many scholars perceive that a multi-method methodology, through internal cross-checking, can triangulate and enhance the convergent validation of research results (e.g., Gill & Johnson, 1997; Wilk, 2001). Triangulation in social science indicates diverse theoretical perspectives, data gathering procedures and analysis approaches, which gives a deeper understanding of research (Denzin, 1978; Janesick, 1994). One of the primary advantages of triangulation relies on the development of converging lines of inquiry (Yin, 1994). As Huberman and Miles (1994) explained, it is "self-consciously setting out to collect and double check findings." It emphases on verification of the accuracy of data where multiple sources contribute to revealing unknown and new aspects of the research problem (Dubois & Gadde, 2002).

Therefore, in this thesis, the author applies mixed methods with relevant analytical techniques for triangulation purpose, such as mathematical modelling (including validity and reliability test), survey research (including sampling) and case study (including interviewing and comparative analysis). In this section (3.3), different data collection, analysis approaches and ethical issues considered in this thesis are introduced. In particular, the justifications of the three primary strategies, including FBR modelling, survey and case study are detailed illustrated in 3.5.

Before utilising these methods, a critical review regarding climate adaptation in the transportation systems has been undertaken in Chapter 2. Literature review refers to 'the idea of situating a study within the existing body of knowledge' (Petchko, 2018a, pp. 207). It aims to compare, contrast and analyse the historical literature and data, etc., in order to summarise the tendency and future direction of the research in a specific field. Petchko (2018a) summaries three types of literature sources: scholarly literature, policy literature and popular literature. In particular, this thesis mainly refers to scholarly literature, which includes scholarly journals, scholarly books, doctoral thesis and conference papers. In Chapter 2, the author applies a Systematic Literature Review approach (e.g., Rousseau et al., 2008b) through setting up specific searching rules and only focusing on peer-review papers to guarantee the high quality of this review. However, in other chapters, such as chapter 7, the author integrates a variety of literature sources, not only scholarly literature but also policy literature (government reports, discussion and working and unpublished papers) and other popular literature (e.g., local reports, news, magazines and online articles). Combining the analysis of the diverse data and interviews with domain transport experts, it aims to offer a comprehensive and objective view about climate adaptation planning.

3.4.1 Mathematical modelling

As Buckminster Fuller's saying (Sieden, 2011, pp. 357), "to change something, build a new model that makes the existing model obsolete." Mathematical modelling suggests the applications of mathematical concepts or languages inform objective reality (Wan et al., 2018). It is an iterative process starting with the phenomenon in reality to the virtual mathematical object, namely a model that generates results regarding the behaviours in the scenarios of hypotheses (Castiglione et al., 2018). Castiglione et al. (2018) further classify the models into *dynamic* or *static* models, *stochastic* or *deterministic* models, and *continuous* or *discrete* models in terms of their models' structure, the randomness of the involved elements, and space's structure of the values that the variables are taken respectively.

Simske (2019) suggests meta-analytics for fitting a 'less arbitrary' model in problem-solving, together with two essential principles for new model creation and development. Generalise to social science, including a series of methods drawing the exceptional experiences of relevant areas, and analyses allowing researchers to optimise the model setting of data. Based on the above statement, this thesis applies a hybrid Fuzzy Bayesian Reasoning (FBR) model, which is a dynamic, stochastic and discrete model combining fuzzy set and Bayesian network theories with evidential reasoning techniques to overcome the uncertainties of climate data and difficulties in risk assessment. The justification of why this FBR is applied in this study, including the research background, a critical review of the three concepts and their technical evolution and applications in transport studies are elaborated in 3.5.1 and 4.1.

3.4.2 Survey and sampling

A 'survey' is a commonly utilised strategy to collect research information. Sampling is a critical approach to data gathering. It implies the logic of using a smaller sample of subjects to be generalised to a broader population (Berg, 2001). In quantitative research, for example, researchers prefer to utilise probability sampling, which means the subgroup of some large population can be mathematically represented by a smaller sample (Senese, 1998).

Survey research has developed into a more rigorous approach in recent years. To guarantee a high-quality research process and outcome, it requires a series of scientific examination on the representativeness of samples, survey method, reduction of nonresponse error etc. The conduction of survey needs considers research aims, sampling and recruitment strategies, data collection and administration (Ponto, 2015).

In social science studies, researchers rely on nonprobability sampling rather than probability samples used in large-scale surveys. In this case, researchers neither require full details of factors in a population nor the capacity to get in otherwise sensitive or challenging to research study populations. They usually create 'a kind of quasi-random sample' to reflect the situation of a larger group (Berg, 2001). Notably, one of the most common types of nonprobability samples is snowballing, which is particularly useful for investigating sensitive themes or the population hard to research (Lee, 1993). Snowballing usually starts with identifying several people who have a relevant background and are willing to engage in an interview or survey. Afterwards, the researcher asks them to provide contacts of other potential participants (Dabney & Berg, 1994). In this thesis, the author utilises non-probability sampling, which integrates judgment sampling with snowball sampling techniques (Wang, 2015) to collect survey data.

3.4.3 Case studies and interviewing

Case studies refer to an in-depth examination of a typical situation, individual or society, which usually can be achieved via interviews. It is considered as a methodological approach integrating multiple data-gathering measures (Hamel et al., 1993). The objects of a case study range from a person, a group to an entire society while the data gathering techniques varies from documents, in-depth interviews, life and oral histories, and participant observation (Hagan, 1993; Yin, 1994). It sometimes is an extension of survey research to obtain more detailed, more vibrant and in-depth data (Champion, 1993).

Interviewing is a sound qualitative method for data collection. It is particularly appropriate in interpreting 'the perceptions of participants or learning how participants come to attach certain meanings to phenomena or events, interviewing provides a useful means of access' (Taylor & Bogdan, 1998, pp. 98). Notably, this thesis utilises semi-structured interviews (e.g., Rossman, 1992) to reveal the 'hidden' issues of adaptation planning for climate change. First of all, the developed or to be developed adaptation plans are suggested to use interviews and interviewers to communicate so as to reflect the full procedure and details of planning. Secondly, similar to previous climate adaptation studies on ports (e.g., Wang, 2015), the author (as an interviewer) concerns with five corresponding issues (Parts A - E) based on a pre-sent question framework in each interview. It not only provides the interviewees with enough time to prepare their answers but also allows the interviewer to cover the entire question list, as well as compare and contrast the context, features and dilemmas of different case studies at the analysis stage. Nevertheless, the author also encourages interviewees to express their views freely to reflect their "real thinking" on climate risks and adaptation planning.

3.4.4 Validity and reliability

By what and whose standards are the design, data collection, analysis and interpretation of research findings deemed valid and reliable? Before the distribution of the questionnaire survey, a pilot study has been conducted in both rail and road surveys. Quoted by Hinds & Gattuso (1991, pp.133), "preliminary research that can be used to assess a study's design, methodology and feasibility and typically includes participants who closely resemble those who will meet the criteria for inclusion in a study that is to follow the pilot work". Besides refining research strategies, developing analytical instruments and data collection processes (Creswell & Poth, 2017; Yin, 2011), pilot work is also beneficial to the research team in a deep understanding of the research plan and ethical issues and realising a self-reciprocal and transparent research process (Morrison et al., 2016). Therefore, a pilot study was undertaken in this study before the implementation of this framework by consulting with five academic and industrial experts to examine the structure, logic and context of each step.

Simultaneously, a small-scale exploratory study (e.g., two samples of each rail and road surveys) at an initial stage was supported to improve the validity and reliability of the entire modelling results.

3.4.5 Qualitative comparative analysis

In conducting multiple case studies, researchers usually seek for not only in-depth insight and complexity of the cases (Ragin & Becker, 1992) but also generalisation on a certain level (Ragin, 1987). Nevertheless, a few dilemmas are requiring to be addressed as discussed by Rihoux (2009), including the limited number of cases or population (‘small-N' situation) (De Meur & Rihoux, 2002) and the insufficient scientificity in comparative analysis owing to the incompact material (Gerring, 2004). To cope with these challenges, qualitative comparative analysis (QCA), initiated by Charles Ragin in 1980s with a goal to ‘integrate the best features of the case-oriented approach with the best features of the variable-oriented approach' (Ragin, 1987; pp. 84) has widely applied in diverse disciplines (e.g., De Meur & Rihoux, 2002; Onwuegbuzie & Weinbaum, 2017).

Rihoux (2009) further explained the combined advantages of QCA embodying in both quantitative and qualitative approaches (Ragin, 1987; De Meur and Rihoux, 2002). On the one hand, generalisation in quantitative research can be boosted by allowing researchers to analyse a considerable number of cases, which is rarely achieved in case-oriented studies. Operated by Boolean algebra, for instance, it enables each case transforms into a series of variables with conditions and an outcome. By doing so, it realises better replication (De Meur & Rihoux, 2002) that other researchers can confirm or debate the analytical results to facilitate the progress in knowledge generation (Popper, 1963). On the other hand, it is a case-sensitive qualitative approach, by which each case is regarded as a whole and complex entity. Other strengths of using QCA include simply summarising data and checking data coherence, as well as examining existing and new theories or assumptions to achieve data exploration and formulation of new segments in theory (e.g. Hicks, 1994, George & Bennett, 2005, Sager, 2004; Woodside & Zhang, 2012). Considering the above advantages, this thesis utilises a systematic QCA in studying the four cases in Chapter 8. To answer the third research question of this study, namely what are the potential dilemmas in climate adaptation planning for the UK transport systems, it imperative to explain why particular adaptation plan work well but others do not work well, and which factors impact the success of adaptation planning.

3.4.6 Ethics

Last but not least, researchers need to consider ethical issues during the whole process of their study. The four principles in research ethics proposed by Beauchamp & Childress (2001) include autonomy, beneficence, non-maleficence and justice. These can be summarised into the three vital ethical issues that a researcher should bear in mind: consent, confidentiality, risks and benefits. In this study, the author has considered all the ethical factors in both the survey and interview.

Consent: prior to participants' decision to participate, the author (as a surveyor and interviewer) asked provided everyone whom participants in this survey with an information sheet to allow them to understand why the research is being done and what it involves by three weeks from sending the invitation. The online survey lasts for around 20 minutes, and the interview lasts for about 1 hour. A cover letter and written consent were out before conducting it and which was followed by two reminder emails sent one week before and one day before the deadline respectively. The participation is voluntary and entirely participants' own choice. They are still free to withdraw before any data collection (survey or interview) at any time and without giving a reason. A decision to withdraw before the testing period, for any reason, do not affect their rights/any future treatment/service they receive.

Confidentiality: the survey and interview should not lead to any undue discomfort. If any discomforts happen, the participants have every right to withdraw in either before or after measurement. Their identity remains confidential through the whole process, and only the research team project investigators have access to the information they provide. All the data collected in this study are used for academic purposes and all the participants in this study will be ‘anonymous'. All the materials are carefully preserved and coded. All the collected data are stored in a computer dedicated to this project. The collected data are protected by password and is only accessible by the project investigators. Meanwhile, all the hard copies are stored in a lock-in space and are only accessible by the project investigators. All the data are coded, only known by principal researchers. When the results of this study are published or presented, individual names and other personally identifiable information are not used. All the data collected recorded/written are used during the period of this study, which lasts for 2-4 years and will be destroyed afterwards.

Risks and benefits: there is no known risk to participants from taking part in this study. However, thanks to their expertise in the field, the author believes that their participation will significantly help to understand the current situation of adaptation planning in the UK and be beneficial to the construction of road and rail systems, economic and social development and human welfare. Most importantly, the author that the findings of this project and thesis will offer participants valuable references in transport adaptation planning and an excellent opportunity to enhance the quality of road and rail planning. At the end of this study, a 2-page summary of the results of this project or thesis will be shared with participants by mail or e-mail.

3.5 Mix-Method Research (MMR) for Climate Adaptation Planning

This section illustrates a mixed method approach, combining FBR models, survey and case study. A mixed method approach is chosen in this thesis to triangulate data sources and minimise the limitations of single methods to realise convergence across quantitative and qualitative methods (Jick, 1979). In particular, the sequential procedure (Creswell, 2013) starts with a quantitative conception (i.e. in constructing a mathematical FBR model and a nationwide online survey, followed by qualitative methods involving in-depth case studies and telephone interviews. The qualitative research results, in some sense, explain the quantitative results.

3.5.1 A new Fuzzy Bayesian Reasoning model

Risk analysis as a critical element in climate change adaptation has been extensively utilised through a variety of approaches and techniques. In this thesis, risk analysis mainly involves the selection of cost-effective adaptation measures depends upon systematically analysing risk reduction combined with the associated costs. A variety of methods in risk quantification have been proposed (e.g., sensitivity analysis, empirical downscaling and dynamical downscaling (Wilby et al., 2009)). However, their availability and effectiveness are challenged in existing climate risk studies (Yang et al., 2015). One of the main challenges is that unavailable or incomplete objective data sometimes fail to generate precise assessment regarding the risk reduction and adaptation costs, resulting in difficulties in risk analysis. Owing to the inadequacy of historical or statistical data on climate risks assessment, the high-level uncertainties in data (UNCTAD, 2012) make traditional probabilistic risk analysis methods, such as Quantitative Risk Assessment (Nicolet-Monnier & Ghenorghe, 1996; Urciuoli, 2011) unsuited for climate adaptation study at this stage (Yang et al., 2018).

The assessment of climate change risks on the rail and road transportation systems in this thesis is mainly conducted by utilising subjective judgments, owing to the scarcity of historical/statistical data (UNCTAD, 2012). It may contain various types of uncertainties including, but not limited to, fuzziness and incompleteness. Hence, a linguistic assessment will be one of the highly effective ways to cope with these uncertainties. However, such linguistic descriptions define risk assessment parameters to a discrete extent so they can, at times, be inadequate. Therefore, the fuzzy set theory is appropriate to model such subjective linguistic variables and cope with the discrete problem (Yang et al., 2008). In this theory, linguistic variables can be characterised by their membership functions to describe the degrees of the linguistic variables, namely, the stakeholders' perceptions of climate impacts. Three parameters closely related to climate change risks were identified based on the Failure Mode and Effect Analysis (FMEA) approach (Yang et al., 2008; 2009), including timeframe (T), likelihood (L) and severity of consequences (S) (Ng et al., 2013; Yang et al., 2016). In this study, fuzzy rule bases are used to model subjective input data (i.e., linguistic terms) on climate risk estimates in road and rail, respectively based on the stakeholders' perceptions through questionnaire surveys.

Nevertheless, the employment of multiple sets of data makes the use of standard fuzzy rule inference mechanisms complicated as the calculation could take a long time. BNs, as a sound mathematical method in minimising the uncertainties and increasing knowledge, can integrate probability distributions or functions of various parameters and update their probabilities if new information emerges (Wang, 2003). Tighe et al. (2007) summarised the advantages of BNs noting that it incorporates uncertainties by modelling probabilities of variable responses, is easily updated with additional information by using quantitative and qualitative data and is easily revised and adopted at a local level through developing in a modular and somewhat spatially explicit fashion. As a result, previous studies have identified the benefits to combine fuzzy logic and Bayesian reasoning to compensate their disadvantages, especially in the applications of Fuzzy-Bayesian approaches into safety and reliability (Bott & Eisenhawer, 2002), and which can be utilised to address the above challenge.

In the meantime, there is an inadequate solution to addressing the challenge of an inconsistent unit to express risk and costs (Yang et al., 2015). On the basis of Dempster-Shafer theory, the ER method has been widely used to address risk and safety issues through realising an efficient synthesis of fragmentary information from various criteria, assessors, and evaluators

(Wang et al., 1995; 1996; Yang & Xu, 2002). Yang et al. (2015; 2016) proposed a new FBR model combining fuzzy set modelling and ER to make full use of the information to achieve climate risk and adaptation cost synthesis without scarifying too much information loss. However, in previous studies, risk variables are defined at a high level at which experts, in some cases, feel insufficiently confident to carry out their evaluations. For instance, the consequences of climate change on many occasions need to be further interpreted from three perspectives, including economic loss, human injuries/deaths, and environmental damage. Having them separately illustrated to model climate risk consequences in this thesis will facilitate the use of raw data/subject judgements from experts and thus, provide a more rational and better climate risk evaluation mechanism. Furthermore, the proposed model by Yang et al. (2018a) has only been applied in a port area. As stated by the authors, it is vital to collect more empirical evidence to prove its feasibility in other areas and enhance its generalisation.

In this regard, taking the advantages of BNs and ER approaches in dealing with complex uncertainties as well as non-linear relationships between risk parameters and outputs, a new FBR model is established and applied into multi-mode transportation system in this thesis. It extends to rail and road modes which probably involve more risk parameters, risk data uncertainties, more complex climate variables and relations among diverse networks to further verify the feasibility of the Fuzzy-Bayesian approach posed by Yang et al. (2015; 2016; 2018). In particular, in terms of risk parameters, previous studies have mainly investigated the impacts of risky external events to infrastructure (e.g., the likelihood and severity of consequence) but rarely taken into account the resilience of the infrastructure itself. A new risk parameter, namely "climate resilience", therefore, has been added to address this need. To facilitate large-scale data synthesis and analysis, software packages capable of dealing with uncertainty in data, namely Intrusion Detection System (IDS) (Yang & Xu, 2000) and Hugin (Andersen et al., 1989), are supported to develop a new user-friendly climate risk analysis and adaptation decision support tools.

3.5.2 A nationwide online survey on climate risk and adaptation assessment

The author conducted a nationwide survey to collect data by examining the perceptions of road stakeholders on the impacts of climate change, and the effects of adaptation to climate change. This survey aims to illustrate the general situation of climate risks in the UK road and railway systems and further justify the necessity of adaptation planning. The data collection contribute to climate risk assessment and prioritisation of adaptation measures for climate change. The raw data collected for the climate risk model is based on linguistic terms. Different with the traditional survey based on Likert scale where numerical values are employed to express the expert opinion. As discussed in the thesis and the critic from the literature, numerical crisp values are not suitable to model risk parameters in this study because of the high uncertainty they contain. It is the reason that linguistic terms and fuzzy numbers are hired to address such uncertainty. Their statistical analysis are inherently presented in the fuzzy-Bayesian based risk models (in Section 3.5.1). It is also believed to be a pioneering survey to investigate the climate risks and adaptation issues in both UK road and rail systems to fill the gaps of insufficient climate risk data and cost-benefit analysis in climate adaptations. In particular, it aims to deal with two questions:

1) What are the primary risks on the UK road and rail networks posed by climate change?
2) What are the most cost-effectiveness measures for the UK road and rail stakeholders to use to adapt to climate change?

To guarantee the validity of this questionnaire, a pilot study was undertaken in April 2017 by speaking with eight professional transport experts and academics in the UK[3]. It contributed to modifying several unclear or misleading wording and simplifying the structure of linguistic chooses to offer sufficient and efficient data for the FBR model. The population of this survey is the road and rail stakeholders in the UK. In the road survey, it included but was not limited to CEOs/transport directors, transport planners, transport engineers, environmental managers, private operators, transport authorities, highway agencies, road academics, and NGOs. Transport entities in charge of the major “M” and “A” roads in the UK were targeted as primary participants in the road survey. In rail, survey participants include rail companies and authorities, governmental departments, academics and NGOs etc. The databases of the national rail networks were used to select the transport entities (NR, 2016).

Given the uniqueness and complexity of climate change issues (e.g., the characteristics, geographic distribution, scales and types of climate risks on roads), non-probability sampling, including a combination method of judgment sampling and snowball sampling, was utilised in this survey (Wang, 2015). Some small entities in remote regions were excluded as they might lack necessary knowledge or experience of climate change issues, and the

[3] Basic information of survey participants in the pilot study can be found in Appendix A.

representativeness of the samples is more critical than its universality in judgment sampling (Vogt et al., 2012). Combining the above factors, participants for the road/rail survey sampling were selected from: 1) members of The UK Roads Liaison Group (UKRLG), members of the Railway Industry Association (RIA) and the Rail Freight Group (RFG), and 2) other main road and rail entities to provide the geographical balance for each area in the UK.

Afterwards, the author invited one or two critical participants from the targeted population to help distribute the questionnaire from the targeted 100 populations by a snowballing method. Suppose that the confidence level is 95%, the confidence interval is 8%, the standard deviation is 0.5, the sample size is computed as 60. Consequently, a sample of 60 participants representing the essential transport institutions of different regions in the UK (e.g., Highways England (HE), Network Rail (NR), Transport for Greater Manchester (TfGM), AECOM UK) was selected.

From May to December 2017, the 60 questionnaires were distributed through Bristol Online Survey (2017). E-mails and phone calls were used to contact all the respondents. In the end, the author received 39/60 (19 road, 20 of rail) usable responses with a high response rate of 65%. The survey questions are divided into two types: closed-end questions which utilise multiple choices, and a linguistic evaluation approach to quantify responses; and open-ended questions, which provide more freedom to respondents in generating data not necessarily anticipated by the question framing and design.[4]

3.5.3 Case studies

A qualitative approach is used to get access to a considerable amount of unpublished qualitative information, to analyse relationships and social process, which could be hard to achieve by only using quantitative methods (such as modelling) especially when data is scarce (Miles & Huberman, 1984). In addition to documental review, we conducted five semi-structured, in-depth interviews with the associated domain experts from HE, NR, Transport for London (TfL), Environment Agency (EA) and Devon County Council (DCC) in early 2018. Their positions included policymakers, transport planners, environmental specialists, and climate change advisors.[5]

[4] The questionnaire can be found in Appendix B1 and Appendix B2.

[5] Basic information of interviewees can be found in Appendix C.

The interview, as a commonly used qualitative method, was used to collect data in four case studies. These data were expected to reveal some "hidden" problems (e.g., the key factors, processes and references in a climate change adaptation plan) in adapting to the risks posed by climate change in the UK transport systems. Besides the primary threats posed by climate change, the interviews attempted to figure out the current risk assessment and planning processes, as well as the crucial elements and dilemmas in current and future adaptation planning for climate change. The primary interview questions were:

(1) What are the significant risks and uncertainties posed by climate change? Do road/rail stakeholders have an adaptation plan and measures to cope with such climate risks?

(2) How are these climate risks assessed in their entities? Is there a risk analysis system for climate change? What are the priorities and fundamental principles for adaptation planning in a short- and longer-term?

(3) How do road/rail decision-makers conceive the unique conditions of their entities? What kind of recourses, information and references has been used or would be used for adaptation planning?

(4) What are the perceptions of road/rail decision-makers on climate adaption planning? Who are the involved participants or will be involved in the climate adaptation planning process?

(5) What is the planning horizon of climate adaptation planning? What are the critical factors influencing the success of an effective climate adaptation plan?

These interview questions were semi-structured and open-ended in terms of their expected answers. The five corresponding issues were: Part A, identifying the vulnerabilities of rail and road posed by climate change; Part B, assessing risk and planning priorities; Part C, recognising the characteristics and differences between rail and road's conditions; Part D, analysing the preparation, environment and stakeholders involving an adaptation plan; Part E, implementing an adaptation plan and developing adaptation strategies.[6]

[6] The interview question framework can be found in Appendix D.

All the interviewees were asked similar major questions based on a pre-set framework, which gave interviewees enough time to prepare their answers and allowed us to cover all questions adequately. However, the author (as interviewer) did not strictly limit them only to answer the above questions but encouraged them to express their views freely to reflect their "real thinking" on climate risks and adaptation planning. After then, the author integrated multi-source evidence for triangulation, including the interviews, official reports, and local news and archival data, to enhance the validity of our understanding. The interview data was coded by a thematic coding analysis approach, which provided a practical and flexible approach to categorise and summarise the key characteristics of various qualitative data (Braun & Clarke, 2006).

Finally, both within-case (i.e., EA and TfL in London) and cross-cases (e.g., NR and HE) analyses were undertaken to compare and contrast the similarities and differences of the organisations' adaptation plan, which also reinforced the external and internal validity (Yin, 2003). First, in a single case, within-case analysis allows us to recognise the existing and potential climate risks and adaptation strategies by hearing diverse voices from different entities in a specific region (i.e., London). Cross-case analysis facilitates the development of a comprehensive view on how the rail and road adapt to the risks posed by climate change respectively, so as to reveal the common issues and potential collaborative opportunities in an integrated inland transport system.

In summary, Chapter 3 explores the methodology of this thesis by reviewing the fundamental research philosophy, strategies and approaches to justify the methods selected for this research and how they are developed. Through comparing the strengths and weaknesses of diverse research methodologies and linking to the research background, research audience and researcher's experience, this study is designed as an MMR, which is based on pragmatism and conducted by abductive approach. A series of quantitative and qualitative methods and their relevant analytical techniques utilised in this thesis, including mathematical modelling, questionnaire survey, case study, sampling, interviewing, qualitative comparative analysis as well as ethical considerations. In particular, the author detailed justifies how the three primary methods (i.e. FBR model, survey and case study) to cope with the impacts of climate change. Before the exploration of climate risks and adaptation measures in the UK rail and road sector, it is essential to review the relevant concepts in the FBR modelling and the model construction process in Chapter 4.

Chapter 4 A Novel Fuzzy Bayesian Reasoning Model for Adapting to the Impacts of Climate Change on Multi-mode Transportation Systems

This chapter starts by critically reviewing the basic ideas of fuzzy sets and fuzzy logic, Bayesian networks and evidential reasoning, and their technical evolution and applications in transport studies. After explaining the merits of utilising the Fuzzy Bayesian Reasoning approach to reason about climate adaptation, this chapter works through the step-by-step modelling/model construction process.

4.1 Critical Review

4.1.1 Fuzzy sets and fuzzy logic

There are three main types of uncertainty in mathematical approaches to risk analysis: fuzziness, randomness and incompleteness. Fuzziness is different from probability, but is concerned with vagueness and uncertainty in the set-membership and categorisation. As mentioned in Chapter 3, fuzziness is an ontological claim related to real world in which some cases are partial members of conceptual sets (Goertz & Mahoney, 2012). Mathematically, a fuzzy set can be defined by assigning each possible individual in the universe of discourse a value on behalf of its grade of membership in the fuzzy set (Klir & Yuan, 1995). Different from crisp boundaries which usually define separately diverse areas of the data by distinct lines, fuzzy boundaries are on behalf of wider areas of change that in determining the boundary, some regions are more significant than others.

In fuzzy set theory, a set A of universe X is defined by function μA (x), called the membership function of set A. Namely, $\mu A (x): X \rightarrow [0, 1]$, where $\mu A (x) = 1$ if x is totally in A; $\mu A (x) = 0$ if x is not in A; $0 < \mu A (x) < 1$ if x is partly in A. This set allows a continuum of possible grades of membership for each set member. For any element x of universe X, its membership function μA (x) defines the degree to which x is an element of set A. This degree of membership, a value between 0 and 1, is also called the membership value, of element x in set A.

One of the main approaches to reasoning under uncertainty is that offered by the possibility theory of fuzzy logic (Jenso, 2001). This is logic of classes with unsharp/fuzzy boundaries, and has been widely used to cope with the problem of computer understanding of natural language (Zadeh, 1992; 2010). Essentially, instead of crisp membership of classical binary logic, fuzzy logic is a set of mathematical principles for knowledge recreation based on degrees of membership (Zadeh, 1965). In qualitative studies of risk analysis, some popular methods have been developed on the basis of fuzzy logic, divided into logical operations based on fuzzy arithmetic calculation, and a logic based on rules. One of the crucial functions of fuzzy logic is to allow linguistic information, concepts and knowledge to be processed in an accurate mathematical manner. In other words, linguistic variables such as “very strong”, “weak” become an essential medium to describe continuous and overlapping states, by which qualitative reasoning statements can be integrated into fuzzy algorithms or fuzzy rule bases to create more “intelligent” models (Yang, 2006).

The notion of fuzzy logic was conceived by Zadeh in 1965, as the first innovative approach to addressing uncertainty alongside the developments of probability theory (Zadeh, 1965). Fuzzy set and fuzzy logic have been widely accepted tools in risk assessment, providing a theoretical framework to support expert decision making under uncertainty (Sii *et al.*, 2002). For instance, Singh & Benyoucef (2011) utilised Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS) as a sound solution for multi-criteria decision making (MCDM) problems in selection of supply chain coordination. Yang *et al.* (2011) employed F-TOPSIS for vessel selection under uncertain environments, and Yazdani-Chamzini (2014) applied Fuzzy Analytic Hierarchy Process (F-AHP) and F-TOPSIS for selection and evaluation of available handling facility.

Fuzzy set methods had also made successful attempts in climate risk assessment for climate change in recent years (Yang et al., 2015). For example, in some pioneering studies of climate risks assessment on ports (i.e., in Hong Kong, Taiwan and Mainland China), linguistic terms were regarded as variables, namely, the stakeholders' perceptions on climate impacts (Ng et al., 2013; Yang et al., 2015; 2016; 2018). The linguistic variables can be characterised by their membership functions to describe their degrees of membership. Three parameters closely related to climate change risks were identified by using the FMEA approach (Yang et al., 2008; 2009): timeframe (T), likelihood (L) and severity of consequences (C) (Ng et al., 2013; Yang et al., 2016). The stakeholders’ interpretations of climate risks’ frequencies, consequences and timeframes in which they occur, were used as subjective input data into the model, to estimate climate risks. In some early research, the fuzzy risk score R was defined by using a discrete fuzzy set, $R = C \circ (L \times T)$ (Ng et al., 2013) or a fuzzy set manipulation approach, $R = T \otimes C \otimes L$ (Yang et al., 2015). Nevertheless, neither of these methods could avoid the loss of useful information in fuzzy operations nor are capable of dealing with a huge amount of risk input data (Yang et al., 2016).

A novel Fuzzy-Bayesian model proposed by Yang et al. (2018a) overcame these issues by taking advantages of fuzzy rule bases (i.e., IF-THEN rules) in modelling non-linear relation between risk parameters and output and Bayesian networks in realising fuzzy rule integration and risk inference. Employing fuzzy IF-THEN rules in Fuzzy logic theory allows the antecedent and conclusion parts containing linguistic variables to model the qualitative features of experts' knowledge and reasoning process when there is a lack of precise quantitative analysis.

The assessment of climate change risks on the rail and road transportation systems in this thesis, is similarly in a context of scarce statistical data (UNCTAD, 2012); and, therefore, mainly conducted by using subjective judgments. It may contain various types of uncertainties including, but not limited to, fuzziness and incompleteness. Hence, the linguistic assessment can be an effective way to cope with such imprecision. However, such linguistic descriptions define risk assessment parameters to a discrete extent so that they can at times be inadequate. Thus, the fuzzy set theory is appropriate to model such subjective linguistic variables and cope with the discrete problem (Yang et al., 2008).

4.1.2 Bayesian networks

When multiple sets of data (from different experts) are employed, it is challenging to utilise standard fuzzy rule inference mechanisms, because the involved calculations are usually not very accessible to mathematically unsophisticated users. Bayesian networks (BNs) is an effective tool to minimise uncertainties and increase knowledge for the mathematically unsophisticated users. This is achieved by combining probability distributions or functions of different parameters, and updating their probabilities when new data emerges (Wang, 2003).

BNs, also known as "belief nets", "casual nets", "probabilistic networks", "Directed acyclic graphs" or "Bayesian belief networks", can be interpreted as "causal networks with the strength of the casual links represented as conditional probabilities" (Nielsen & Jensen, 2007). In a BN, each variable is represented as a node, and connected by directed links represented as arrow or arcs, with conditional probability table values assigned to the variables. In general, a BN consists of the following elements (Jensen & Nielsen, 2007, pp.33):

- *A set of variables and a set of directed edges between variables.*
- *Each variable has a finite set of mutually exclusive states.*
- *The variables together with the directed edges form an acyclic directed graph (traditionally abbreviated DAG); a directed graph is acyclic if there is no directed path A1 →· · ·→An so that A1 = An.*
- *To each variable A with parents B1,…, Bn, a conditional probability table P(A|B1,…, Bn) is attached.*

Bayes' theorem/rule, named after 18th-century British mathematician Thomas Bayes, is a mathematical formula for determining conditional probability and updating the subjective beliefs when new information emerges (Hayes, 1998). The probability of a parameter value given the observation is referred to as the posterior probability. This distinguishes it from the prior probability held by the analyst prior to the collection and analysis of the observation. If the model parameter is a discrete variable, then the formal definition of Bayes theorem can be symbolic. Given two events M and N such that P(M) ≠ 0 and P(N) ≠ 0, the posterior probability of M,

$$P(M|N) = \frac{P(N|M) \times P(M)}{P(N)}$$

where: "|" symbolises conditional probability,
P(M|N) denotes the posterior probability of M occurring given the condition/observation that N has occurred,
P(M) denotes the prior probability of M occurring, and this is what usually causes all the arguments in reasoning in this way,
P(N) refers to the marginal (total) probability of N occurring, and
P(N|M) refers to the conditional probability of N occurring given that M occurs too (It is often viewed in this sense as the likelihood distribution).

A critical aspect of Bayesian inference is that previous knowledge is allowed to be updated once new data becomes available. This process can be repeated any number of times, with the posterior probability playing the role of the prior for the next set of calculations (Lindley, 1970). In other words, the posterior probability of unobservable variables can be continuously updated by utilising the prior probability of all available ones. Hence, this theorem is especially useful in estimating knowledge about the probability distribution of variables of interest or making reliable predictions where direct observations by the researcher/modeller are unavailable, or data are hard to collect.

Given there are mutually exclusive and exhaustive events M_1, M_2,…M_y, such that $P(M_k) \neq 0$ for all k, $1 \leq k \leq y$, then the posterior probability of M_k

$$P(M_k|N) = \frac{P(N|M_k) \times P(M_k)}{P(N|M_1) \times P(M_1) + P(N|M_2) \times P(M_2) + \cdots\ P(N|M_y) \times P(M_y)}$$

Bayesian modelling is a proven interdisciplinary tool (Tebaldi et al., 2005). There are a variety of benefits with BNs including integrating different types of data within a framework, and efficiently being updated when new information becomes available (Castelletti & Soncini-Sessa, 2007, Cinar & Kayakutlu, 2010). In particular, BNs are capable of compensating the absence of historical statistics and handling incomplete uncertainty through combining various pieces of information and making use of expert judgments (Tighe et al., 2007). BNs has achieved a wide range of application in multiple fields in transportation, such as safety assessment (e.g. Yang et al., 2018b; Yang et al., 2018c), decision making (e.g. Arentze and Timmermans, 2009; Ulengin et al., 2007) and transport network analysis (e.g. Perrakis et al., 2012), which involve uncertainty due to incomplete data and limited cognitive capacity (Zhang et al., 2013). It was employed for the estimation of future climate change conditions, such as precipitation mean state and seasonal cycle in South Africa (Boulanger et al., 2007) and quantitative prediction and assessment of long-term shoreline change related to SLR and its uncertainty (Gutierrez et al., 2011). Combining with System Dynamics (Yeo et al., 2013), Bertone et al. (2015) integrated BNs into the development of a risk evaluation tool for managing water-associated health risks related to extreme weather.

Nevertheless, a significant disadvantage of BNs in incorporating expert judgements is that it may fail to probabilistically forecast subjective fuzziness in a precise way as it lacks understanding of possibility theory. It usually requires too much information in prior probabilities which are hard to receive in risk analysis. Also, this information mainly relies on subjective judgments provided by experts' knowledge, which introduce unexpected bias into BN formulations (e.g., Tversky & Kahneman, 1975; 1990). BNs may also be computationally inefficient if a great number of variables involve in models at a parent level (Liang & Lee, 2008); in particular, BNs cannot process time-series data and address feedback regulations (Ristevski, 2013).

To compensate these disadvantages of BNs, theoretical and applied research have identified some benefits from combining fuzzy logic and Bayesian reasoning, especially in the applications of Fuzzy-Bayesian approaches in safety and reliability research (Bott & Eisenhawer, 2002). Fuzzy Bayesian Networks which links fuzzy set theory to BNs was formed to deal with randomness and fuzziness of uncertainty relying on a single approach (Yang, 2006). Nevertheless, one typical problem with this method is that it might ignore the requirement of "completeness" of states and the complexity of computing algorithms (Yang, 2006). Therefore, more advanced and efficient methods are required to improve structure learning algorithms, allowing for constraints based upon experts' knowledge, with precise rules for managing risks and making decision (Zhou et al., 2014; Constantinou et al., 2016).

Overall, the evaluation of climate change risks in the road and rail systems in this thesis contains various types of uncertainty. Similarly, due to the scarcity of historical/statistical data, this research is mainly carried out by subjective judgments. Hence, a fuzzy set method through modelling subjective linguistic variables can help tackle these issues (Yang et al., 2018a).

Through combining fuzzy set theory and BNs, the author proposes a well justified approach to model subjective linguistic variables, cope with the discrete problem, and handle incomplete information and uncertainty. Previous studies using FBR in climate risk analysis have exposed modelling weaknesses, including definition of risk variables not being specific enough for easily accommodating expert judgements. An innovation of the current work is evidenced in the fact that there are no previous empirical studies on the use of advanced uncertainty modelling in climate risk analysis in the road and rail sectors. Therefore, this study, through creating a new FBR model with applications in the UK road and road transportation systems, will provide planners a more feasible and standardised thinking pattern in risk assessment to be used in diverse transport modes.

4.1.3 Evidential reasoning

In evidential reasoning, there is an inadequate solution to addressing the challenge in an inconsistent unit express of risk and costs (Yang et al., 2015). To overcome this challenge together with uncertainties of this risk model including incompleteness and randomness, a methodology combining fuzzy set modelling and evidential reasoning (ER) is proposed to make full use of the information to obtain climate risk and adaptation cost synthesis without any available information loss (Wang et al., 1996). The theory of evidence generated by

Dempster (1967) and Shafer (1976) provides a solid foundation for ER within this thesis, namely Dempster-Shafer theory or D-S theory. As a reasoning tool initially used for data aggregation in expert systems (Buchanan & Shortliffe, 1984), D-S theory has been applied into risk decision making under uncertainty contrary to Bayesian decision theory (Yager, 1992; 1995). Based on the development of D-S theory, ER has been widely utilising in a variety of research for expressing and assessing uncertainty in decision making (e.g., Denœux 1999; Murply, 2000).

One of the crucial contributions of applying ER in decision making, as Beynon et al. (2000) noted, is integrating it into conventional MCDM approaches. Since the early 1990s, ER based methods in decision making for MCDM problems have been developed with both quantitative and qualitative criteria under uncertainty (Yang & Sign, 1994; Yang & Sen, 1994). Compared with D-S theory, a significant achievement of ER relies on the fact that it is based on a distributed framework that degrees of belief (DoBs) at lower level criteria are aggregated through their weightings, so as to overcome the drawback of the D-S theory when there is conflicting evidence (Yang, 2006).

On the grounds of early works (e.g., Yang & Singh, 1994; Yang & Sen, 1994; Yang, 2001), ER approach has been developed, improved and modified to achieve greater rationality in effectively synthesising pieces of evaluation from various criteria and/or evaluators (Yang & Xu, 2002; Yang et al., 2016). In continuously researching and practising processes, the main ideas/innovations of this method include: handling incomplete, uncertain and imprecise data so as to avoid the loss of useful information in their inference processes (Yang & Sigh, 1994), overcoming the main problem of aggregation of preference in utilizing fuzzy decision making tools (Herrera et al., 1997), and providing its users flexibility to express their judgements in both a quantitative and subjective way (Yang, 2006). The illustration of applying the ER to climate risk and cost analysis often starts with describing its inherent algorithm. The latest algorithm, which has been analysed and fully explained (Yang and Xu, 2002; Yang et al., 2005), has been included in some climate adaptation studies (Yang et al., 2015; Yang et al., 2016). Based on these, the details of the algorithm are explained step-by-step in 4.2.

In a recent study, Wan et al. (2018a) quantitatively assessed the state quo of international green port development. On the basis of the Drivers, Pressures, States, Impacts and Responses (DPSIR) framework, they utilised the analytic hierarchy process (AHP) and evidential reasoning (ER) methods to calculate the weight of 16 indexes in the hierarchical model mathematic model. The model was further examined by a case study composing of five major Chinese ports. Alyami et al. (2014) applied Fuzzy Rule-Based Bayesian Networks (FRBN) method into the evaluation of container port safety. Based on traditional Failure Mode and Effects Analysis (FMEA) approach, through combining the advantages of FRB and BN techniques, the new model allowed users to flexibly describe input failure information and easily update real-time risk analysis results.

Another study developed a novel port performance measurement model though using a hybrid approach of decision making trial and evaluation laboratory (DEMATEL) tool, analytical network process (ANP) and fuzzy evidential reasoning (FER) (Ha et al., 2017). In particular, as qualitative port performance indicators are sometimes too ambiguous to be adequately understood due to subjective evaluation issues, fuzzy logic was exerted to address such vagueness. Afterwards, the ER was utilised to synthesise the assessment results of all performance indicators from different dimensions. This model, by combining both quantitative and qualitative port performance indicators, provided port stakeholders with a sound tool for performance evaluation.

The fuzzy-rule-based evidential reasoning (FRB-ER) approach, based on the concept of DoB to model the knowledge incompleteness of decision makers in using fuzzy linguistic variables to estimate the attribute values, has been applied into risk analysis of maritime security (Yang et al., 2009). In recent years, fuzzy set, BNs and ER methods have been applied to climate risk assessment on ports in several pioneering studies by a group of scholars (Ng et al., 2013; Yang et al., 2015; 2016; 2018). Through modelling subjective linguistic variables extracted from the stakeholders' perspectives, climate risks are evaluated based on their occurrence frequencies, the severity of consequences and timeframes of climate risks.

Despite showing some attractiveness, such studies yet reveal applicable concerns in practice, including the difficulty of accurately evaluate the severity of consequence, and lack of empirical evidence on feasibly adopting it from seaports to another transport context. More specifically, in previous studies (e.g., Yang et al., 2018a), risk variables were defined at a high level, which reduced the confidence of experts in carrying out their evaluations for climate change impacts. For instance, the consequences of climate change on many occasions need to be further interpreted from three perspectives including economic loss, human injuries/deaths, and environmental damage. The use of raw data/subject judgements from experts, separately presented from these three perspectives to model climate risk consequences in this thesis, will provide a more rational and better climate risk evaluation mechanism. With reference to risk parameters, previous studies have mainly investigated the impacts of risky external events to infrastructure (e.g., the likelihood and severity of consequence) but not yet taken into account the resilience of the infrastructure itself.

Wan et al. (2018b) emphasised the necessity of incorporating the diverse characterises of transportation resilience into a new evaluation framework, together with advanced quantitative modelling methods to deal with uncertainties in resilience assessment. Hence, in this thesis, a new risk parameter namely "climate resilience" has been added to address this need. It can be interpreted as the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a required period and cost of recovery (IPCC, 2012a). Nevertheless, it noted that previous Fuzzy Bayesian modelling studies have only been applied in the port area, while a systematic climate risks and adaptation framework for the other transportation systems has yet been created. Therefore, as stated in thesis, it is vital to collect more empirical evidence to prove the model's feasibility in rail and road systems for climate adaptation and enhance its generalisation. In this regard, taking the advantages of BNs and ER approaches in dealing with complex uncertainties as well as non-linear relationships between risk parameters and outputs, a new Fuzzy Bayesian Reasoning (FBR) model is established and applied into multi-mode transportation systems in this thesis.

4.2 A Novel Fuzzy Bayesian Reasoning Climate Risk Analysis Framework

In this section, the FBR risk analysis model for port adaptation to climate change (Yang et al., 2018) has been tailored to apply in the rail and road sectors, with new risk parameters and risk inference hierarchical structure. The following step-by-step description is therefore mainly focused on the new developments with new primary empirical information appropriately presented.

4.2.1 Identify environmental drivers

Based on the literature review (e.g., Jenkins et al., 2009; Jaroszweski et al., 2010; Hooper & Chapman, 2012; Dora, 2012; NR, 2015; RSSB, 2016), the author investigates four primary environmental drivers due to climate change affecting British roads and railways: 1) temperature increase, 2) intense rainfall /flooding, 3) more intense and/or frequent high wind and/or storms, and 4) sea level rise. Hence, the risk analysis is made with respect to each of these environmental drivers, to evaluate the climate risk level of their corresponding potential climate threats. During this process, all critical climate threats are first identified, then examined by 16 transport experts via a preliminary study, and then finally listed in the questionnaire survey for further evaluation.

4.2.2 Identify climate risk variables

First, eight climate risk parameters are newly identified and presented in a hierarchy structure of three levels respectively. On the first level is the top parameter called "*Climate Risk Level (CRL)*". It can be described by linguistic terms such as *"Very High", "High", "Medium", "Low" and "Very Low"* (e.g. Ng et al., 2013; Yang et al., 2015; 2016). On the second level, there are four parameters associated with climate risk evaluations. The linguistic terms used to describe the first three parameters *"Timeframe (T)", "Likelihood (L)" and "Severity of Consequences (C)"* in this level are consistent with those used in previous studies on port adaptation to climate change (e.g. Yang et al., 2008; 2009; Ng et al., 2013; Yang et al., 2016). Definitions of parameters can be found in Tables 4.1-4.4. For example, *"Timeframe"* means 'when does an expert expect first to see this climate change impact'. Hence, the sooner he/she expect to see this impact, the higher risk level will be. Timeframe has been widely used to describe climate risks in previous studies (e.g. Yang et al., 2008; 2009; Ng et al., 2013; Yang et al., 2016). It has also been validated in the pilot study by the domain expert in the road transport sector.

To reflect new climate adaptation studies, the author adds a new parameter "*Climate Resilience (S)*" (IPCC, 2012) in this study after a careful consultation from the domain experts, which is descripted as *"Very Weak", "Weak", "Average", "Strong"* and *"Very Strong"*. Here, the new parameter "*S"* implies how resilient the infrastructure or operations are to the investigated climate threat. Because the traditional risk consequences are categorised into three groups including loss of life or injury, economic and environmental impacts and infrastructure damage (UNISDR, 2017), the *"Severity of Consequences (C)"* is divided into three sub-parameters: *"Damage to Infrastructure (INF)"*, *"Injuries and/or Loss of Lives (INJ)"*, and *"Damage to Environment (ENV)"*. All of definitions of the above parameters, sub-parameters as well as the descriptions of their linguistic terms are carefully examined by domain experts with reference to previous works in subjective risk modelling

(Wang et al., 2018a, 2018b). Figure 4.1 indicates a complete three-tier structure of parameters.

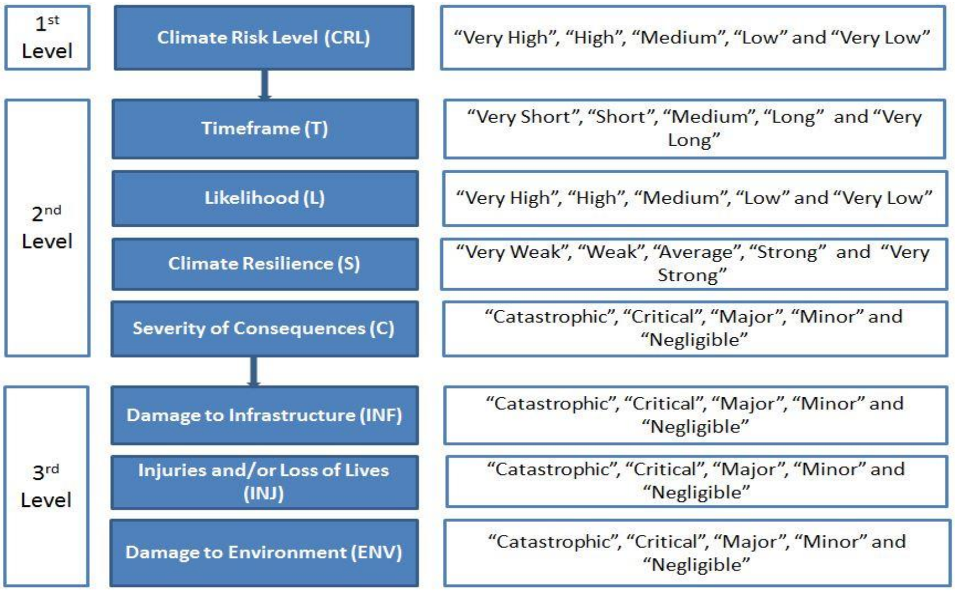


Figure 4.1 Three-tier structure of parameters

Under fuzzy logic theory, the existing situational elements in risk analysis are each allocated a value or degree to a linguistic term used to describe the risk parameters. Triangular and trapezoidal membership functions are selected in this thesis, given they are simple/accessible to a wide audience, and also commonly used in risk analyses (e.g., Dyck et al., 2014). These functions are based on the literature (e.g. Yang et al., 2018a), and domain experts' verification, expressed by five sets of overlapping triangular or trapezoidal curves, which are shown in Tables 4.1-4.4.

Table 4.1 Timeframe — when you expect to first to see this impact

Grade	Linguistic terms	Approximate timeframe	Fuzzy memberships
1	Very Short (VS)	<1 year	**(0, 0, 0.1, 0.3)**
2	Short (S)	1-5 years	**(0.1, 0.3, 0.5)**
3	Medium (M)	5-15 years	**(0.3, 0.5, 0.7)**
4	Long (L)	15-20 years	**(0.5, 0.7, 0.9)**
5	Very Long (VL)	>20 years	**(0.7, 0.9, 1, 1)**

Table 4.2 Likelihood that the effect will occur

Grade	Linguistic terms	Likelihood	Fuzzy memberships
1	Very High (VH)	>90%	**(0, 0, 0.1, 0.3)**

2	High (H)	60-90%	**(0.1, 0.3, 0.5)**
3	Average (A)	40-59%	**(0.3, 0.5, 0.7)**
4	Low (L)	10-39%	**(0.5, 0.7, 0.9)**
5	Very Low (VL)	<10%	**(0.7, 0.9, 1, 1)**

Table 4.3.1 Severity of Consequence — Damage to infrastructure

Grade	Linguistic terms	The damage committed to property is valued	Fuzzy memberships
1	Catastrophic (CA)	>£2million	**(0, 0, 0.1, 0.3)**
2	Critical (CR)	£1million - £2million	**(0.1, 0.3, 0.5)**
3	Major (Ma)	£500,000 - £999,999	**(0.3, 0.5, 0.7)**
4	Minor (MI)	£100,000 - £499,999	**(0.5, 0.7, 0.9)**
5	Negligible (NE)	<£100,000	**(0.7, 0.9, 1, 1)**

Table 4.3.2 Severity of Consequence — Injuries and/or Loss of Life

Grade	Linguistic terms	Injuries and/or loss of life	Fuzzy memberships
1	Catastrophic (CA)	Life-threatening injuries or loss of life	**(0, 0, 0.1, 0.3)**
2	Critical (CR)	Major injuries and lost time incident	**(0.1, 0.3, 0.5)**
3	Major (Ma)	Injuries and lost time incident	**(0.3, 0.5, 0.7)**
4	Minor (MI)	Minor injuries, no lost time incidents	**(0.5, 0.7, 0.9)**
5	Negligible (NE)	No injuries, no lost time incidents	**(0.7, 0.9, 1, 1)**

Table 4.3.3 Severity of Consequence — Damage to Environment

Grade	Linguistic terms	The percentage of this event contributes to the total amount of damage of surrounding environment	Fuzzy memberships
1	Catastrophic (CA)	>50%	**(0, 0, 0.1, 0.3)**
2	Critical (CR)	30-50%	**(0.1, 0.3, 0.5)**
3	Major (Ma)	20-29%	**(0.3, 0.5, 0.7)**
4	Minor (MI)	10-19%	**(0.5, 0.7, 0.9)**
5	Negligible (NE)	<10%	**(0.7, 0.9, 1, 1)**

Table 4.4 Climate Resilience[7]

Grade	Linguistic terms	Description	Fuzzy memberships

[7] The climate resilience can be influenced by three factors. The worst-case scenario is applied to assess the system's resilience for simplifying the description to allow experts choose linguistic terms. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

1	Very Weak (VW)	Very weak (0-20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery(£10million above)	**(0, 0, 0.1, 0.3)**
2	Weak (W)	Weak (20-39%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)	**(0.1, 0.3, 0.5)**
3	Average (A)	Average (40-59%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a certain length of time (a week) and cost of recovery (£100,001-£1million)	**(0.3, 0.5, 0.7)**
4	Strong (S)	Strong (60-80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,001-£100,000)	**(0.5, 0.7, 0.9)**
5	Very Strong (VS)	Very strong (80% above) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring a slight cost of recovery (0-£10,000)	**(0.7, 0.9, 1, 1)**

Source: IPCC (2012a)

4.2.3 Model the relation between low level and high-level variables using fuzzy rule bases

A typical feature of fuzzy logic systems is knowledge-based or rule-based one based on human knowledge and expressed by fuzzy IF-THEN rules (Wang, 1997). IF-THEN rules collected from expert's knowledge are combined into a single system, by which the fuzzy theory offers an efficient transformation from knowledge bases to non-linear mappings (Sii & Wang, 2002; Yang, 2010).

A complete IF-THEN rule consists of two components: an antecedent which response to the fuzzy input, and a consequence which is the fuzzy output. In a traditional fuzzy rule-based (FRB) system, the input and output are usually expressed by single linguistics variables with 100% certainty and the rules are also regarded as a single output case. For instance, a fuzzy

IF-THEN rule having multiple antecedents, for example, can be structured as: IF T is "Very Short", L is "Very High", C is "Catastrophic", S is" Very Weak", THEN CRL is "Very High". A typical expression of IF-THEN rule in climate risk analysis is:

$$Rule_n\text{: IF } t_n \text{ and } c_c \text{ and } l_n \text{ and } S_n\text{, THEN } r_n \tag{4.1}$$

Here, t_k, c_k l_k and S_n represent linguistic variables of *T, C, L and S* used in the n_{th} rule, $Rule_n$, respectively; r_n describes the results in $Rule_n$ expressed by one of the five linguistic variables, such as {Very Short (r_1), Short (r_2), Medium (r_3), Long (r_4), Very Long (r_5)}.

However, in some real cases, the knowledge representation power of the fuzzy rule systems could be restricted if only single variables are used to express uncertain knowledge. Hence, in order to enhance the ability of the traditional fuzzy IF-THEN rule in modelling the correlation between premise and conclusion, a simple IF-THEN rule can be extended to a belief rule with every possible consequences associated with belief degrees. A collection of belief rules consists of a FRB with complete belief structure is defined as follows (Yang et al., 2008):

$$Rule_n\text{: IF } t_n \text{ and } C_n \text{ and } l_n\text{, and } S_n\text{ , THEN } \{(\beta_k^1, r_1), \ldots, (\beta_k^5, r_5)\}(\sum_{j=1}^{5} \beta_k^j = 1) \tag{4.2}$$

To model the incomplete data from expert judgements, subjective DoBs are utilised and assigned to the linguistic terms to represent the uncertainty in data. For instance, a fuzzy rule with DoB, describing the first and second level risk parameters, can be developed as follows:

If T is Very Short (VS), L is Very High (VH), C is Catastrophic (CA) and S is Weak (W), then CRL is Very High with a 75% DoB, High with a 25% DoB, Medium with a 0% DoB, Low with a 0% DoB and Very Low with a 0% DoB. (4.3)

The rationalisation of the DoB distribution of these rules is achieved by a proportion method (Alyani et al., 2014). Consequently, four second-level fuzzy input parameters including 20 (5+5+5+5) linguistic variables are assembled to generate 625 (5×5××5×5) antecedents with appropriate DoB distribution to the conclusions (i.e., the THEN part). Simultaneously, the author construct a third-level network between the three parameters (INF, INJ and ENV) and the second-level parameter C, containing 15 (5+5+5) linguistic variables assembling to create 125 (5××5×5) antecedents. Table 4.5 indicates a complete FRB with belief structure concerning relationships between the four main input parameters and climate risks level.

Table 4.5 FRB with belief structures for climate risk analysis

Rules	Antecedent Attributes				Climate Risk Level (CRL)				
	Timeframe (*T*)	Likelihood (*L*)	Severity of Consequence (*C*)	Climate Resilience (*S*)	Very High	High	Medium	Low	Very low
1	Very Short (VS)	Very High (VH)	Catastrophic (CA)	Very Weak (WV)	100%	0	0	0	0
2	VS	VH	CA	Weak (W)	75%	25%	0	0	0
3	VS	VH	CA	Average (A)	75%	0	25%	0	0
…	…	…	…	…	…	…		…	…
623	Very Long (VL)	Very Low (VL)	Negligible (NE)	A	0	0	25%	0	75%
624	Very Long (VL)	Very Low (VL)	Negligible (NE)	Weak (W)	0	0	0	25%	75%
625	Very Long (VL)	Very Low (VL)	Negligible (NE)	Very Strong (VS)	0	0	0	0	100%

4.2.4 Prioritise risk levels by a BN technique

The employment of multiple sets of data makes it hard to use normal fuzzy rule inference mechanisms as the calculation causes loss of information and takes a long time. BN, as a sound mathematical method in minimising the uncertainties and increasing knowledge, is able to integrate probability distributions or functions of diverse parameters and update their probabilities if new information emerges (Wang, 2003). It has been widely used in risk diagnosis and prediction in various areas, such as quantitative prediction and assessment of coastline change due to sea level rise (Gutierrez et al., 2011) and water-related health issues triggered by extreme weather events (Bertone et al., 2015). In this study, BN is utilised to facilitate the synthesis of fuzzy rules and to evaluate climate risks in a semi-automation manner.

After constructing the FRB structure, it can be used to conduct risk inference using a BN technique. First of all, the rule base with belief structures is expressed in the form of conditional probabilities. According to formula (4.2), taking the rule base of the first and second level as an example, it can be represented as:

R_3: IF Very Short (T1), Very High (L1), Catastrophic (C1) and Weak (S2), THEN {(75%, Very High (R1)), (25%, High (R2)), (0%, Medium (R3)), (0, Low (R4)), (0, Very Low (R5))}. (4.4)

Furthermore, it can be further expressed in the form of conditional probability as:

Given *T1*, and *L1*, *C1* and *S2*, the probability of *CRLh* (*h* = 1, …, 5) is (0.75, 0.25, 0, 0,0) or
$p(CRLh|T1, L1, C1, S2) = (0.75, 0.25, 0, 0, 0)$ (4.5)

where "|"symbolises conditional probability.

Similarly, FRB constructed in Table 4.5 can be modelled and converted into a five-node converging connection. It includes four parent nodes, N_T, N_L, N_C and Ns (Nodes *T*, *L*, *C* and *S*); and one child node N_{CRL} (Node *CRL*). After transferring the rule base into a BN framework, the rule-based risk inference for the failure criticality analysis is simplified as the calculation of the marginal probability of the node N_{CRL}. To marginalise *CRL*, the required conditional probability table of N_{CRL}, $p\ (CRL|T, L, C, S)$, can be obtained using (4.5), together with the FRB shown in Table 4.5. It indicates a 5×5×5×5×5 table containing values $p(CRLh|Ti, Lj, Ck, Sl)(h, i, j, k \text{ or } l = 1, \ldots, 5)$.

In the questionnaire survey, the author ask participants to estimate the impacts of a particular climate threat on their road or rail networks regarding *"Timeframe", "Likelihood", "Severity of consequence"* and *"Climate resilience"* with reference to their individual linguistic terms, so as to obtain the prior probabilities of all four nodes. The prior probabilities of N_L, *p(L)*, for example, can be obtained by asking the question, "how likely the effect will occur when you expect first to see this climate threat poses impacts on the railway/road that your organisation is associated with?". The author averaged all the data received from different experts. For the multiple data from one group, the data was firstly averaged within the group to minimise the input of obvious subjective bias. Through analysing all the prior probabilities, the marginal probability of N_{CRL} can be computed based on the given prior probabilities (Jensen, 2001):

$$p(CRLx) = \sum_{a=1}^{5} \sum_{b=1}^{5} \sum_{c=1}^{5} \sum_{d=1}^{5} p(CRLx|T_a, L_b, C_c, S_d)p(T_a)p(L_b)p(C_c)p(S_d)(x = 1, \ldots, 5)$$

(4.6)

Where a, b, c and d can be any defined linguistic variables (e.g., from *"Very Short"* to *"Very Long"* for a) of the four parameters in order. It is not helpful to rank the identified climate risks unless the utility values of the given linguistic terms are defined. The linguistic description can then be converted into a crisp value using a centroid defuzzification method (Yang *et al.*, 2009) (finding centre of area or centre of gravity) method as *CRLx (x=1,…,5)=* {0.11, 0.3, 0.5, 0.7, 0.89} (Timothy, 2010, pp.102). Finally, a new risk criticality ranking index (RY) is generated as follows:

$$RY = \sum_{x=1}^{5} p(CRLx) U_{CRLx} \tag{4.7}$$

After the allocation of utility values to the linguistic terms of N_{CRL}, the final climate risk ranking value is obtained by multiplying the obtained marginal probabilities and the associated utility value of the climate risk levels. As the risks were evaluated from the highest to lowest level (e.g., from "*Very High"* to *"Very Low"*), therefore, the lower the climate risk ranking value, the higher the risk level is.[8] When adaptation measures involve, the risk reduction (RR_{mn}) of the m^{th} climate threat by the use of the n^{th} adaptation measure can be obtained as follows:

$$RR_{m,n} = RI_{m,n} - RI_m = \sum_{x=1}^{5} p(CRLx)' U_{CRLx} - \sum_{x=1}^{5} p(CRLx) U_{CRLx} \tag{4.8}$$

Here, $RI_{m,n}$ and RI_m represent the risk indexes of the m^{th} climate risk with and without the n^{th} adaptation measure respectively. The author then utilises the Hugin software to simplify the calculations (Andersen et al., 1989). Using the above equations and the Hugin software, the reduction of risk level between with and without the adaptation measures can calculated.

[8] The risk result from the fuzzy Bayesian model was presented by grade assessment with belief degrees. To obtain a crisp value to prioritise the climate threats, the author assigned each assessment grade a utility value and then calculated the final risk score by the addition of multiplying the belief degree associated with a specific grade and the grade's utility value.

4.3 Synthesises of Climate Risk Estimates and Adaptation Costs by ER Algorithm

This section applies an ER approach to synthesise the risk reductions results obtained by fuzzy Bayesian method and the associated adaptation costs data from the questionnaire survey to select the most cost-effective adaptation measures (Yang et al., 2015; Yang et al., 2016). The risk reductions can be calculated by the described FBR model as the corresponding adaptation costs were collected through survey and expert opinions.

4.3.1 The algorithm pathway

The latest algorithm can be analysed and explained in the context of climate adaptation by the following pathway:

Let A be the set of risk estimate with five grades (B_1, B_2, B_3, B_4, B_5), which has been synthesised from two subsets A1 and A2 associated with β_1^j and β_2^j (j=1, 2, 3, 4, 5). Then, **A**, *A1* and *A2* can separately be expressed by (Yang et al., 2013):

$A = \{\beta^1 B_1, \beta^2 B_2, \beta^3 B_3, \beta^4 B_4, \beta^5 B_5\}$

$A1 = \{\beta_1^1 B_1, \beta_1^2 B_2, \beta_1^3 B_3, \beta_1^4 B_4, \beta_1^5 B_5\}$

$$A2 = \{\beta_2^1 B_1, \beta_2^2 B_2, \beta_2^3 B_3, \beta_2^4 B_4, \beta_2^5 B_5\} \quad (4.9)$$

where $\sum_{j=1}^{5} \beta^j$, $\sum_{j=1}^{5} \beta_1^j$ and $\sum_{j=1}^{5} \beta_2^j$ equal 1.

Suppose the normalised relative weights of two risk assessors in the risk evaluation process are given as $\omega 1$ and $\omega 2$, and $\omega 1 + \omega 2 = 1$, where, $\omega 1$ and $\omega 2$ can be estimated by using established methods such as simple rating methods or more elaborate methods based on the pair-wise comparisons (Yang et al., 2001). Suppose M_1^j and M_2^j ($j = 1, 2, 3, 4, 5$) are individual degrees to which the subsets A1 and A2 support the hypothesis that the synthesised evaluation is confirmed to the five grades. Then, M_1^j and M_2^j can be obtained as follows:

$$M_1^j = \omega 1 \beta_1^j \text{, and } M_2^j = \omega 2 \beta_2^j \quad (4.10)$$

where $j = 1, 2, 3, 4, 5$. Therefore,

$M_1^1 = \omega 1\beta_1^1, M_1^2 = \omega 1\beta_1^2, M_1^3 = \omega 1\beta_1^3, M_1^4 = \omega 1\beta_1^4, M_1^5 = \omega 1\beta_1^5$

$M_2^1 = \omega 2\beta_2^1, M_2^2 = \omega 1\beta_2^2, M_2^3 = \omega 1\beta_2^3, M_2^4 = \omega 1\beta_2^4, M_2^5 = \omega 1\beta_2^5$

Suppose H_1 and H_2 are the individual remaining belief values unassigned for M_1^j and M_2^j (j = 1, 2, 3, 4, 5). Then, H_1 and H_2 can be expressed as follows (Yang & Xu 2002):

$$H_1 = \overline{H_1} \times \tilde{H}_1,\ H_2 = \overline{H_2} \times \tilde{H}_2 \tag{4.11}$$

Where $\overline{H_m}$ (m = 1 or 2), which represents the degree to which other assessors can play a role in the assessment, and $\tilde{H}_m$ (m= 1 or 2), which is caused due to the possible incompleteness in the subsets A1 and A2, can be described as follows respectively:

$$\overline{H_1} = 1 - \omega 1 = \omega 2,\ \overline{H_2} = 1 - \omega 2 = \omega 1 \tag{4.12}$$

$$\tilde{H}_1 = \omega 1\ (1 - \sum_{j=1}^{5} \beta_1^j) = \omega 1\ [1 - (\beta_1^1 + \beta_1^2 + \beta_1^3 + \beta_1^4 + \beta_1^5)], \text{ and}$$

$$\tilde{H}_2 = \omega 2\ (1 - \sum_{j=1}^{5} \beta_2^j) = \omega 2\ [1 - (\beta_2 + \beta_2^2 + \beta_2^3 + \beta_2^4 + \beta_2^5)] \tag{4.13}$$

Suppose $\beta^{j'}$ (j = 1, 2, 3, 4, 5) represents the non-normalised degree to which the climate risk evaluation is confirmed to the five risk expressions as a result of the synthesis of the judgments produced by assessors 1 and 2. Suppose H_U' represents the non-normalized remaining belief unassigned after the commitment of belief to the four safety expressions as a result of the synthesis of the judgments produced by assessors 1 and 2. The ER algorithm can be stated as follows:

$$\beta^{j'} = K\ (M_1^j M_2^j + M_1^1 H_2 + H_1 M_2^j) \tag{4.14}$$

$$\overline{H_U}' = K\ (\overline{H_1}\ \overline{H_2}) \tag{4.15}$$

$$\tilde{H}_U' = K\ (\tilde{H}_1 \tilde{H}_2 + \tilde{H}_1 H_2 + H_1 \tilde{H}_2) \tag{4.16}$$

$$K = (1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_1^T M_2^R)^{-1} \tag{4.17}$$

After the above aggregation, the combined degrees of belief β^j are generated by assigning back to the five control modes using the following normalisation process:

$$\beta^j = \beta^{j'} / (1 - H_U')\ (j = 1, 2, 3, 4, 5) \tag{4.18}$$

$$H_U = \tilde{H}_U' / (1 - H_U') \tag{4.19}$$

The whole calculation process can be computerised by the ER software IDS (Yang and Xu, 2002). As indicated in Equation (4.9), the two subsets need to be expressed on the same utility universe in order to have the ER applied for the synthesis. Referring to previous climate adaptation research on ports, the fuzzy membership functions of "Cost-effectiveness of adaptation measure" were as "*Very effective", "Effective", "Average", "Slightly effective"* and *"Ineffective"* (Yang et al., 2015; 2016; 2018). The fuzzy membership functions of "Cost-effectiveness of adaptation measure" in this model utilise the same five-level definitions as previous climate adaptation research on ports (e.g., Yang et al., 2018). However, in the cost-effectiveness evaluation of adaptation measures, risk reduction is expressed by a crisp value through Equation (4.8) (i.e. quantitative data), while the cost evaluations will be largely conducted by domain experts using linguistic terms (i.e. qualitative data). To facilitate the synthesis, both quantitative and qualitative data are transformed into the same scale.

4.3.2 Risk reduction modelling

In Section 4.2.4, the risk reduction of the i[th] climate threat by the j[th] adaptation measure is expressed by RR_i^j. To map the numerical RR_i^j onto the five defined cost-effectiveness expressions, five risk reduction grades are first defined as {RD^1, RD^2, RD^3, RD^4, RD^5} and calculated as follows, respectively.

$$RD_1 = \max\{ RR_i^j \}$$
$$RD_2 = \frac{RD^1 + RD^3}{2} = \frac{3\max\{RR_i^j\} + \min\{RR_i^j\}}{4}$$
$$RD_3 = \frac{RD^1 + RD^5}{2} = \frac{\max\{RR_i^j\} + \min\{RR_i^j\}}{2}$$
$$RD_4 = \frac{RD^3 + RD^5}{2} = \frac{\max\{RR_i^j\} + 3\min\{RR_i^j\}}{4}$$
$$RD_5 = \min\{ RR_i^j \} \tag{4.20}$$

Hence, RR_i^j can be expressed by RD_m (*m=1, 2, 3, 4, 5*) when $RR_i^j = RD_m$. When $RR_i^j \neq RD_m$, RR_i^j belongs to RD_m with a belief degree of $\frac{RD_{m+1} - RR_i^j}{RD_{m+1} - RD_m}$ and RR_i^j belongs to RD_{m+1} with a belief degree of $\frac{RR_i^j - RD_m}{RD_{m+1} - RD_m}$.

(4.21)

When an adaptation measure contributes to the maximal risk reduction (e.g., RD_1), it is considered to be *"Very effective"* in the utility universe as far as the risk factor is concerned.

Similarly, when risk reduction is RD_2, RD_3, RD_4 or RD_5, the adaptation measure is *"Effective", "Average", "Slightly effective"* or *"Ineffective"*, respectively.

4.3.3 Cost modelling

Normally, risk reduction and cost are two conflicting objectives, with higher risk reduction leading to higher costs. This means that if the risk reduction associated with an adaptation measure is improved, higher costs could happen. The cost incurred for the risk reduction associated with an adaptation measure is usually affected by many factors that consist of high uncertainties, largely depend upon the implementation of new adaptation measures. In the early design stage, it can be challenging to assess the factors in quantitative forms. With the fuzzy approach in risk estimation, it is common that decision makers often prefer to estimate costs incurred in risk reduction using a qualitative way, namely linguistics variables (Wang et al., 2006). The cost incurred due to adaptation measures can be described using linguistic variables such as {*"Very high", "High", "Average", "Low", "Very low"*}. The definitions of five linguistic variables can also be referred to previous studies (e.g., Yang et al., 2018). Essentially, the cost expressions and the utility expressions are defined by the same membership functions. Cost descriptions can be directly mapped onto the cost-effectiveness utility universe as follows:

When the cost is "*Very low*", the adaptation measure is described as "Very efficient". Similarly, when the cost is "*Low*", "*Average*", "*High*" or "*Very high*", the adaptation measure is "*Effective*", "*Average*", "*Slightly effective*" or "*Ineffective*", respectively.

To select the most cost-effective adaptation measure, it is necessary to describe the five utility expressions using numerical values. The linguistic description can then be converted into crisp values {0.11, 0.3, 0.5, 0.7, 0.89} through the centroid defuzzification method (Mizumoto, 1995; Yang et al., 2009). By doing so, a numerical cost effectiveness index of an adaptation measure can be obtained by the following calculation:

$$I\left(CE_{m,n}\right) = \beta_{m,n}^{1} \times 0.11 + \beta_{m,n}^{2} \times 0.3 + \beta_{m,n}^{3} \times 0.5 + \beta_{m,n}^{4} \times 0.7 + \beta_{m,n}^{5} \times 0.89 \quad (4.22)$$

where the lower the value of $I\left(CE_{m,n}\right)$, the better the adaptation measure is.

Furthermore, the ER approach and its computing software IDS (Yang & Xu, 2002) allows us to integrate the results of risk reduction with adaptations cost of the n^{th} adaptation measure for tackling the m^{th} climate threat to obtain its cost-effectiveness.

In summary, this chapter introduces the basic concepts involved in the FBR model, including fuzzy sets and fuzzy logic, BNs and ER, and their technical evolution, applications and drawbacks in transport and climate-related studies. Through constructing an innovative mathematical model which mainly contributes to bringing new parameters and layers in the risk assessment framework, it provides users more confidence in evaluating climate change impacts and adaptation options to precisely reflect the realities. The background of climate adaptation in the UK transportation systems will be firstly introduced in Chapter 5. Afterwards, the feasibility and flexibility of this model will be further examined in different transport modes (railway and road) of the UK in Chapters 6 and 7.

Chapter 5 Adapting to the Impacts of Climate Change on the UK Rail and Road systems

This chapter introduces the background of the UK inland transport networks, and how do they adapt to the impacts posed by climate change in the past decades. This is mainly based on the official climate projections in the UK (UKCP09 and UKCP18), together with other governmental policies, reports and other local documents.

5.1 The UK Roads and Railways and Climate Risks

The rapid rate of climate change challenges the infrastructure, operation and policy-making in the context of transport systems, and the UK is not an exemption. In general, flood, storm and extreme weather had been considered as the top climate disasters in the UK in terms of their historical data in frequency, mortality and economic damages from years 1990 to 2014 (Centre for Research on the Epidemiology of Disasters, 2015; United Nations Office for Disaster Risk Reduction (UNISDR), 2015).

In the UK, the transport sector is recognised as one of six key departments which is the most vulnerable to the risks posed by climate change (McKenzie Hedger et al., 2000). The country has a network covering 422,100 km of paved roads with different quality and capacity (Department for Transport, 2017; Department for Infrastructure, 2017). A unified road numbering system is used to classify and identify all the roads in the UK. Cooperated with the Department for Transport, Highways England (HE), for example, operates, maintains and improves motorways and major “A” roads in England (Highways England, 2018a).

The UK opened locomotive-hauled public passenger railways in 1825. As the oldest railway system in the world, it has a network of 15,760 km of standard-gauge lines, including 5,272 km electrified lines today (Wikinow, n.d.). The majority of railway track is managed and maintained by Network Rail (NR). Also, there are some services on public rail-based mass transit systems run by local authorities and an undersea rail link to France called the Channel Tunnel operated by Getlink. Some short tourist rail lines are managed by private railways.

In a transportation system, the impacts of climate change affect vulnerable groups, transport infrastructure and the environment. The assessment of local sensitivities is based on a review of historical climate change events and the spatial relevance of the receptors. Some reviews have been conducted to investigate the impacts of climate change on the British roads and railways in recent years (e.g., Wang *et al*., 2018b; 2019; Koetse & Rieveld, 2009). However, research on climate impacts on road and rail freight in the UK has remained relatively unexplored (Jaroszweski, 2015). It is only recently that more attention has been given to the impacts of climate change on roads and railways (e.g., Hooper & Chapman, 2012; Wang *et al*., 2018b; 2019). Current action plans in British roads have not been developed from a published, detailed, and official adaptation plan but mainly focus on internal technical documents within the relevant business areas (Committee on Climate Change, 2014). Likewise, the existing adaptation plan of NR mainly concerns with the identification of several climate thresholds and selection of the best risk scenario, owing to the uncertainties of long-term climate change risks and insufficiency of data on change rate and extreme events (Network Rail, 2015). Indeed, a comprehensive adaptation plan covering every aspect has not been published in either British road or rail networks.

In the latest research about climate adaptation, the British inland transport systems are threatened by four primary climate change threats, namely high temperature, heavy precipitation and flooding, high wind and storms, and sea level rise (SLR) (Wang et al., 2018a; 2018b; 2019). The frequently-occurred flooding events in Cumbria and heavy storms in Devon, for example, have caused catastrophic infrastructural and financial losses and casualties due to a variety of impacts including roads and rail line closure, bridges deterioration, traffic disruption, service cancellation and delays (e.g., BBC News, 2015a; BBC News, 2015b; BBC news, 2017; Devon County Council, 2014a; Devon Maritime Forum, 2014). However, with the publication of the latest projection, it requires review multiple sources to identify the primary threats posed by climate change on both rail and road systems, the author firstly collects the scientific evidence by reviewing the official national climate reports, namely the UK Climate Projections.

5.2 The UK Climate Projections

The official climate projections in the UK are presented on the public website called the UK Climate Projections 2009 (UKCP09). Led by the Department for Environment, Food & Rural Affairs (DEFRA) and supported by the Met Office's Climate Model HadCM3 with inputs from over 30 organisations, the UKCP09 has produced a series of results, maps and critical findings for the various purposes of different users. It allows researchers and public to assess scientific information about historical climate data and future climate change projections for land and marine, and over 14 British regions by the end of the 21st century (UK Climate Projections, 2009a; 2009b). In particular, the projection covers the nationwide changes in the 25 km grid squares, indicating the plausible highest and lowest changes for each low, medium and high emissions at the 10%, 50% and 90% probability levels scenario by the 2080s (Murphy et al., 2009). On the basis of the UKCP09, the UK Climate Projections 2018 (UKCP18) upgrades a few findings to help decision-makers assess their risk exposure to climate. Utilising the advanced climate science and tools, the UKCP18 provides the most up-to-date climate change observations, projections and data analysis at both international and domestic scale over this century (UK Climate Projections, 2018). In the UK, the inland transport systems are threatened by four primary climate change threats, namely high temperature, heavy precipitation and flooding, high wind and storms and sea level rise (SLR) (Wang et al., 2018a; 2018b; 2019). The key findings observed in both projections trends include:

Increased temperature: *all regions of the UK have experienced an increase in average temperatures between 1961 and 2006 annually and for all seasons. Increases in annual average temperature are typically between 1.0 and 1.7 °C, tending to be largest in the south and east of England and smallest in Scotland (UKCP09). The temperature in the most recent decade (2008-2017) has been on average 0.3 °C warmer than the 1981-2010 average and 0.8 °C warmer than 1961-1990. All of the top ten warmest years have occurred since 1990 (UKCP18).*

Changing precipitation: *There has been a slight increase in average annual precipitation in all regions of the UK between 1961 and 2006 in the contribution to winter rainfall from heavy precipitation events; in summer all regions except NE England and N Scotland show decreases* (*UKCP09). There has been an increase in annual average rainfall over the UK, particularly over Scotland for which the most recent decade (2008–2017) has been on average 11% wetter than 1961–1990 and 4% wetter than 1981-2010. Changes are largest for Scotland and not significant for most of southern and eastern areas of England (UKCP18).*

Windstorms: *severe windstorms around the UK have become more frequent in the past few decades, though not above that seen in the 1920s (UKCP09). There is an increase in near surface wind speeds over the UK for the second half of the 21st century for the winter season when more significant impacts of wind are experienced (UKCP18).*

Sea level rise: *Sea level around the UK rose by about 1mm/yr in the 20th century, corrected for land movement (UKCP09). The current observed rate of global mean sea level rise is around 3.2 mm/yr (2.8 to 3.6 mm/yr) and typical projected rates averaged over the 21st century are somewhat larger than this (UKCP18).*

5.3 Climate Risks on the UK Railways

The number of articles concerning the impacts posed by climate change on railways has been rapidly growing in some developed nations and regions in recent years. Several studies investigated and assessed the impacts of climate change on rail sectors, for example, in the UK (e.g., Wang et al., 2019). The research includes not only the evaluation and projection of climate change impacts but also the economic impacts when corresponding measures are engaged. However, a majority of climate-related studies tend to focus on its short-term threats, and the rail sector has received little attention (Koetse & Rietveld, 2009). Therefore, the country-specific evaluations and quantification of impacts, together with cost-benefit analyses on adaptation strategies to enhance the resilience of the rail system for climate change (e.g., Wang et al., 2019).

According to the UK Climate Projections (UKCP09) (Jenkins *et al*., 2009) and other literatures (e.g., Peterson et al., 2008, Jaroszweski et al., 2010; Hooper & Chapman, 2012), the key impacts and estimated tendency of climate change were identified in the British rail sector. These include the effects of an increased number of hot days, a decreased number of cold days, increased heavy precipitation, drought, sea level change, seasonal change, extreme events and wind. The extreme events posed the most devastating impacts (e.g. heat waves and storms) on rail transport. Higher temperatures in summer may cause rail buckling as well as decreased thermal comfort, while heavier precipitation in winter could cause landslips, flooding and bridge scour. Dora (2012) investigated the estimated changes in temperature and precipitation were the primary impacts on infrastructure operations for UK rail transport systems. This report stressed the effects, including the increases in track buckling, days of track maintenance and exposure of staff to heat stress and overhead power cables sagging in poor weather.

Flooding was regarded as having one of the significant impacts on the rail network (EPA, 2009). The damage caused by climate change on railway networks took into account approximately 29% to 71% of the total infrastructure value (Chatterton *et al*., 2010). The floods that hit Cumbria had severe impacts as recorded, affecting large areas and major river basins (PERC UK, 2015). During the most catastrophic floods occurred in 2015 (Met Office, 2015), rail services suffered from delays or cancellations, including the West Coast Main Line as the results of 50 - 60 kt strong winds in coastal locations (BBC News, 2015a). On the Settle & Carlisle railway line, a severe landslip caused the route to be blocked for several months before being reopened in March 2017. During the recent flooding events in October 2017, the floods between Carlisle and Maryport led to enormous disruption and block of rail lines (BBC News, 2017). This storm was estimated to cause damages of £1 billion and claimed 18 lives (News & Star, 2017).

Storms are the main threats for Devon County. The cumulative result of the rapid succession of over ten significant storms in December 2013 and January-February 2014 in Devon was the worst since the 1950s (Devon Maritime Forum, 2014; Met Office, 2014). They mainly included the effect on the South West main rail network with the sectionals collapse of the sea wall at Dawlish on the South Devon coast which had significant impacts on transport resilience and local economy across the South West Peninsula (Devon County Council, 2014). In total, the storms had resulted in the two-month closure of the mainline and over 7000 service cancellation (Devon Maritime Forum, 2014). NR estimated that the damage would take "at least" six weeks to recover and an extra £100m for flood repairs was funded across the country (BBC News, 2014; 2015b). In a recent storm in early 2017, high waves in coastal area crashed over flood barriers and flooded sections of railway lines. The boats, lighthouses and seafront rail track were impaired by surges, and some trains between Newton Abbot and Exeter St Davids were temporarily cancelled (The Sun, 2017).

5.4 Climate Risks on the UK Roads

The author firstly identify the predicted climate change trends and impacts on the British road transport based on the UK Climate Projections (UKCP09) (Jenkins et al., 2009), the Highways England's latest report (2016) and other academic studies (e.g., Jaroszweski et al., 2010; Hooper & Chapman, 2012). These include the effects of an increased number of hotter and drier days in summer and warmer and wetter days in winter, increased heavy precipitation and extreme weather events, drought, sea level change, seasonal change, high winds, and reduced number of fog days and cloud cover. For example, higher temperatures in summer can cause road damage; more intense precipitation in winter might result in flooding, landslips, and bridge scour. The changing precipitation (groundwater level/flooding/storm surges) might lead to pollution and asset deterioration, and affect the design and management of existing foundations, drainage and skid resistance. Increase in extreme temperature could alter the geometry of bearings and expansion joints. High winds may have minor effects on structure and gantries but significant risks of disruption of construction work. During this process, all the four critical climate threats (i.e., temperature increase, intense rainfall /flooding, more intense and/or frequent high winds and/or storms, and sea level rise) as well as their corresponding adaptation measures are identified, examined by eight road experts via a preliminary study, and finally listed in the questionnaire survey for further evaluation.

Historically, strong winds are considered to be the most dangerous weather type for the UK roadways (Perry, 1990; Edwards, 1994). The UK is one of the windiest countries located in the mid-latitude westerlies. A destructive wind event, 'Windy Thursday', occurred on 18 January 2007, sweeping over many areas of England, Scotland and Wales (Eden, 2007). This event led to the overturning of approximately 50 goods vehicles, and delays caused £50 million losses (Highways Agency, 2007). The storms over this period also resulted in 111 accidents and lengthy recovery time after the disruption (Eden, 2007). More recently, Storm Ali in September 2018, led to power cuts, vehicle damages and fallen trees which further caused traffic disruptions in Cumbria and Scotland, including the closure of partial sections of M6 and the Tay Road Bridge (BBC news, 2018).

Generally, as the sea level rises, 5% of the UK major road network is expected to suffer 'significantly' increased annual levels of coastal flooding (Edwards, 2017). Around 10% of the UK major road networks are built on floodplains, and 7% has a 'significant to moderate' chance of annual flooding (EPA, 2009). A rapid succession of 12 significant storms from December 2013 to February 2014 was the highest frequency of storms in the UK since the 1950s (Met Office, 2014; Devon Maritime Forum, 2014). The cumulative effect contributed to the collapse of 80 sections of the sea wall at Dawlish on the South Devon coast, severe road deterioration and thousands of fallen trees and branches on the roads, as well as multi-sectional road closures (e.g., A30, A38, A30 and A303) (Devon County Council, 2014).

The most catastrophic floods occurred in Cumbria in 2015, after Storm Desmond, which occurred on the 5th and 6th December, broke 2009's precipitation record with 341.4 mm rainfall (Met Office, 2015). Roads were shut in the severely affected areas, and over 100 bridges were damaged or destroyed. The A595 was closed from the Castle Roundabout at Cockermouth to the Thursby roundabout near Carlisle (BBC News, 2015). With the flooding of A595, the main road was damaged and requires to be rebuilt. The broken traffic lights also caused temporary delays in the both ways of A590 at Lindale (The Mail, 2015).

Based on the UKCP09, the literature review of the impacts of climate change on transportation[9] and consultations with domain experts, the author confirms the four primary environmental drivers due to climate change affecting British roads and railways: 1) temperature increase, 2) intense rainfall /flooding, 3) intense and/or frequent high wind and/or storms, and 4) sea level rise. Therefore, the specific impacts under the four environmental drivers posed by climate change on the road (12 impacts) and rail (11 impacts) systems in the UK are summarised with reference to multi-source literature (e.g., Jenkins et al., 2009; Jaroszweski et al., 2010; Hooper & Chapman, 2012; Dora, 2012; Network Rail, 2015; Rail Safety and Standards Board (RSSB), 2016) and expert consultations. Each threat can be then examined and written into survey questionnaires for prioritisation through a pilot study by speaking with multiple professional transport experts and academics in the UK to guarantee the validity of the survey. Afterwards, a Fuzzy Bayesian Reasoning (FBR) model, combining the Fuzzy set with a Bayesian Networks (BNs) approach, is inserted to quantify the risks posed by climate change, by collecting real data from a nationwide survey among rail and road stakeholders in Chapters 7 and 8 respectively.[10]

5.5 Climate Adaptations for the UK Railway System

Overall, although there have been widespread effects on diverse transport modes, it is only recently that companies/organisations responsible for operating British railways start paying more attention to the impacts of climate change (Hooper & Chapman, 2012). Network Rail owns and operates the national railway infrastructure covering 20,000 miles of track, 30,000 bridges and viaducts, as well as over thousands of tunnels, signals, level crossings and points across England, Wales and Scotland (Network Rail, 2018a). In its latest adaptation report (Network Rail, 2015), Network Rail summarised its understanding of the existing and

[9] See Table 2.3: The impacts of climate change on transportation.

[10] The specific climate threats and results of climate risk assessment in the UK rail and road systems can refer to the two papers (Wang et al., 2018a; 2018b).

potential impacts posed by climate change on its rail performance and safety and the implementation of adaptation actions to deal with them. A few significant climate hazards on rail infrastructure were recognised through an internal risk analysis supported by METEX and GIS tools. These mainly included the changes in temperature precipitation change, leading to increased flooding, but also extreme events, lightning, seasonal changes and sea level rises. For instance, cold weather such as snow and ice would threaten overhead line; heat may increase rail bucking and derailment risk; heavy rainfall and flooding could cause scour of embankment material and damage of electrical equipment.

Network Rail has been responding to the challenges of extreme weather in its daily operation (Network Rail, 2018b). The latest published *Weather Resilience & Climate Change Adaptation Policy* and *Weather Resilience and Climate Change Adaptation Strategy 2017-2019* (Network Rail, 2017a; 2017b) set out Network Rail's approach to creating a safer and more resilient network to the future weather impacts. A four-pillared method was component with *'analysis risk and costs', 'integrate into business as usual', 'streamline operational weather management',* and *'proactive investment'* in 2020 Review and Revise Strategy.

Furthermore, the *Tomorrow's Railway and Climate Change Adaptation Report* (RSSB, 2016) as a part of the T1009 programme funded by Rail Safety and Standards Board (RSSB), established an adaptation framework containing four action steps for the management of summer conditions, winter conditions and flooding risk by drawing the experiences of other countries in weather resilience and climate change adaptation. A recent report called *Rail Adapt: adapting the railway for the future* (Quinn *et al*., 2017) reviewed several documents in the context of climate change on railways, including the issues at stake, strategies and toolkits for addressing them. It also offered case studies in the UK by providing techniques and tools drawn from global experiences.

Nevertheless, the quantification of climate risks and costs is still at an embryonic phase (Network Rail, 2017a). Owing to the kaleidoscopic nature of long-term climate change impacts and insufficiency of precise data on change rate and extreme events (Network Rail, 2015), the existing plan still focuses on the identification of several climate thresholds and selection of the best risk scenario.[1] Some issues in rail sector were also revealed in Dora's report (2012), which included poor air quality in urban areas and remarkable differences between the North and South of the UK due to the rising temperatures, the increased possibility of track inundation and of scouring affecting river bridges' stability and incidence of landslips posed by extreme precipitation. Due to the high uncertainty related to the future climate, adaptation measures should be robust to retain the option value of the measure portfolios. Hence, through conducting a nationwide survey of UK rail systems, Chapter 6 will examine the new FBR risk analysis model which overcomes the shortage of data and the uncertainty of climate risks to reveal the real climate risks for the British railway.

5.6 Climate Adaptations for the UK Road Systems

Likewise, although some recent studies have begun to cope with climate impacts (e.g., Peterson et al., 2008; Koetse & Rieveld, 2009), the existing research on climate impacts on road freight in the UK has remained relatively unexplored (Jaroszweski, 2015). The lack of precise data on the current and potential impacts of climate change, as well as cost-benefit analysis, poses a significant challenge for transportation planners, which could potentially cause the failure of adaptation strategies in the transport sector (Koetse & Rietveld, 2012). Hence, the author proposes an extended climate risk analysis framework by utilising the FBR approach and collecting primary data through a nationwide survey to reveal the real climate risks in British roads.

The UK highway industry began developing a holistic asset management plan for climate change in 2010 (Munslow, 2011). ‘Climate Change Adaptation Framework' (Highways Agency, 2009) and the recently published ‘Climate Adaptation Risk Assessment Progress Update' (Highways England, 2016) described the existing climate risk assessment approaches and adaptation procedures. The current climate risk appraisal considers the rate of climate change, the extent of disruption, the severity of disruption and uncertainties, based on the methodology used in the project of ‘Risk Management for Roads in a Changing Climate' (Conference of European Programme of Roads, 2010). Nevertheless, this method does not take other critical factors influencing climate impact into account, such as the costs, time and capacity of a transport system to recover from the risks of a climate change event. The most up-to-date UKCP18 projections have made changes regarding the level of climate risks, which require reviews of existing action plans and budgets, instead of merely prioritising risks by the formula. The Department for Environment, Food & Rural Affairs (DEFRA) has been looking at a more standardised approach for climate risk assessment. Hence, it is vital to fill the gaps in analysing the cost-effectiveness of adaptation measures and constructing adaption plans for climate change in the UK road network.

In response to the impacts of climate change on transportation infrastructure, the UK government has recognised adaptations on infrastructure as a high priority. For example, an early report called "Climate Resilient Infrastructure: Preparing for a Changing Climate" was published together with guidance on building infrastructure resilience in 2011 (HMG, 2011; HM Cabinet Office, 2011). The "Transport Resilience Review" introduced by the Department of Transport (2014) provided HE with detailed recommendations for adapting to extreme weather. HE's Climate Adaptation Risk Assessment (2016) highlighted a series of current adaptation action plans, mainly focusing on road structures, pavements and drainage management, and will continuously monitor all the potential climate vulnerabilities. Several regional flooding adaptation actions, including the design and constructions of flood defences to protect the people and properties, have been undertaken in severely jeopardised regions. An excellent example of risk management was the success of dealing with the Cockermouth's flooding in 2009. The government allocated approximately £1 million funding to support the clean-up and repairs of damaged roads and bridges within Cumbria. Additionally, Network Rail and Cumbrian County Council implemented a modal shift strategy by converting road traffic to the rail by quickly setting up a new direct rail service and building a rail platform in Workington (Ace Geography, n.d.).

Nevertheless, according to the Adaptation Sub-Committee's Progress Report (Committee on Climate Change, 2014), current action plans are still at the stage of internal technical documents within the relevant business areas; a detailed action plan for climate adaptation has not been officially published. Adaptation strategies are necessary to be incorporated into the planning stages of new developments as well as existing maintenance to minimise risks, reduce costs and enhance the resilience of the UK transport network in the future (Jaroszweski, 2015). Hence, it is vital to fill the gaps in analysing the cost-effectiveness of adaptation measures and constructing adaption plans for climate change in the UK road network.

Tompkins et al. (2010) analysed more than 300 examples of historical adaptation practice for climate change, in order to figure out if climate adaptation is evidence of social transition in the UK. The results showed that the approach to adaptation for the UK government usually relies on the established network by the UK Climate Impacts Programme; many adaptations are only the by-products of mitigation activity or not initially designed to deal with the impacts of climate change. Other issues (for instance, should adaptation activity be promoted through the risk management agenda and how to monitor and evaluate a challenge), were proposed to be solved through further research. The UK Climate Impacts Programme (UK Climate Projections, 2009a) summarised some of the impediments existing in climate adaptations. These include lack of support from regulation, policies, standards, regulations and design, insufficient knowledge of climate change risks and vulnerabilities guidance, restricted budgets for available adaptation options and inappropriate planning horizons.

Therefore, it is highly urgent to figure out the most cost-effective adaptation measures to cope with the impacts of climate change as well as potential dilemmas on the British road and rail sectors. Adaptation measures for road and rail transportation systems will be explored from the hybrid of literature surveys and domain expert consultation in Chapters 6 and 7. More specifically, for tackling the high impacts on the UK roads and railways, the database is first developed through a comprehensive literature review and information from associated experts to identify the primary measures. Examined by transport experts again, all the candidate adaptation options are then summarised for further evaluation. Here the adaptation options for roads and rails can be used for cross-referencing and cross-fertilisation, given both sectors face many identical climate threats of high-risk levels.

Last but not least, having ranked the top climate risks, the identified climate risks and associated costs can be finally incorporated into an appraisal of adaptation measures via multiple criteria decision-making techniques. Here, an evidential reasoning (ER) approach looks promising due to its capability of accommodating both quantitative and qualitative criteria under uncertainty simultaneously. The results of the most cost-effective measures are finally verified and concluded through the ER modelling analysis and interviews of transport authorities in terms of their implications. A preliminary study on the investigation of using ER in the evaluation of climate risk reduction and the associated costs has been conducted by the author in the UK rail and road sector for an illustrative purpose in Chapters 6 and 7 respectively.[11]

[11] The specific adaptation measures and results of climate adaptation evaluation in the UK road system can refer to the paper (Wang et al., 2018b; 2019).

Chapter 6 Risk Analysis of Climate Change Impacts on the UK Rail System[12]

Climate change poses critical challenges for rail infrastructure and operations in the UK. However, the systematic quantification of climate risks and associated costs is still at an embryonic phase due to the kaleidoscopic nature of climate change impacts and lack of precise climatic data. To deal with such challenges, this chapter applies an advanced Fuzzy Bayesian Reasoning (FBR) model in Chapter 4 for understanding climate risk and adaptation planning of the rail system in the UK. This model systematically ranks climate risks under high uncertainty in data and comprehensively evaluates these risks by particularly taking account of infrastructure resilience and specific aspects of the severity of consequence. Through conducting a nationwide survey in the British railway system, it dissects the status quo of primary climate risks. The survey implies that the top potential climate threats are highly related to the intense rainfall/flooding. Especially, bridges collapse and derailment risks due to damages of bridge foundations triggered by the threats of flooding and landslips are primary concerns. Thus, the innovative risk analysis method and practical implications of this chapter offer researchers, industrial practitioners and transport stakeholders strong discernment on investigating climate hazards of high risk to spur the innovation of cost-effective adaptation measures and strategies.

The remainder of this chapter is organised as follows. The survey design and sampling procedure are firstly introduced in Section 6.1. Section 6.2, illustrates the general information of this rail survey, including the geographic distribution and position of responses, primary climate risks in diverse areas and implementation of adaptation plans. Based on the constructed FBR model, step-by-step risk analysis and synthesis framework in the context of rail networks in the UK are presented in section 6.3. By dividing the respondents to different groups, the ranking results of each group are further interpreted in Section 6.4. The FBR model examines the current status of four primary climate risks and cost-effectiveness of adaptation measures on the UK rail systems in Section 6.5. Finally, the discussion concludes with suggestions for further research in Section 6.6.

[12] The rail adaptation to climate risks has been reviewed by Transportation Research Part A (TRA) with a result of Accepted subject to minor revisions (4 reviewers) and now it is recommended to Transportation Part D: Environment (TRD) because it is closer to the main theme of TRD than TRA.

6.1 A Nationwide Rail Survey on Climate Risks and Adaptation Assessment

A nationwide survey was undertaken via distributing online questionnaires to collect the first-hand information by assessing the opinions of rail planners and stakeholders regarding the threats posed by climate change, current measures and future climate adaptation planning within the rail systems.

It illustrates the overview of climate threats in UK rail systems so as to justify the necessity and importance of embedding adaptation planning to rail organisations. Through previous literature reviews, the four main environmental drivers owing to climate change have been recognized, including: 1) higher temperature, 2) heavier precipitation or floods, 3) more intense or frequent high winds and storms, and 4) SLR. The specific potential climate threats and corresponding adaptation measures were summarised according to the Network Rail's adaptation framework (Network Rail, 2015).

A pilot study was initiated between March and April 2017 via consulting with eight domain rail stakeholders within this nation to guarantee the validity and shape the design of a questionnaire. From May to December 2017, a nationwide online survey was completed by 20 rail stakeholders to evaluate their perception of climate change impacts, including general impacts and specific impacts on their rail operation, performance as well as infrastructure resilience.

The survey was sent to all the rail stakeholders in the UK who are from rail companies and authorities, governmental departments, academics and NGOs etc. The databases of the national rail networks were used to select the transport entities (Network Rail, 2016). The author applied non-probability sampling approach, which integrates judgment sampling with snowballing considering the unique and complex features of climate impacts on transportation sector (e.g., Wang, 2015; Wang et al., 2019).

The participants in the railway survey were mainly chosen from members of the Railway Industry Association (RIA) and the Rail Freight Group (RFG) representing major UK-based suppliers of the world's railways and the leading body for rail freight in the UK (RIA, n.d; RFG, n.d.). Over 200 member companies crossing the whole range of railway supply with diverse skills and resources are typical rail entities in the UK national railway. However, this survey excludes several small entities located in remote regions or without sufficient knowledge for climate-related issues. We assume that, in judgment sampling, the representativeness of the samples is more important than its universality (e.g., Vogt et al., 2012).

Afterwards, one or two critical participants were invited from the listed organisations to assist with the distribution of these online questionnaires by a snowball sampling approach. A sample of 30 administrators on behalf of the vital transport stakeholders covering diverse geographic locations of the UK (e.g., Network Rail, Transport for Greater Manchester, AECOM UK, etc.) was finally formed. The 30 questionnaires were then distributed online through the Bristol Online Survey (2017) tool by sending emails and calling the targeted respondents. By December 2017, we received 20 out of 30 effective responses with a relatively high response rate of 66.7%.

6.2 Geographic Distribution, Position of participants, Primary Climate Risks and Adaptation Plans

To illustrate the overview of the primary impacts of climate change, this survey covers all of the UK, including Scotland, Wales, Northern Ireland and the regions of England. By asking 'Which region of the railway does your company/organisation operate on?' (Q3a), the geographic distribution number of the respondents' rail entity is analysed, which can be found in Figure 6.1. It is noted that almost 80% of participants are from the railways in England, where the major rail networks are managed by NR. However, the responses from Wales, Scotland and Northern Ireland only occupy around 8%, 9% and 4% of the total number respectively.

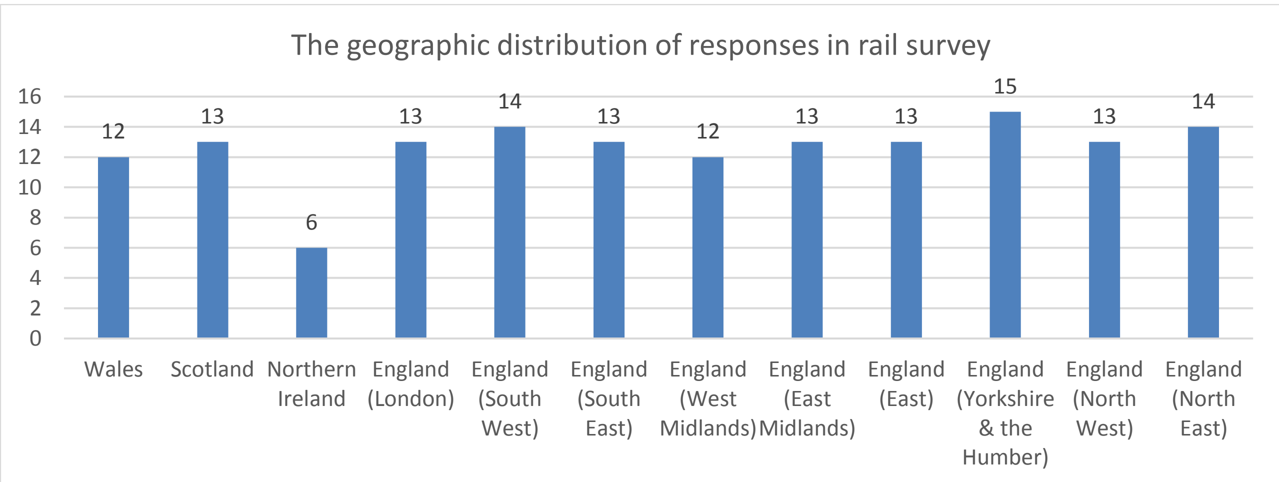


Figure 6.1 Geographic distribution of responses in rail survey

Meanwhile, the data regarding the current position of participants at their companies or organisation are collected (Q4). Figure 6.2 illustrates that the participants are unequally distributed in diverse positions. However, besides the category of 'others', including transport and supply chain managers, associate directors, climate adaptation strategy managers, performance programme manager and principal freight and logistics technologists, CEOs (Chief Executive Officers)/ transport directors are the main participants, followed by transport engineers and scholars.

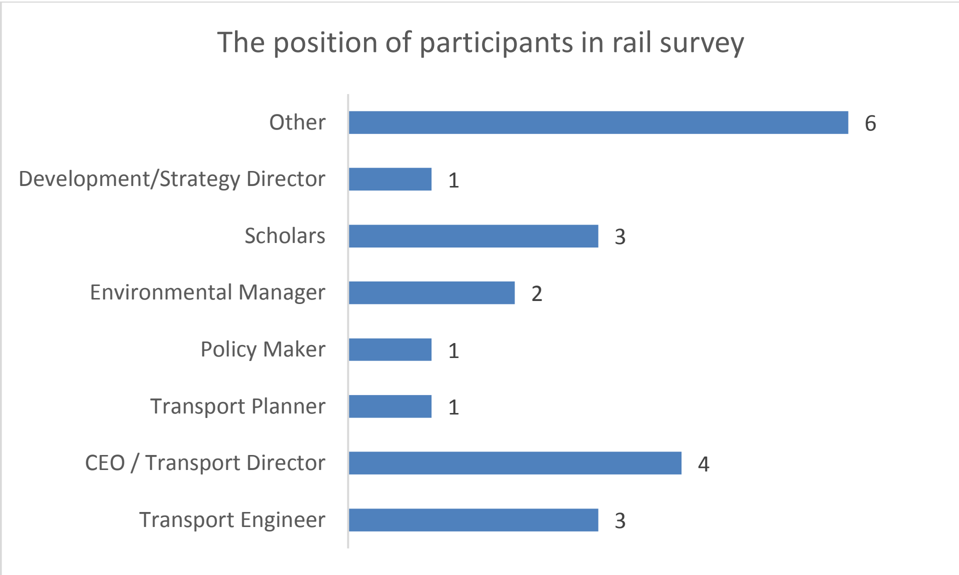
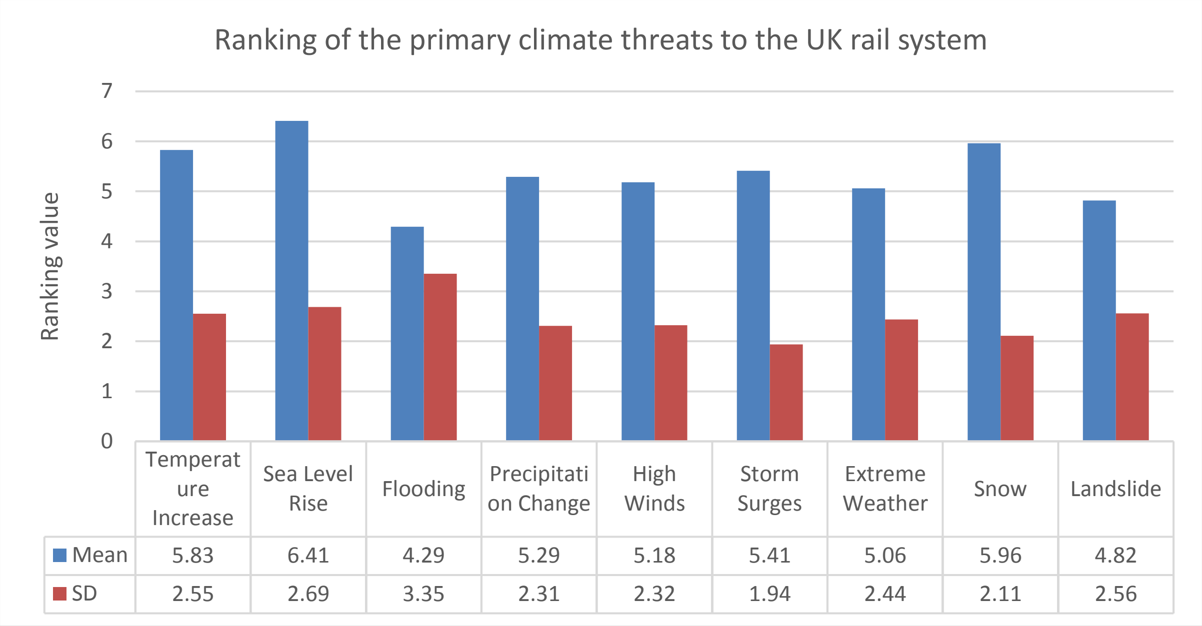


Figure 6.2 Distribution of participants' position in rail survey

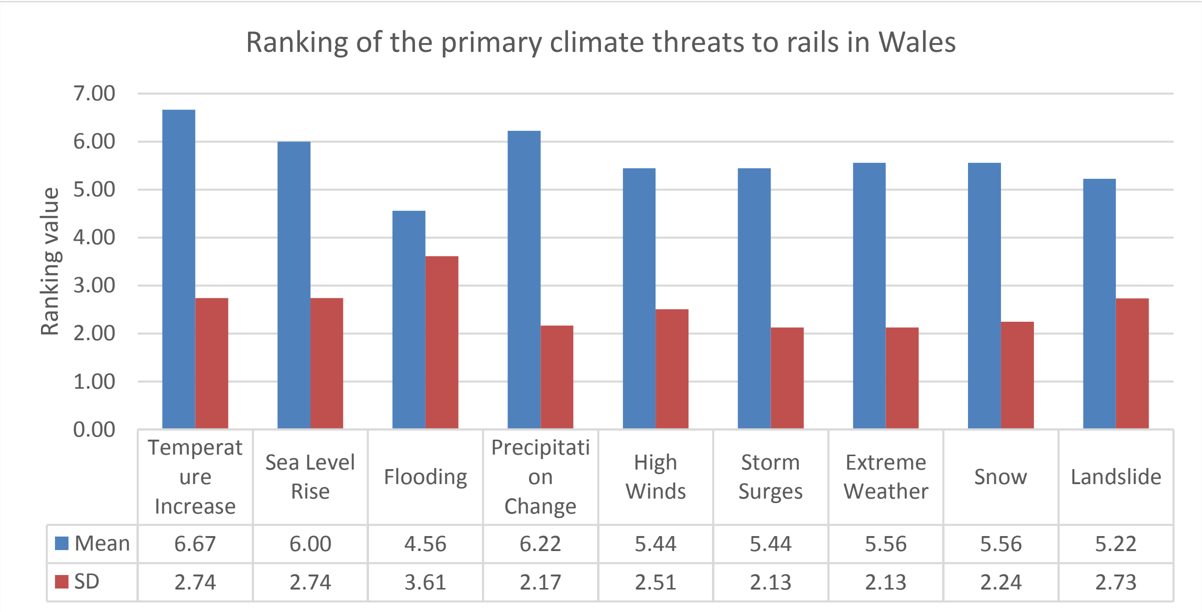
Before evaluating the specific threats of the four climate drivers, respondents were asked to rank the different type of risks that they have witnessed or experienced posed by climate change on the railway their company/organisation are associated with (Q5). Figure 6.3 illustrates the ranking values of the mean and standard deviation of each potential climate threats to the UK rail system. Overall, flooding (M=4.29), landslide (M=4.82) and extreme weather (M=5.06) are the most concerned impacts, followed by high winds (M=5.18) and precipitation change (M=5.29), while sea level rise (M=6.41) is considered the lowest risk. In particular, high winds (SD=2.32) and precipitation change (SD=2.31) relatively invariably occur, whereas the top three risks might have varying influence in different regions. For instance, flooding has the highest SD=3.35. Therefore, the author further analyses the main climate threats to railways in four areas in the UK.



	Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Mean	5.83	6.41	4.29	5.29	5.18	5.41	5.06	5.96	4.82
SD	2.55	2.69	3.35	2.31	2.32	1.94	2.44	2.11	2.56

Figure 6.3 Ranking of the primary climate threats to UK railways

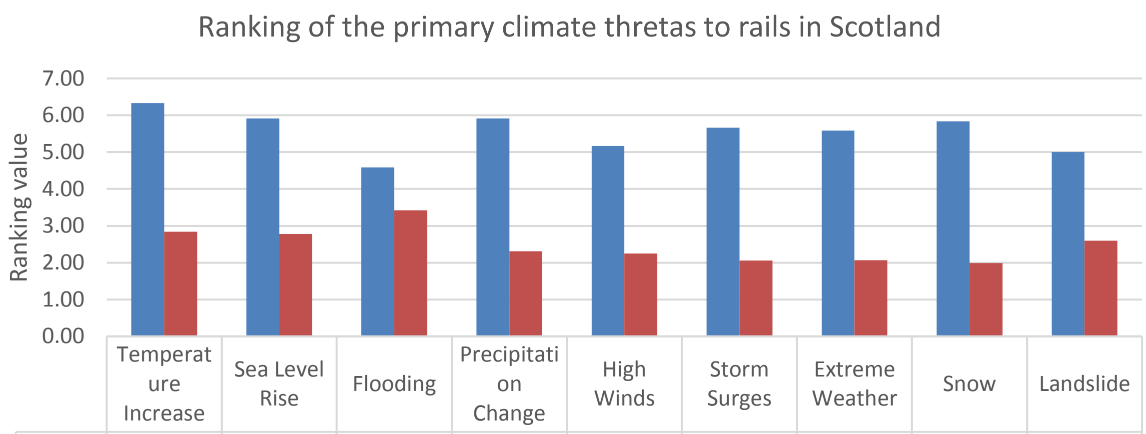
In Wales (Figure 6.4), flooding (M=4.56), landslide (M=5.22), high winds (M=5.44) and storm surges (M=5.44) are regarded as the top threats to its railways, while the lowest threat goes to temperature increase (M=6.67). Meanwhile, the data of storm surges (SD=2.13) and high winds (SD=2.51) are smaller than the one of flooding (SD=3.61) and landslide (SD=2.73), which mean more stable occurrence of storm surges and high winds in this area.



	Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Mean	6.67	6.00	4.56	6.22	5.44	5.44	5.56	5.56	5.22
SD	2.74	2.74	3.61	2.17	2.51	2.13	2.13	2.24	2.73

Figure 6.4 Ranking of the primary climate threats to railways in Wales

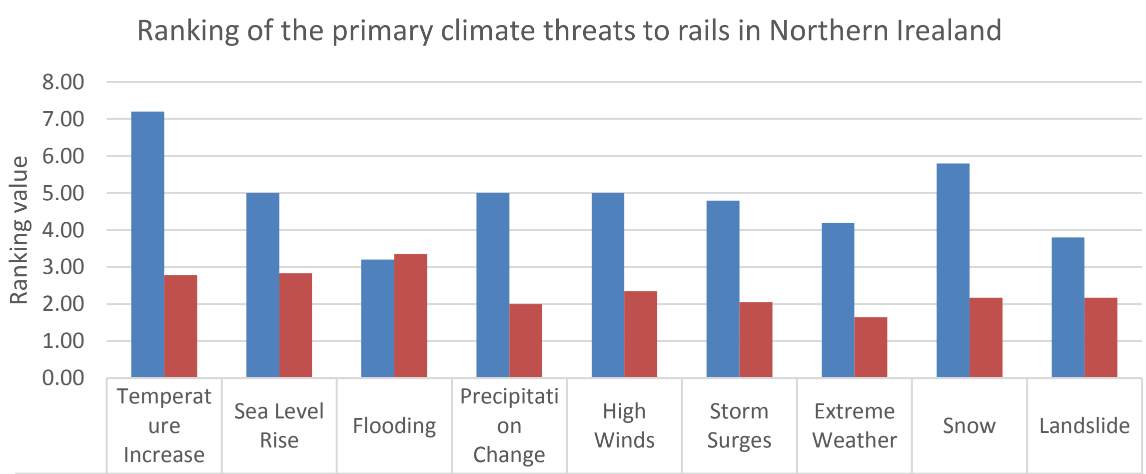
In Scotland, flooding (M=4.58), landslide (5.00) and high winds (5.17) pose the most significant impacts on its rail networks, while temperature increase poses the lowest threats (M=6.33). High winds (SD=2.25) and landslide (SD=2.59) more steadily occur than flooding (SD=3.42).



	Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Mean	6.33	5.92	4.58	5.92	5.17	5.67	5.58	5.83	5.00
SD	2.84	2.78	3.42	2.31	2.25	2.06	2.07	1.99	2.59

Figure 6.5 Ranking of the primary climate threats to railways in Scotland

For the railways in Northern Ireland, the primary climate risks include flooding (M=3.20) landslide (M=3.80) and extreme weather (M=4.20), whereas the lowest threat goes to temperature increase (M=7.20). At the same time, extreme weather (SD=1.64) and landslide (SD=2.17) have more stable influence than flooding (SD=3.35).



	Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Mean	7.20	5.00	3.20	5.00	5.00	4.80	4.20	5.80	3.80
SD	2.77	2.83	3.35	2.00	2.35	2.05	1.64	2.17	2.17

Figure 6.6 Ranking of the primary climate threats to railways in Northern Ireland

Finally, the results demonstrate that flooding (M=3.91), landslide (M=4.82), storm surges and extreme weather (M=4.91) are the top threats for England's railway system. However, sea level rise is considered as the lowest climate threat. Among them, the occurrence of flooding (SD=3.53) and extreme weather (SD=2.39) is relatively unstable compared to storm surges (SD=1.76) and landslide (SD=2.36).

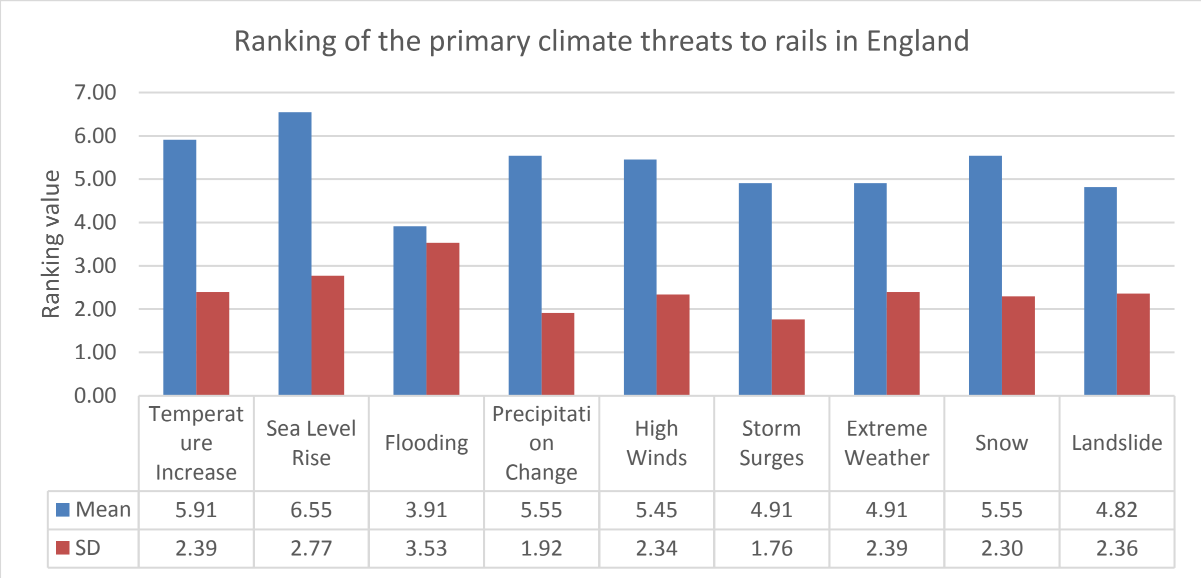


Figure 6.7 Ranking of the primary climate threats to railways in England

Through vertically compare the results of the four areas in the UK (Table 6.1), it can be observed that flooding and landslide are the common climate threats for the all four regions, with particularly highest ranking in England (M=2.98 for flooding and M=3.10 for landslide). Except for Wales, the SDs of landslide are small, which means a stable occurrence. Surprisingly, the SDs of flooding in each area are relatively large, which hints that flooding has variable impacts in different regions. For instance, floods (M=2.98) in England are severer than others. Besides, extreme weather commonly occurs in Northern Ireland and England. High winds are common impacts for Wales and Scotland, storm surges are a common one for Wales and England, together with relatively low SDs. As 79% of response comes from England, the main threats posed by climate change in the UK have affected by the regional opinions, and therefore, flooding, extreme weather and landslides are the top risks, while more liable as whose SDs are more significant than the ones in England.

Table 6.1 Questionnaire results of primary climate threats to UK railways

		Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Wales	Mean	6.67	6.00	4.56	6.22	5.44	5.44	5.56	5.56	5.22
	SD	2.74	2.74	3.61	2.17	2.51	2.13	2.13	2.24	2.73
Scotland	Mean	4.70	4.37	4.08	4.19	3.97	3.79	3.84	3.90	3.98
	SD	2.78	2.31	0.67	2.87	2.08	2.35	2.42	2.34	1.76
Northern Ireland	Mean	4.22	3.85	3.23	3.86	3.50	3.43	3.49	3.51	3.42
	SD	1.87	1.68	1.75	1.78	1.53	1.53	1.57	1.56	1.50
England	Mean	3.83	3.49	2.98	3.52	3.17	3.11	3.17	3.18	3.10
	SD	1.74	1.58	1.48	1.62	1.43	1.42	1.45	1.45	1.40
UK	Mean	5.88	6.41	4.29	5.29	5.18	5.41	5.06	5.94	4.82
	SD	2.55	2.69	3.35	2.31	2.32	1.94	2.44	2.11	2.56

Furthermore, by inquiring participants the details about the impacts posed by climate change on the rail their company/organisation are associated with in the past ten years (Q6), the results show that some rail lines have been damaged due to severe flooding and landslide. There was a particular issue on the east coastline between Scotland and Newcastle and also on the west coastline between Scotland and Carlisle. Extreme wet weather caused landslips and embankments to slip on to open running lines. Some significant events can be witnessed from the flooding at Dawlish (Railway Line) in 2013/2014 and at Exeter (Railway Line) junction with Barnstaple line, as well as landslips on the Aberdeen-Inverness line in 2016 and flooding affecting various bridges on the Aberdeen-Dundee route.

In respect to the implementation of climate adaptation plans on railways (Q7), although most of the participants have acknowledged the significance of climate risks, when talking about climate adaptations, only 32% of them have undertaken an adaptation plan while 47% of the total will consider developing one in the future.

6.3 Risk Prioritisation by the FBR Model

Data screening was conducted to eliminate missing and ineffective data such as incomplete input information and incorrect responses before proceeding with the risk analysis. Accordingly, 3 out of 20 feedbacks became invalid after the screening process. The consistency of the remaining 17 sets of data was addressed through the comparative climate risk analysis. Finally, associated data from the eight questions (Q8 to Q15) were put into an FBR model to rank and analyse the top potential risks posed by climate change.

Based on the literature review in relation to the impacts posed by climate change in the UK, four main environmental drivers affecting British railways have been identified (e.g., RRSB, 2016; Network Rail, 2015; Hooper & Chapman, 2012; Dora, 2012; Jaroszweski et al., 2010; Jenkins et al., 2009). These include higher temperature, heavier precipitation or floods, more intense or frequent high wind and storms, and SLR. The potential climate threats resulting from these four environmental drivers are identified and examined by interviewing eight stakeholders in the rail sector. The 11 pivotal threats identified are then listed in the questionnaire survey. Thus, the following risk assessment aims to prioritise the climate risks level of all listed threats within the above environmental drivers.

On the basis of the fuzzy Bayesian approach, the climate risk result of each potential climate threat of the environmental driver related to UK rails was calculated and elaborated in Table 6.2. The impacts of temperature increase, for instance, were divided into two potential threats, namely, "A1. Track buckling causing derailment risks & reducing opportunities for track maintenance" and "A2. Unreliable signalling, power lineside systems, failure of temperature controls and overheating of electronic equipment". The evaluations of each threat depend on the four aforementioned risk parameters: *Timeframe (T), Likelihood (L), Severity of Consequence (C) and Climate Resilience (S) and the three sub-parameters of C namely "Damage to Infrastructure (INF)"*, *"Injuries and/or Loss of Lives (INJ)"*, and *"Damage to Environment (ENV)"*.

Utilising FBR and its associated Hugin software (Hugin v. 8.5, 2017; Andersen *et al*., 1989), the risk results of "A1. Track buckling causing derailment risks & reducing opportunities for track maintenance" and can be calculated as {11.54% *Very High*, 18.08% *High*, 30.03% *Average*, 19.22% *Low*, 21.16% *Very Low*}. After assigning the utility values to the five linguistic terms, A1's risk index value is calculated as 0.54. The results of risk analysis on A1 by Hugin software can be found in Figures 6.8.

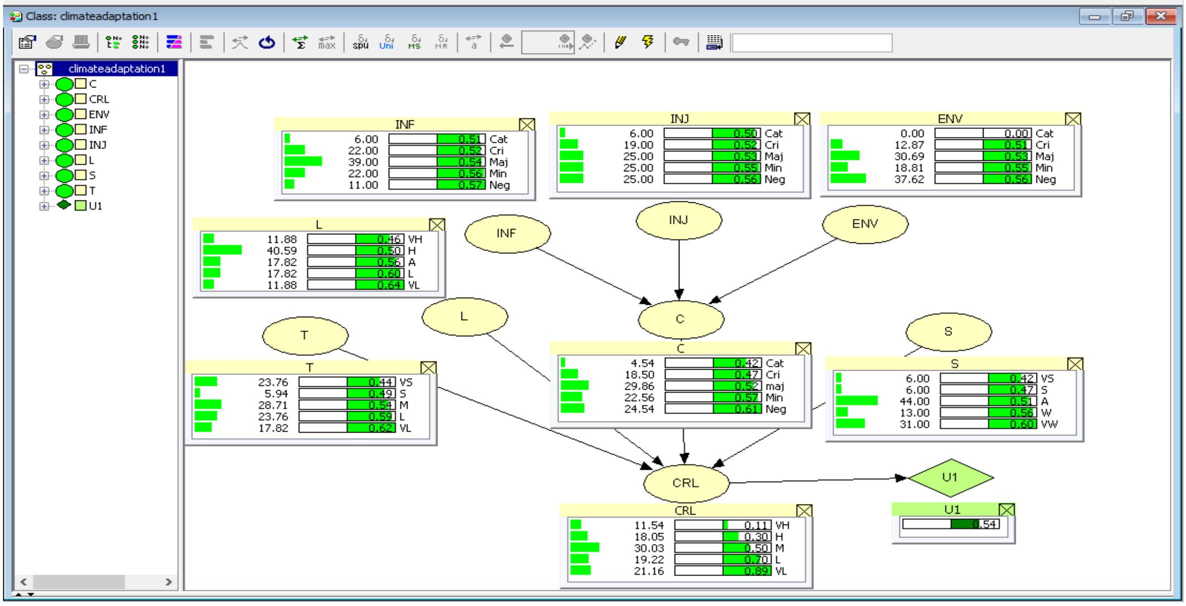


Figure 6.8 Climate risk analysis of "A1.Track buckling causing derailment risks & reducing opportunities for track maintenance" using Hugin

Based on the ranking in Table 6.2, the highest potential climate threats to the railways in Britain go to "B1. Bridge foundations damaged leading to bridge collapse and derailment risk", "B2.Landslips causing obstruction, increasing derailment risk" and "B4. Track drainage overloaded leading to flooding of the track" due to the intense rainfall/flooding, as well as "D1. Breach of seawall, flooding and derailment risk" due to sea level rise.

Table 6.2 Questionnaire results of climate risk analysis on UK railways

Environmental driver	**climate threat on the railway**	**CRL**	**Utility value**	**Ranking**
Temperature increase	A1.Track buckling causing derailment risks & reducing opportunities for track maintenance	**{0.1154, 0.1808, 0.3003, 0.1922, 0.2116}**	**0.54**	**6**
	A2.Unreliable signalling, power lineside systems, failure of temperature controls and overheating of electronic equipment	**{0.0858, 0.2016, 0.3228, 0.2116, 0.1783}**	**0.54**	**6**
Intensive rainfall/flooding	B1.Bridge foundations damaged leading to bridge collapse and derailment risk	**{0.1083, 0.3299, 0.2613, 0.2109, 0.0896}**	**0.47**	**1**
	B2.Landslips causing obstruction, increasing derailment risk	**{0.1590, 0.2313, 0.2406, 0.2700, 0.0991}**	**0.48**	**2**

	B3. Heavy rain affecting visibility, scheduled work may have to be rescheduled for safety and welfare reasons	**{0.0621, 0.1617, 0.2115, 0.3192, 0.2455}**	**0.6**	**8**
	B4.Track drainage overloaded leading to flooding of track	**{0.0927, 0.2874, 0.2502, 0.2716, 0.0981}**	**0.5**	**3**
More intense and/or frequent high winds and/or storms	C1.Trees falling onto the line	**{0.1138, 0.2045, 0.2863, 0.2944, 0.1010}**	**0.51**	**4**
	C2.High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons	**{0.0997, 0.2689, 0.2229, 0.1833, 0.2252}**	**0.53**	**5**
	C3.Instability of structures	**{0.0500, 0.1482, 0.4197, 0.1832, 0.1899}**	**0.56**	**7**
Sea level rise	D1.Breach of sea wall, flooding and derailment risk	**{0.0830, 0.2974, 0.3390, 0.2142, 0.0663**	**0.48**	**2**
	D2.Reduced maintenance opportunities, bridges/ sea walls may not be safely inspected	**{0.0156, 0.2488, 0.3305, 0.2458, 0.1594}**	**0.56**	**7**

Sources: RSSB (2016); Dora (2012); NR (2015); United Nations Economic Commission for Europe (UNECE) (2012).

Interestingly, almost all the top potential climate threats are attributed to the intense rainfall/flooding. This finding is also consistent with the current priorities for tackling flooding issues in climate change adaptation in the UK. However, the lowest threats are "B3. Heavy rain affecting visibility, and scheduled work may have to be rescheduled for safety and welfare reasons" owing to the increase in intense rainfall/flooding. It is probably because the visibility and rescheduling issues do not cause significant hazards to infrastructure, which usually results in operational disorder and the associated costs.

6.4 Risk Analysis of Diverse Groups

To further investigate the different opinions from different groups regarding climate risks on railways, this survey questionnaire asked for the information of participants' positions and names of their organisation. Afterwards, we analysed this data by dividing it into three categories:

1) Engineers (including transport engineers and freight and logistics technologists); CEOs (including associate directors, transport directors, development/strategy director); managers (including supply chain managers, transport managers, strategy managers, performance programme managers and environmental managers), as well as scholars (including rail research fellows and PhD candidates) by their position;

2) Consulting companies, NGOs (Non-Governmental Organizations), transport companies and academia, in terms of their entities' type;

3) Large (>10,000 employees), middle (1,000-10,000 employees) and small (<1,000 employees) companies or organisations based on the entities' scale.

Figure 6.9 illustrates the percentage distribution of each group. Small companies/organisations and CEOs take account the most substantial portion (40%) of the total responses in terms of the scale of the entity and participants' position. Meanwhile, transport companies and consulting companies are the primary types of entities, occupying 30% of the total responses, respectively.

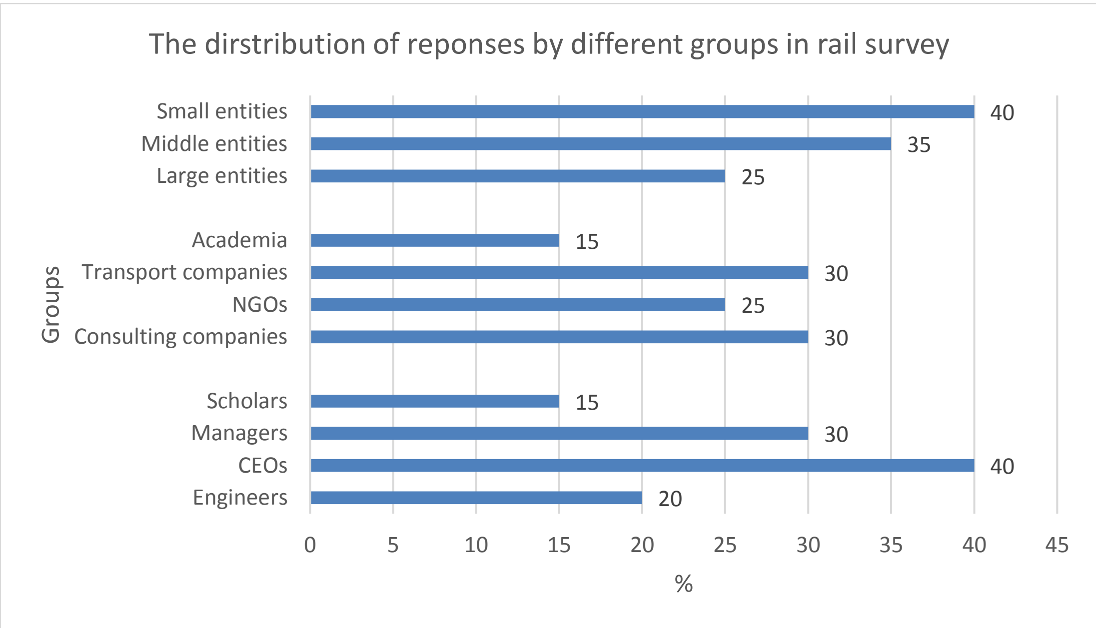


Figure 6.9 Distribution of responses by participants' position, type and scale of their entity

The modelling results of climate risk level, including the utility values and rankings of all potential climate threats owing to the four environmental drivers, are calculated in each category (See Tables 6.3-6.5).

Table 6.3 Questionnaire results of climate risk analysis on UK railways by position

Environmental driver due to climate change	Potential climate threat on the railway	Position	Utility value	Ranking of risk level
Temperature increase	A1.Track buckling causing derailment risks & reducing opportunities for track maintenance	**Engineer**	**0.55**	**14**
		CEO	**0.51**	**11**
		Manager	**0.47**	**5**
		Scholar	**0.53**	**12**
	A2.Unreliable signalling, power line side systems, failure of temperature controls and overheating of electronic equipment	**Engineer**	**0.51**	**11**
		CEO	**0.49**	**7**
		Manager	**0.48**	**6**
		Scholar	**0.68**	**21**
Intensive rainfall/flooding	B1. Bridge foundations damaged leading to bridge collapse and derailment risk	**Engineer**	**0.38**	**2**
		CEO	**0.50**	**9**
		Manager	**0.54**	**13**
		Scholar	**0.54**	**13**
	B2.Landslips causing obstruction, increasing derailment risk	**Engineer**	**0.36**	**1**
		CEO	**0.46**	**4**
		Manager	**0.43**	**3**
		Scholar	**0.51**	**11**
	B3.Heavy rain affecting visibility, scheduled work may have to be rescheduled for safety and welfare reasons	**Engineer**	**0.57**	**15**
		CEO	**0.55**	**14**
		Manager	**0.54**	**13**
		Scholar	**0.70**	**22**
	B4.Track drainage overloaded leading to flooding of tracks	**Engineer**	**0.48**	**6**
		CEO	**0.58**	**16**
		Manager	**0.51**	**11**
		Scholar	**0.53**	**12**
More intense and/or frequent high winds and/or storms	C1.Trees falling onto the line	**Engineer**	**0.51**	**11**
		CEO	**0.51**	**11**
		Manager	**0.47**	**5**
		Scholar	**0.55**	**14**
	C2.High winds affect visibility, scheduled work may have to be rescheduled for safety and welfare reasons	**Engineer**	**0.53**	**12**
		CEO	**0.51**	**11**
		Manager	**0.63**	**18**
		Scholar	**0.73**	**23**
	C3.Instability of structures	**Engineer**	**0.49**	**8**
		CEO	**0.48**	**6**
		Manager	**0.61**	**17**

		Scholar	0.77	23
Sea level rise	D1.Breach of seawall, flooding and derailment risk	Engineer	0.50	10
		CEO	0.43	3
		Manager	0.49	8
		Scholar	0.67	20
	D2.Reduced maintenance opportunities, bridges/ sea walls may not be safely inspected	Engineer	0.46	4
		CEO	0.49	8
		Manager	0.65	19
		Scholar	0.73	23

With regard to the participants' position, the two lowest utility values are attributed to engineers (0.36 and 0.38) regarding "B1" and "B2" risks caused by intensive rainfall/flooding, respectively. It indicates that they expect sooner, stronger, more likely and weaker resilient climate risks on their railways compared to CEOs and scholars. This is probably because engineers are the people who are involved in day-to-day rail operation and experience the damage to the rail infrastructure caused by climate change. However, managers, CEOs and academics may lack witnessed evidence compared to engineers working in the forefront of working places, and their information about climate risks is gained more from official documents and publications. In particular, scholars hold the lowest risk-level opinions for all the four environmental drivers ("A2", "B3", "C2", "C3" and "D2"). It is relevant to their background more on rail research than climate risk study. After all, climate risk in rail systems has a backseat role compared to other rail research such as optimisation.

Table 6.4 Questionnaire results of climate risk analysis on UK railways by type of entity

Environmental driver due to climate change	Potential climate threat on the railway	Type	Utility value	Ranking of risk level
Temperature increase	A1.Track buckling causing derailment risks & reducing opportunities for track maintenance	Consulting	0.47	8
		NGO	0.49	9
		Rail operator	0.51	11
		Academia	0.53	13
	A2.Unreliable signalling, power line side systems, failure of temperature controls and overheating of electronic equipment	Consulting	0.54	14
		NGO	0.57	21
		Rail operator	0.64	24
		Academia	0.68	21
Intensive rainfall/flooding	B1. Bridge foundations damaged leading to bridge collapse and derailment risk	Consulting	0.50	10
		NGO	0.43	5
		Rail operator	0.46	7

		Academia	0.56	16
	B2. Landslips causing obstruction, increasing derailment risk	Consulting	0.38	2
		NGO	0.36	1
		Rail operator	0.50	10
		Academia	0.51	11
	B3.Heavy rain affecting visibility, scheduled work may have to be rescheduled for safety and welfare reasons	Consulting	0.51	11
		NGO	0.51	11
		Rail operator	0.68	24
		Academia	0.70	25
	B4.Track drainage overloaded leading to flooding of tracks	Consulting	0.47	8
		NGO	0.47	8
		Rail operator	0.61	19
		Academia	0.61	19
More intense and/or frequent high winds and/or storms	C1.Trees falling onto the line	Consulting	0.42	4
		NGO	0.52	12
		Rail operator	0.55	15
		Academia	0.65	22
	C2.High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons	Consulting	0.43	5
		NGO	0.46	7
		Rail operator	0.66	23
		Academia	0.71	26
	C3.Instability of structures	Consulting	0.44	6
		NGO	0.51	11
		Rail operator	0.63	20
		Academia	0.77	27
Sea level rise	D1.Breach of the sea wall, flooding and derailment risk	Consulting	0.40	3
		NGO	0.44	6
		Rail operator	0.55	15
		Academia	0.68	24
	D2.Reduced maintenance opportunities, bridges/ sea walls may not be safely inspected	Consulting	0.43	5
		NGO	0.56	16
		Rail operator	0.58	18
		Academia	0.68	24

Regarding the type of participants' entity, NGOs and consulting companies expect the highest-level climate risks concerning "B2" (flooding) and "D1" (sea level rise). They have more chances to engage with a variety of projects and stakeholders in the rail system and are more likely to have comprehensive views in considering multiple perspectives of railways, including climate impacts. Similarly, the lowest risk-level is attributed to academia, in particular, for the impacts posed by intensive rainfall/flooding and increased intensity and/or frequency of high wind and/or storms ("B3", "C2" and "C3").

Table 6.5 Questionnaire results of climate risk analysis on UK railways by the scale of the entity

Environmental driver due to climate change	Potential climate threat on the railway	Scale	Utility value	Ranking of risk level
Temperature increase	A1.Track buckling causing derailment risks & reducing opportunities for track maintenance	Large	0.48	8
		Middle	0.57	14
		Small	0.52	12
	A2.Unreliable signalling, power line side systems, failure of temperature controls and overheating of electronic equipment	Large	0.45	4
		Middle	0.61	17
		Small	0.54	13
Intensive rainfall/flooding	B1.Bridge foundations damaged leading to bridge collapse and derailment risk	Large	0.41	2
		Middle	0.50	10
		Small	0.45	5
	B2.Landslips causing obstruction, increasing derailment risk	Large	0.40	1
		Middle	0.51	11
		Small	0.42	3
	B3.Heavy rain affecting visibility, scheduled work may have to be rescheduled for safety and welfare reasons	Large	0.50	10
		Middle	0.73	21
		Small	0.58	15
	B4. Track drainage overloaded leading to flooding of tracks	Large	0.48	8
		Middle	0.67	19
		Small	0.46	6
More intense and/or frequent high winds and/or storms	C1.Trees falling onto the line	Large	0.48	8
		Middle	0.51	11
		Small	0.60	16
	C2.High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons	Large	0.47	7
		Middle	049	9
		Small	0.73	21
	C3.Instability of structures	Large	0.52	12
		Middle	0.48	8
		Small	0.73	21

Sea level rise	D1.Breach of seawall, flooding and derailment risk	**Large**	**0.48**	**8**
		Middle	**0.66**	**18**
		Small	**0.47**	**7**
	D2.Reduced maintenance opportunities, bridges/ sea walls may not be safely inspected	**Large**	**0.50**	**10**
		Middle	**0.68**	**20**
		Small	**0.48**	**8**

In terms of the organisation scale, large-size organisations estimate a highest-level risk scenario due to intensive rainfall/flooding, including “B1” and “B2”. On the contrary, small-size and middle-size organisations hold the lowest risk-level perspectives regarding more intense and frequent high winds and storms as well as SLR (“C2”, “C3” and “D2”). This might be because large organisations usually have more channels to receive diverse information about climate risks as well as resources in climate assessment and adaptation.

Finally, the overall group ranking of climate risk level can be obtained by averaging the utility values of each category of an individual group (Table 6.6). Despite the environmental driver due to climate change and specific potential climate threat in the railway, engineers from large consulting companies have the highest risk-level opinions. Their top concerns, according to the above group analyses, are “B1” and “B2” caused by heavier precipitation or floods, which is consistent with the previous findings in Table 6.2. Besides the aforementioned threat posed by "B3" due to the intensive rainfall/flooding increases, "C2. High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons" and "C3. Instability of structures" owing to intense or frequent high winds and storms received the least attention from academics and small companies/organisations. Interestingly, it is noticeable that the invisibility and rescheduling issues ("C2") raised by high winds or storms are similar to the issues owing to heavy rain ("B3"), with the least likely to generate critical damages to infrastructure and operations in the short term.

Table 6.6 Questionnaire results of climate risk analysis on UK railways in the different group

Category		**Average Utility value**	**Overall Ranking of Risk Level**
Position	Engineer	0.49	1
	CEO	0.50	2
	Manager	0.53	3
	Scholar	0.63	4
	Consulting	0.45	1

Type	NGO	0.48	2
	Transport Company	0.58	3
	Academia	0.64	4
Scale	Large	0.47	1
	Middle	0.58	3
	Small	0.54	2

6.5 Prioritisation of Adaptation Measures for the UK Railways

In this section, the author applies an ER approach described in Chapter 4 to synthesise the risk reduction results obtained by the Fuzzy Bayesian method and the associated adaptation costs data from questionnaire survey in order to select the most cost-effective adaptation measures. In the questionnaire, the author asked the experts to evaluate each climate threat with and without the adaptation measures, in terms of the aforementioned risk parameters *("Timeframe (T)", "Likelihood (L)", "Severity of Consequences (C)"* and *"Climate Resilience (S)")*. For each adaptation measure, they were also required to evaluate the costs of implementation.

The risk reductions can be calculated by the described FBR model, while the corresponding adaptation costs were collected through the survey and expert opinions. The parameter "Cost-effectiveness of adaptation measure" is defined by five levels, namely, *"Very effective", "Effective", "Average", "Slightly effective"* and *"Ineffective"* while "Adaptations cost" is defined by the five levels *"Very low", "Low", "Average", "High"* and *"Very High"* by the same membership functions as other risk parameters (Yang *et al*., 2015; 2018). For each adaptation measure, the risk reduction of the m^{th} climate threat by implementing n^{th} adaptation measure is calculated by the difference between,

(i) the risk index of the m^{th} climate risk with the n^{th} adaptation measure and
(ii) the risk index of the m^{th} climate risk index without any measure.

The author then utilises the Hugin software to simplify the calculations to obtain all of the climate risk levels, with and without the adaptation measures. These are shown in Table 6.6. The evaluation of risk reduction can be illustrated regarding the potential threat of "A2". In this case, the threat of "A1. Track buckling increasing risk of derailment & reducing opportunities for track maintenance" due to the "Temperature increase" has a risk index of 0.54. The adaptation measure "(A1b) Impose speed restrictions at 'compromised' sites" reduces the risk index to 0.55, a reduction of 0.01. Likewise, the risk results of all potential threats of the environmental driver on the UK rails are elaborated in Table 6.7, in which the adaptation measures receiving no significant risk reduction are eliminated.

Table 6.7 Questionnaire results of risk reduction and adaptation costs on UK railways

Environmental driver due to climate change	Potential climate threat on the railway	Adaptation measures	Risk result without adaptation measures	Risk result with adaptation measures	Risk reduction (RR_i^j)	Risk reduction grades {VE, E, A, SE, I}	Cost {VH, H, A, L, VL}
Temperature increase	A1. Track buckling increasing risk of derailment & reducing opportunities for track maintenance	(A1a) Change CWR stressing design standards to reflect a higher temperature range - Financial Cost of Adaptation	**0.54**	**0.55**	**0.01**	{0, 0, 0, 0.3077, 0.6923}	{0.25, 0.17, 0.17, 0.33, 0.08}
		(A1b) Impose speed restrictions at 'compromised' sites	**0.54**	**0.55**	**0.01**	{0, 0, 0, 0.3077, 0.6923}	{0, 0.09, 0.27, 0.36, 0.27}
		(A1c) Restrict ballast disturbance activity during hot weather	**0.54**	**0.57**	**0.03**	{0, 0, 0, 0.9231, 0.0769}	{0, 0.10, 0, 0.80, 0.10}
		(A1d) Paint rails white at critical locations to reflect the heat	**0.54**	**0.55**	**0.01**	{0, 0, 0.3077, 0.6923}	{0, 0, 0.25, 0.33, 0.42}
	A2. Risk: Unreliable signalling, power line side systems, failure of temperature controls and overheating of electronic equipment	(A2a) Use active or passive cooling of equipment cabinets	**0.54**	**0.57**	**0.03**	{0, 0, 0, 0.0231, 0.0769}	{0.09, 0.18, 0.45, 0.18, 0.09}
		(A2b) Make use of high thermal inertia design	**0.54**	**0.58**	**0.04**	{0, 0, 0.2308, 0.7692, 0}	{0.11, 0.22, 0.33, 0.22, 0.11}
		(A2c) Position cabinets in shade	**0.54**	**0.61**	**0.07**	{0, 0.1538, 0.8462, 0, 0}	{0, 0.20, 0.20, 0.50, 0.10 }
		(A2d) Re-specify and replace equipment	**0.54**	**0.61**	**0.07**	{0, 0.1538, 0.8462, 0, 0}	{0, 0.45, 0.27, 0.18, 0.09}
	A3. Track drainage overloaded leading to flooding of track	(A3a) Upgrade track drainage systems to increase capacity	**0.54**	**0.55**	**0.01**	{0, 0, 0, 0.3077, 0.0923}	{0.10, 0.50, 0.20, 010, 0.10}
Intensive rainfall/flooding	B1. Bridge foundations damaged leading to bridge collapse and derailment risk	(B1a) Improve scour resilience during routine renewal of scour protection systems	**0.47**	**0.58**	**0.11**	{0.3846, 0.6154, 0, 0, 0}	{0, 0.40, 0.30, 0.20, 0.10}
		(B1b) Design future bridges to withstand climate change	**0.47**	**0.6**	**0.13**	{1, 0, 0, 0, 0}	{0.20, 0.20, 0.30, 0.20, 0.10}
		(B1c) Introduce flood risk monitoring linked to flood agency forecasts and monitor river levels	**0.47**	**0.55**	**0.08**	{0, 0,4615, 0.5383, 0, 0}	{0, 0.20, 0.20, 0.40, 0.20 }

	B2. Landslips causing obstruction increasing derailment risk	(B2a) Map water concentration locations	**0.48**	**0.54**	**0.06**	{0, 0, 0.8462, 0.1538, 0}	{0, 0.20, 0.40, 0.20, 0.20 }
		(B2b) Identify and introduce resilience measures at vulnerable sites, such as shaping to reduce slope angles	**0.48**	**0.56**	**0.08**	{0, 0.4615, 0.5383, 0, 0}	{0.22, 0.11, 0.44, 0.11, 0.11}
		(B2c) Vegetation management	**0.48**	**0.51**	**0.03**	{0, 0, 0, 0.9231, 0.0769}	{0, 0, 0.44, 0.22, 0.33}
		(B2d) Improve earthworks and drainage management	**0.48**	**0.56**	**0.08**	{0, 0.4615, 0.5385, 0, 0}	{0,0.38, 0.38, 0.13, 0.13}
	C3. High winds affect visibility, scheduled work may have to be rescheduled for safety and welfare reasons	(C3a) Strengthen greater flow under a bridge	**0.53**	**0.57**	**0.04**	{0, 0, 0.2308, 0.7692, 0}	{0, 0.38, 0.38, 0.13, 0.13}
Sea level rise	D1. Breach of sea wall, flooding and derailment risk	(D1a) Build protective flood defence wall to appropriate standards	**0.48**	**0.54**	**0.06**	{0, 0, 0.8462, 0.1538, 0}	{0.22, 0.56, 0.11, 0, 0.11}
		(D1b) Introduce an SLR forecasting including monitoring system	**0.48**	**0.54**	**0.06**	{0, 0, 0.8462, 0.1538, 0}	{0, 0.20, 0.50, 0.10, 0.20}

Sources: RSSB (2016); Dora (2012); NR (2015); United Nations Economic Commission for Europe (UNECE) (2012).

In order to transform both climate risk and cost data into the same level, the risk reduction grades are mapped onto the five-level cost-effectiveness, where maximal risk reduction grade is interpreted as to be *"Very Effective"* and minimal risk reduction grade means *"Ineffective"* adaptation measures. The risk reduction values in between are allocated using a linear distribution. Simultaneously, adaptation costs from the survey responses are averaged and then converted into the five-level cost-effectiveness, where *"Very low"* cost is taken as to be *"Very Efficient"* adaptation measure and *"Very High"* cost means *"Ineffective"* measure.

Furthermore, the ER approach (Yang & Xu, 2002) allows us to integrate the results of risk reduction with adaptations costs of the n^{th} adaptation measure for tackling the m^{th} climate threat in order to obtain its cost-effectiveness. The final cost-effectiveness analysis results of all adaptation measures are shown in Table 6.8.

Table 6.8 Questionnaire results of cost-effectiveness of adaptation measures on UK railways

Environmental driver due to climate change	**Potential climate threat on the railway**	**Adaptation measures**	**Cost-effectiveness index of adaptation measures**	**Cost effectiveness ranking**
Temperature increase	A1. Track buckling increasing risk of derailment & reducing opportunities for track maintenance	(A1a) Change CWR stressing design standards to reflect a higher temperature range - Financial Cost of Adaptation	**0.6572**	**15**
		(A1b) Impose speed restrictions at 'compromised' sites	**0.7553**	**20**
		(A1c) Restrict ballast disturbance activity during hot weather	**0.6982**	**18**
		(A1d) Paint rails white at critical locations to reflect the heat	**0.7905**	**21**
	A2. Risk: Unreliable signalling, power line side systems, failure of temperature controls and overheating of electronic equipment	(A2a) Use active or passive cooling of equipment cabinets	**0.6157**	**14**
		(A2b) Make use of high thermal inertia design	**0.5839**	**13**
		(A2c) Position cabinets in shade	**0.5282**	**9**
		(A2d) Re-specify and replace equipment	**0.4723**	**6**
Intense rainfall/flooding	B1. Bridge foundations damaged leading to bridge collapse and derailment risk	(B1a) Improve scour resilience during routine renewal of scour protection systems	**0.3561**	**2**
		(B1b) Design future bridges to withstand climate change	**0.2695**	**1**
		(B1c) Introduce flood risk monitoring linked to flood agency forecasts and monitor river levels	**0.5033**	**8**
	B2. Landslips causing obstruction increasing derailment risk	(B2a) Map water concentration locations	**0.5485**	**11**
		(B2b) Identify and introduce resilience measures at vulnerable sites, such as shaping to reduce slope angles	**0.4363**	**3**
		(B2c) Vegetation management	**0.6966**	**17**
		(B2d) Improve earthworks and drainage management	**0.4415**	**5**
	B4. Track drainage overloaded leading to flooding of track	(B4a) Upgrade track drainage systems to increase capacity	**0.4922**	**7**
More intense	C2. High winds affect visibility,	(C2a) Strengthen greater flow under a bridge	**0.5767**	**12**

and/or frequent high wind and/or storms	scheduled work may have to be rescheduled for safety and welfare reasons	(C2b) More frequent maintenance/inspection programme	**0.7536**	**19**
	C3. Instability of structures	(C3a) Strengthen greater flow under a bridge	**0.6662**	**16**
Sea level rise	D1. Breach of sea wall, flooding and derailment risk	(D1a) Build protective flood defence wall to appropriate standards	**0.4407**	**4**
		(D1b) Introduce a sea level rise forecasting including monitoring system	**0.5377**	**10**

According to the results of Table 6.8, the most cost-effective adaptation measures in the rail system are "(B1a) Improve scour resilience during routine renewal of scour protection systems", "(B1b) Design future bridges to withstand climate change", and "(B2b) Identify and introduce resilience measures at vulnerable sites, such as shaping to reduce slope angles" which address the top potential threats "(B1)" and "(B2)" due to "Intense rainfall/flooding" respectively. The adaptation measure which is assessed to be least effective is "(A1d) Paint rails white at critical locations to reflect the heat" to cope with the potential threat "A1. Track buckling increasing risk of derailment & reducing opportunities for track maintenance" due to the "Temperature increase". However, there is no effective adaptation listed to address "(B4) Track drainage overloaded leading to flooding of the track" due to "intense rainfall/flooding".

6.6 Discussion and Conclusion

Through an in-depth investigation of relevant literature, as well as the application of an advanced mathematical model supported by a large-scale survey, this chapter systematically conducts a climate risk analysis and adaptation assessment within the context of the UK rail systems. Before the assessment of climate risks by the FBR model, the author asked the respondents to rank the diverse type of risks that they have witnessed or experienced posed by climate change on the UK railways. The investigation shows that flooding, landslide and extreme weather are the top three impacts, whereas these threats might be varying pose to the rails in different areas. The other main threats (i.e., high winds and precipitation change) occur more invariably. Sea level rise is regarded as the lowest risk overall. Moreover, through analysing and comparing the results of the four regions in the UK, the author notices that flooding and landslide are the common primary climate impacts. Similar to the overall ranking, flooding has variable impacts in each area, with severest influences in England. However, the landslide is considered as having a stable occurrence except for Wales. Additionally, extreme weather is a common threat for the rails in Northern Ireland and England, high winds are a common risk for Wales and Scotland, and storm surges are a common one for Wales and England. The above risk assessment presents an overall picture of how climate change possesses threats to the UK rail transport system.

Four primary environmental drivers due to climate change are identified through the literature review. The climate risk level for each potential climate threat was evaluated by the timeframe and likelihood of risks occurrence, the severity of consequences, as well as infrastructure resilience. Unsurprisingly, the top potential climate threats are highly related to the heavier precipitation and floods (“B1”, “B2” and “B4”), which coheres with the current priorities of flooding adaptation in the UK. The research findings reinforce the most significant climate threats in the rail sector by providing new empirical evidence. Flooding and landslide are deemed to be most significant threats as mentioned by respondents, which mainly affect the east coastline between Scotland and Newcastle and the west coastlines, e.g., the storm in Devon closed the line at Dawlish after the coastal railway fell into the sea. Increased temperature shows particular impacts on urban areas, such as for London Underground. Ayrshire coastlines are electrified and are subject to tripping when sea surges short-circuit power lines.

Through dissecting the perception of different groups, engineers from large consulting companies hold the highest risk-level opinions. Simultaneously, "B1. Bridge foundations damaged leading to bridge collapse and derailment risk" and "B2. Landslips obstructing increasing derailment risk" posed by intense rainfall/flooding are still the top issues from the perspective of engineers at large consulting companies. By contrast, the invisibility and rescheduling issues ("C2. High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons" and "B3. Heavy rain affects visibility, and scheduled work may have to be rescheduled for safety and welfare reasons") posed by high winds or storms and heavy rain are considered to pose the lowest risk threats in overall, with lower possibilities leading to catastrophic damages to infrastructure and operations in the short term.

Admitted that the UK has started paying more attention to the impacts of climate change on the railways (Hooper & Chapman, 2012), only one-third of our survey participants have implemented an adaptation plan. Nevertheless, the silver lining is that there is no hurt to hold a positive attitude for climate adaptation, and unsparingly, nearly half the participants acknowledged that they would consider developing adaptation plans in the future. Through further analysing the adaptation measures by the FBR model, the ranking of cost-effectiveness of each measure is obtained. The least effective measure is "(A1d)" to cope with the potential threat "A1." due to the "Temperature increase". The top three cost-effective measures go to "(B1a)", "(B1b)", and "(B2b)" which tackle the primary threats "(B1)" and "(B2)" due to "Intense rainfall/flooding" respectively. However, the listed adaptation listed (i.e., "(B4a)) is ineffectively to address "(B4) Track drainage overloaded leading to flooding of the track" due to "intense rainfall/flooding".

Having established the national adaptation framework (e.g., Adaptation Reporting Power) and adaptation strategy in railways by Network Rail and RSSB in recent years, there is still an urgent and continuous demand to analyse the responses to the primary impacts of climate change (e.g., flooding, landslips and extreme weather) and decision making procedure of transport stakeholders, in particular at a local base (Jude, 2017). The recently published official climate projections (UKCP18) by the UK government is believed to provide useful global information covering the full range of climate variables at a more detailed resolution (UK Climate Projections, 2009b). Supplementary with the results of this survey, the projection is also expected to offer scientific guidance for dealing with the challenges of estimation and selection of risk scenarios under diverse climate conditions. Thus, it will be great timing for regions, where there is a lack of detailed or dated climate information for risk assessments, to be able to produce a climate adaptation plan.

It is noted the survey is heavily weighted to England (79%) and senior staff (i.e., CEOs and transport directors), while the respondents from Wales, Scotland and Northern Ireland only take account around 8%, 9% and 4% of the total respectively. The participants from small companies/organisations (40%), transport companies (30%) and consulting companies (30%) are the main force regarding the scale and type of the entity. Due to sampling limit, it is possibly under-reporting some threats (e.g., snow in Scotland) and opinions from other groups (e.g., large entities and scholars) leading to a bias in certain areas and institutions. Therefore, more work is required to verify these findings by consultation with a broader pool of stakeholders in under-reached regions. Moreover, further research on other transport modes (e.g., road and air) and multiple regions (e.g., developing countries) are imperative to create a practical and resilient adaptation framework on climate change.

Nevertheless, the present preliminary investigation of this study makes a pioneering attempt in climate risk analysis and will be incorporated into a broader comparative study of climate risks and adaptation affecting the rail system at the next stage. More quantitative estimates, cost-effectiveness evaluations are suggested to test the feasibility of this risk model. Hence, in the next Chapter, the current FBR model and evidential reasoning techniques will apply to the road industry in the UK.

Chapter 7 Risk Analysis of Climate Change Impacts on the UK Road System[13]

This chapter aims to analyse the impacts of climate change on the current and predicted future situations of road transportation in the UK and evaluate the corresponding adaptation plans to cope with them. It examines the resilience and sustainability of road transport systems under various climate risks such as flooding and increased temperature. To do so, an advanced Fuzzy Bayesian Reasoning (FBR) model is first employed to evaluate the climate risks in the UK road transport networks. This modelling approach can tackle the high uncertainty in risk data and thus facilitate the development of the climate adaptation framework and its application in the UK road sector.

Similar to Chapter 6, this work brings novelty by expanding the risk attribute "the severity of consequence" into three sub-attributes, including economic loss, damage to the environment, and injuries and loss of life. It advances the-state-of-the-art technique in the current relevant literature from a single to multiple tier climate risk modelling structure. Furthermore, an Evidential Reasoning (ER) approach is used to prioritise the best adaptation measure(s) by considering both the risk analysis results from the FBR and the implementation costs simultaneously. The main new contributions of this part lie in the rich raw data collected from the real world to provide useful, practical insights for achieving road resilience when facing increasing climate risk challenges. During this process, a qualitative analysis of several national reports regarding the impacts posed by climate change, risk assessment and adaptation measures in the UK road sector is conducted for the relevant decision data (e.g., risk and cost). The findings provide road planners and decision-makers with useful insights on the identification and prioritisation of climate threats as well as the selection of cost-effective climate adaptation measures to rationalise adaptation planning.

The remainder of this chapter is structured as follows. Section 7.1 firstly presents the design and sampling procedure of the road survey. The general information of this survey is analysed in Section 7.2, which includes the geographic distribution and position of responses, primary climate risks in each region and implementation of adaptation planning. Similar to Chapter 6,

[13] The modified version of this chapter has been published by Transportation Research Part D. Wang T.^, Qu Z, Nichol T., Yang Z.*, Dimitriu D., Clarke G. and Bowden D. (2019), “How Can the UK Road System be Adapted to the Impacts Posed by Climate Change? By Creating a Climate Adaptation Framework”, Transportation Research Part D: Transport Environment, Accepted in press.

the climate risk evaluation regarding the four primary threats on the UK road system is then undertaken by using the constructed FBR model in section 7.3. Afterwards, Section 7.4 accurately interprets the ranking results of each participants' group. The cost-effectiveness of each adaptation measure is further examined by the FBR model in Section 7.5. Finally, the discussion and conclusion, with suggestions for further research, are summarised in Section 7.6.

7.1 Survey Design and Distribution

This survey included the evaluation of overall impacts and specific threats on the operations, performance, and infrastructure of British roads. The questions were categorised into two types: closed-ended and open-ended. In particular, participants were asked to describe the risk level of each specific risk threat with and without adaptation measures by the linguistic terms concerning its timeframe, severity of consequence, likelihood and climate resilience. In addition, the author required the information about the financial costs of each adaptation measure for further cost-effectiveness assessment. To guarantee the validity of this questionnaire, a pilot study was undertaken in April 2017 by speaking with eight professional road experts and academics in the UK. The 12 potential climate threats on the road and their corresponding adaptation measures were then finalised (see Table 6.1 and Table 6.3) by combining the literature review (e.g., UNECE, 2012; Regmi & Hanaoka, 2011) and the results from the domain experts' survey.

From May to December 2017, the author assessed the perception of 19 road experts on climate change risks through a nationwide online survey. The survey participants widely ranged from CEOs/transport directors, transport planners, transport engineers, environmental managers, private operators, transport authorities, highway agencies and NGOs to road academics. A summary listing the background information of domain experts can be found in Appendix A. Transport entities in charge of the "M" (i.e., motorway) and "A" class roads in the UK were targeted as primary participants in this survey.

There were two criteria for the survey sampling: 1) members of the UK Roads Liaison Group (UKRLG); 2) Other main road entities that can provide the geographical balance of each region in the UK. Consequently, a sample of 30 administrators representing the essential transport institutions of different regions in the UK (e.g., HE, TfGM, AECOM UK, etc.) was selected to assess their perceptions of climate change risks. Afterwards, the author invited one or two critical informants at each entity from the targeted population to help distribute the questionnaire by a snowballing method. 30 questionnaires were distributed through the Bristol Online Survey (2017). E-mails and phone calls were used to contact all the respondents. In the end, 19 out of 30 valid responses were received with a high response rate of 63.3%.

7.2 Geographic Distribution, Position of Participants, Primary Climate Risks and Adaptation Plans in Road Survey

Similar to Chapter 6, this section firstly analyses the general information about the participants. These include the name (Q3) and region(s) (Q3a) of the road their entity operate on, their current position (Q4 and Q4a), the type(s) and level(s) of climate risks are on the road their entity is associated with (Q5, Q5a and Q6) as well as the implementation of climate adaptation planning (Q7). The regions involved in this survey cover all of the UK, namely Wales, Scotland, Northern Ireland and England. The geographic distribution of the number of respondents' entity is analysed, as shown in Figure 7.1. It can be observed that around 79% of road-related entities are located in England where the major networks are managed by Highways England. The entities which come from Wales, Scotland and Northern Ireland only take account of about 10%, 7% and 4% of the total responses respectively.

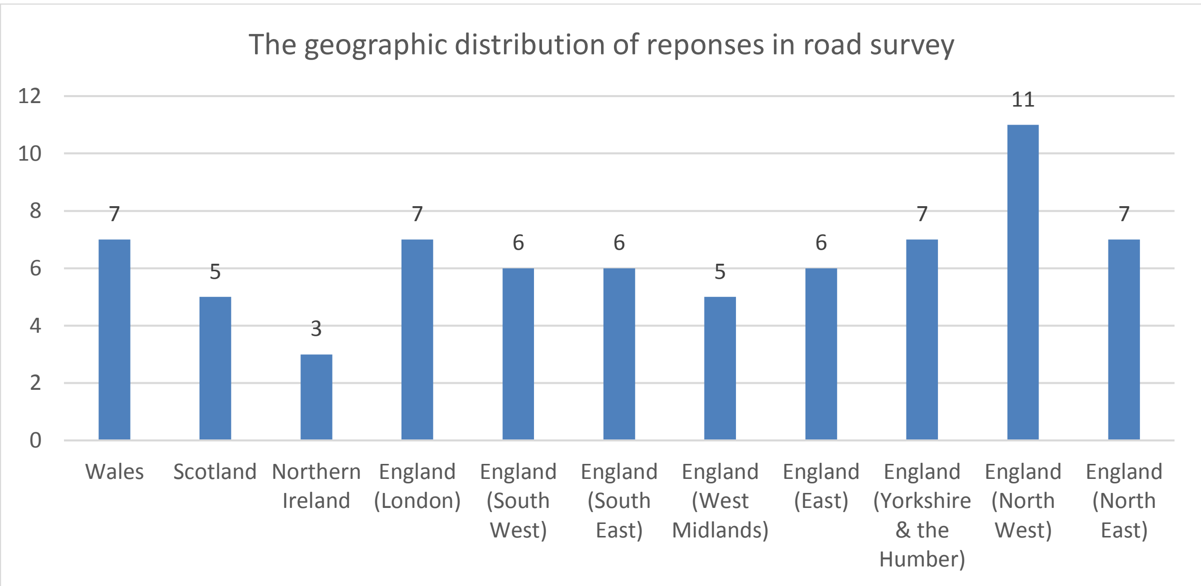


Figure 7.1 Geographic distribution of responses in road survey

In respect to the current position of participants, Figure 7.2 illustrates that the number of participants is unequal in different positions. The primary responses are from transport planners (5), followed by CEOs/transport directors (2) and transport engineers (2) are the main. The ‘others' include bridge design leads, traffic and local road associate directors, research consultants, heads of highways, waste and property and advanced solution managers.

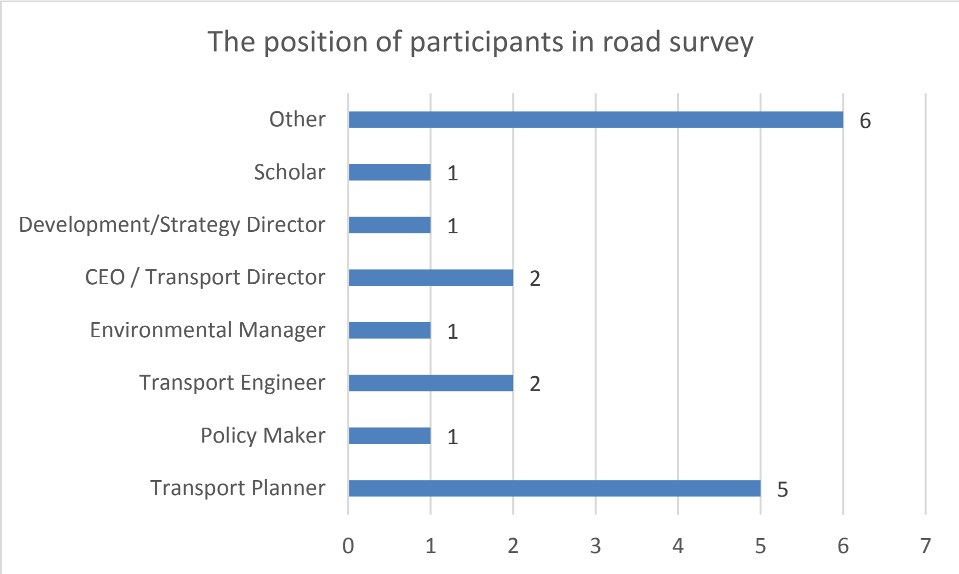


Figure 7.2 Distribution of participants’ position in road survey

Before diving to the assessment the specific threats of the four climate drivers by the FBR model, the survey requires participants to rank the diverse type of risks that they have witnessed or experienced posed by climate change on the road their company/organisation are associated with (Q5 and Q5a).

By calculating the ranking values of the mean and standard deviation of each potential climate risk to the UK road network, in overall, flooding (M=5.44), precipitation change (M=5) and extreme weather (M=5.11) are the top concerns, followed by snow (M=5.24) and flooding (M=5.44). However, sea level rise (M=6.63) is considered the lowest risk. Among them, temperature increase (SD=2.50) and snow (SD=2.66) in particular, occur more stable when compared to precipitation change (SD=2.78), flooding (SD=3.60) and extreme weather (SD=2.97). Hence, the regional assessment is conducted regarding the primary climate threats to the railways in four areas.

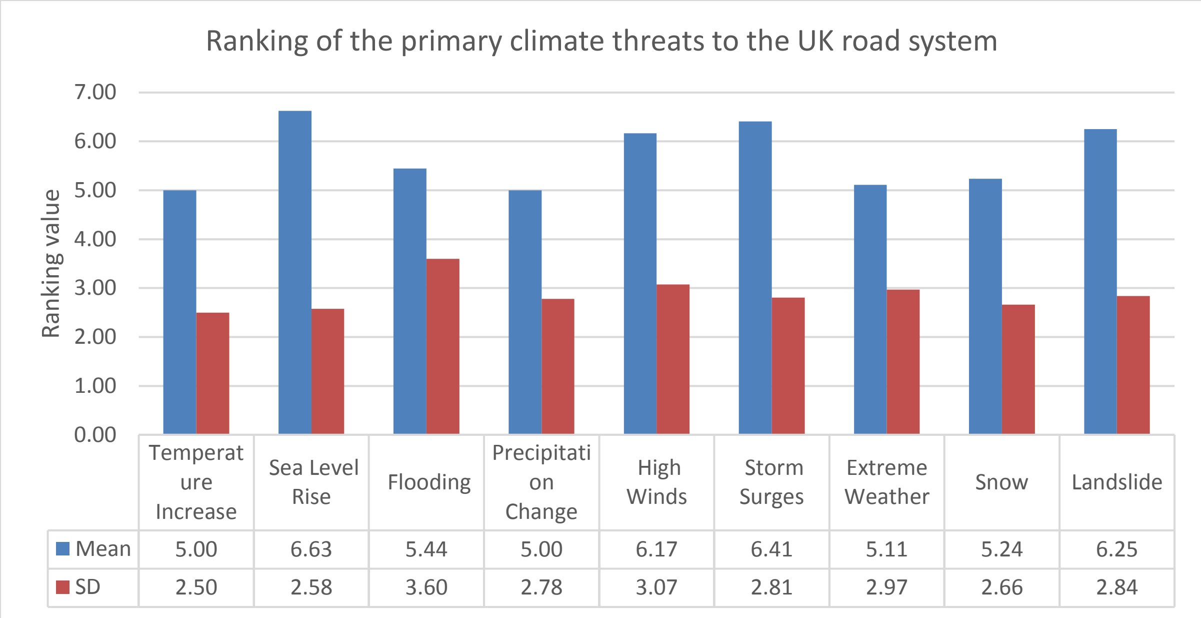


Figure 7.3 Ranking of the primary climate threats to the UK road system

Figure 7.4 shows that snow (M=3.33), temperature increase (M=4) and extreme weather (M=4.86) are considered as the top threats to the roads in Wales. Whereas, the lowest threat is landslide (M=6.50). Meanwhile, as the SD values of snow (SD=2.25) and temperature increase (SD=2.45) are smaller than the one of extreme weather (SD=3.39), thus snow and temperature have a higher possibility to happen.

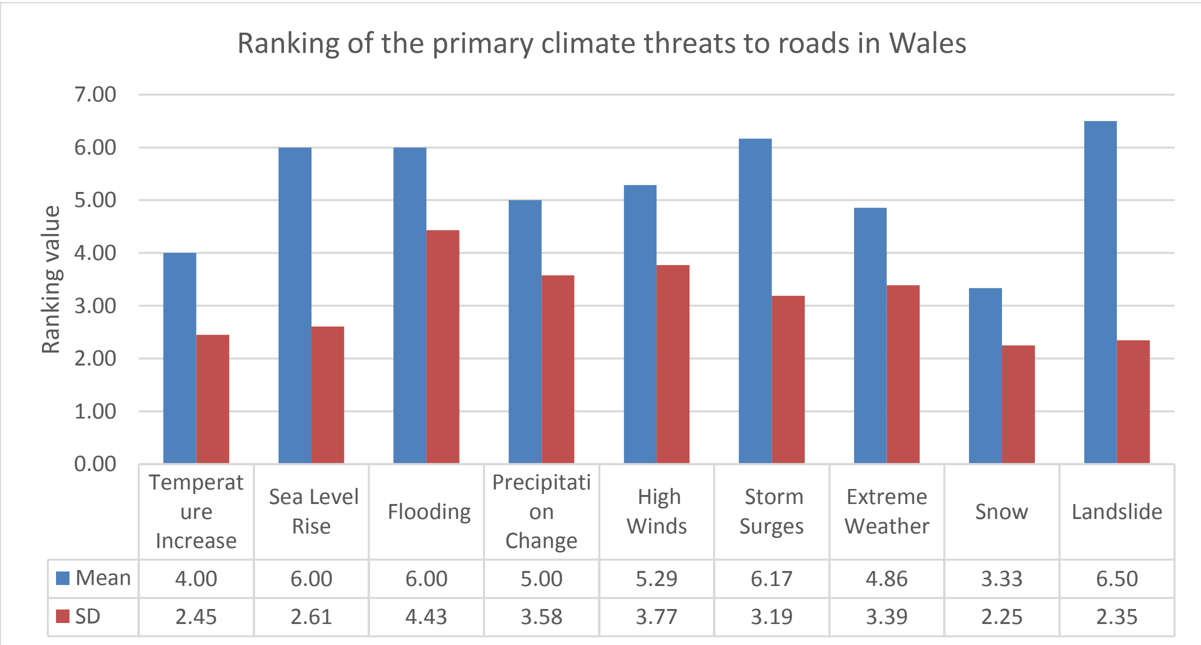


Figure 7.4 Ranking of the primary climate threats to roads in Wales

As for the road network in Scotland (Figure 7.5), snow (M=3), temperature increase (M=4) and precipitation change (M=5) pose the most significant threats by climate change. However, storm surge and landslide pose the lowest impacts (M=7.50). Meanwhile, snow (SD=2.83) and temperature increase (SD=3) occur more steadily than precipitation change (SD=3.92).

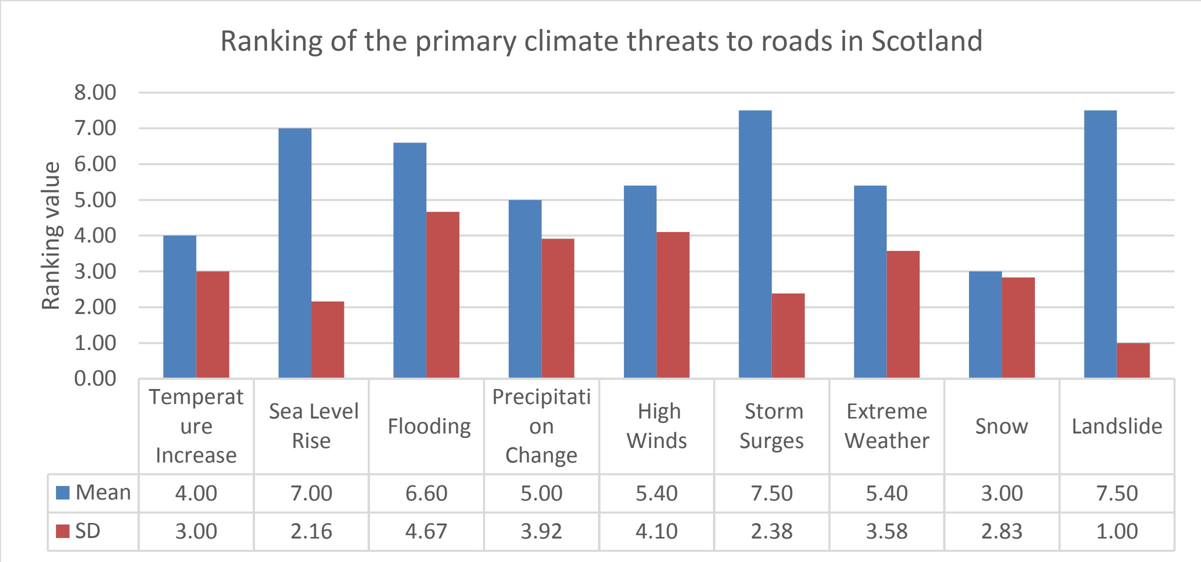


Figure 7.5 Ranking of the primary climate threats to roads in Scotland

In Northern Ireland (Figure 7.6), the primary climate impacts attribute to snow (M=1.67), temperature increase (M=2) and precipitation change (M=3.5), and the lowest threat is landslide (M=7). Snow (SD=1.15) and temperature increase (SD=1.73) are more likely to occur stably instead of precipitation change (SD=3.54).

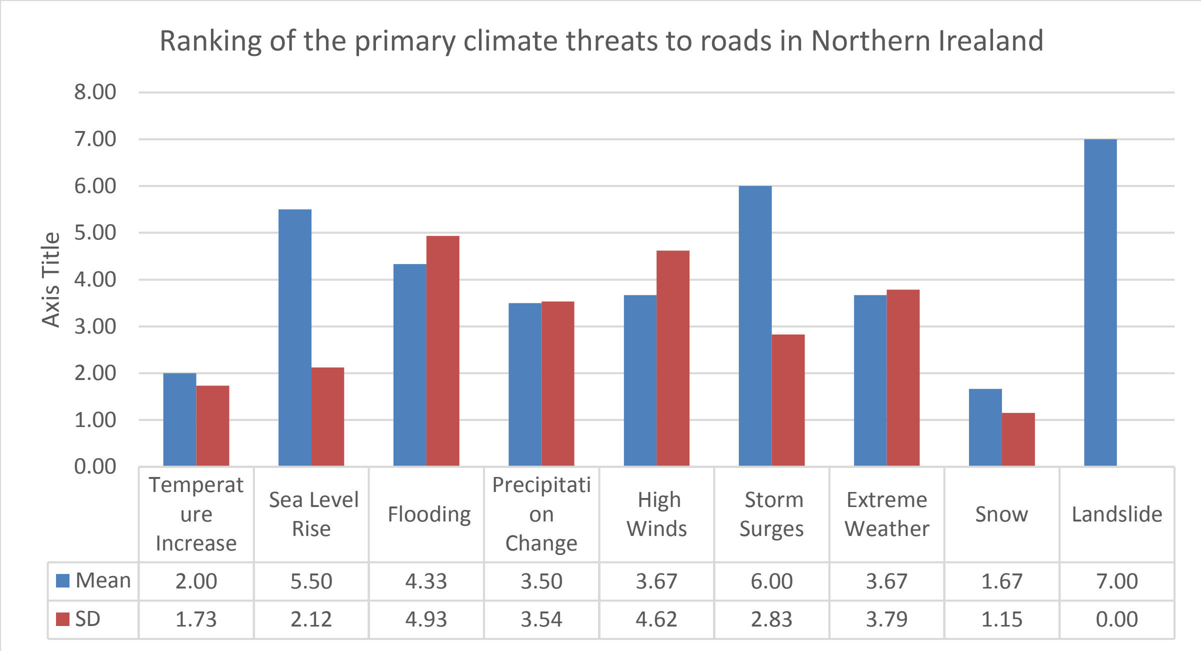


Figure 7.6 Ranking of the primary climate threats to roads in Northern Ireland

Last but not least, as Figure 7.7 shows, temperature increase (M=5.13), precipitation change (M=5) and extreme weather (M=5.31) are the critical threats for England's road system. However, sea level rise is regarded as the lowest climate one (M=7). Among the top risks, extreme weather (SD=2.96) occurs more instable, comparing to temperature increase (SD=2.63) and precipitation change (SD=2.75).

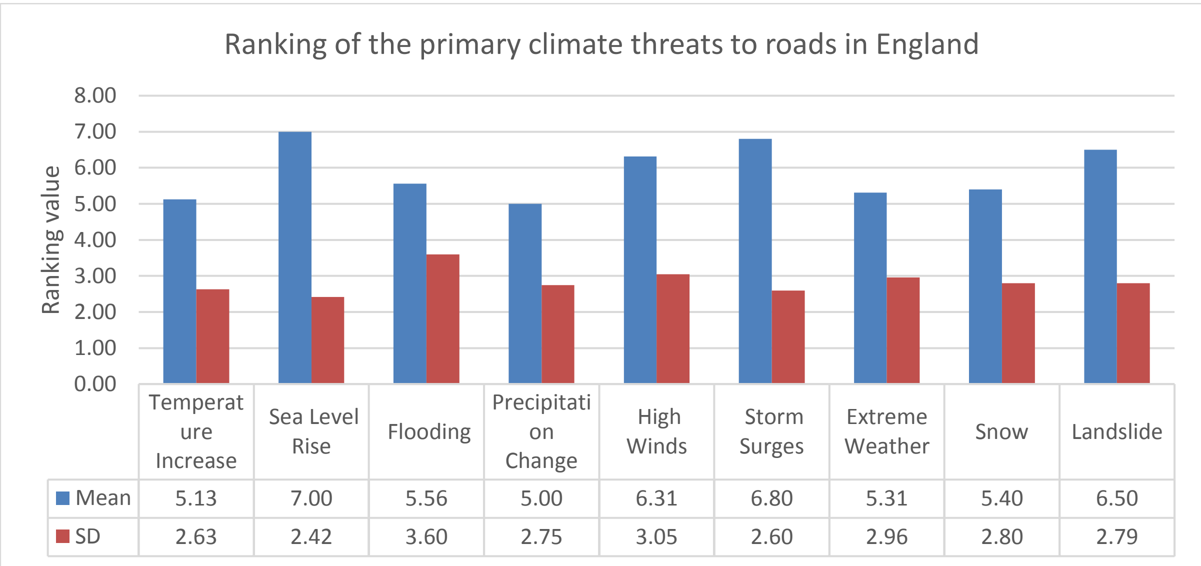


Figure 7.7 Ranking of the primary climate threats to roads in England

By vertically comparing the results of the primary climate risks in four primary regions of the UK (Table 7.1), it is noticed that temperature increase are the common threats posed by climate change for the roads within all regions with particular high ranking (lowest mean and SD value) in Northern Ireland (M=2 and SD=1.73). The SDs of temperature increase in the four regions are also small, which informs a stable occurrence. Precipitation change is a top issue for the UK roads as a whole (M=5), which are ranked as one of the top threats in Scotland, Northern Ireland and England. Nevertheless, the high SDs indicate unsteady occurrences in almost of the regions expect England (SD=2.75).

Additionally, extreme weather is the second top issue for the UK, which poses common impacts for Wales and England but without a stable occurrence. Snow is the third severest threats for the rails in the UK as a whole and the three areas including Wales, Scotland and Northern Ireland (with low mean and SD values); however, it is not the case for England. Interestingly, as over 70% of respondents are from England, the main threats posed by climate change in the UK have also affected by the regional data. Hence, among the top threats for the UK roads, the temperature increase is considered as the absolute top risk for all the four regions, while precipitation change is one of the top concerns for most of the regions except Wales and snow is the main threat for the major areas expect from England.

Table 7.1 Questionnaire results of primary climate threats to UK roads

		Temperature Increase	Sea Level Rise	Flooding	Precipitation Change	High Winds	Storm Surges	Extreme Weather	Snow	Landslide
Wales	Mean	4.00	6.00	6.00	5.00	5.29	6.17	4.86	3.33	6.50
	SD	2.45	2.61	4.43	3.58	3.77	3.19	3.39	2.25	2.35
Scotland	Mean	4.00	7.00	6.60	5.00	5.40	7.50	5.40	3.00	7.50
	SD	3.00	2.16	4.67	3.92	4.10	2.38	3.58	2.83	1.00
Northern Ireland	Mean	2.00	5.50	4.33	3.50	3.67	6.00	3.67	1.67	7.00
	SD	1.73	2.12	4.93	3.54	4.62	2.83	3.79	1.15	0.00
England	Mean	5.13	7.00	5.56	5.00	6.31	6.80	5.31	5.40	6.50
	SD	2.63	2.42	3.60	2.75	3.05	2.60	2.96	2.80	2.79
UK	Mean	5.00	6.63	5.44	5.00	6.17	6.41	5.11	5.24	6.25
	SD	2.50	2.58	3.60	2.78	3.07	2.81	2.97	2.66	2.84

Moreover, the details about the threats posed by climate change on the roads the participants' company/organisation associated with (Q6) are collected. Notably, almost all the respondents who have experienced climate impacts in the past ten years, emphasise flooding. For example, significant floods caused widespread damage to highway infrastructure, road deterioration and closures, service stoppage, as well as bridges being washed away in June 2000, November 2006, June 2012, July 2014 and December 2015.

Regarding the implementation of climate adaptation plans on the UK road system (Q7), a majority of participants said that they had noticed the importance of climate risks; however, only 28% of them have undertaken an adaptation plan while one-third of the total will consider an action plan in the future.

7.3 Climate Risk Assessment of the UK Roads by the FBR Model

Similar to the risk analysis on the rail survey, the climate risks of each potential climate threat for each environmental driver are calculated by the aforementioned FBR approach. Table 7.2 shows the results for UK roads with no adaptation measures being implemented. The evaluations of each threat take into account the four risk parameters: *Timeframe (T), Likelihood (L), Severity of occurrence (C)* and *Climate Resilience (S)*.

Table 7.2 Questionnaire results of climate risk analysis on UK roads

Environmental driver due to climate change	Potential climate threat on the road	Risk ranking value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	0.54	9
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	0.51	8
	A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	0.40	1
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	0.43	2
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	0.44	3

	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	**0.47**	**4**
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	**0.48**	**5**
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	**0.50**	**7**
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	**0.51**	**8**
	C3. High wind and storms can increase traffic accidents and affect road safety	**0.48**	**5**
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	**0.49**	**6**
	D2. Sea level rise can deteriorate road base and bridge supports, cause bridge scour and pollution under bridges	**0.50**	**7**

Sources: Conference of European Directors of Roads (2012); IPCC (2012b); Regmi & Hanaoka (2011); The Royal Academy of Engineering (2011); UNECE (2012)

Table 7.2 shows the risk results for each of the 12 Potential Climate Threats utilising FBR and its associated Hugin software (Hugin v. 8.5, 2017; Andersen et al., 1990). For example, the risk results of “A1", can be calculated as {2.38% Very high, 20.78% High, 35.21% Average, 36.15% Low, 5.48% Very low}. After assigning the utility values to the five linguistic terms, A1's risk index value is calculated as 0.54. The result of the risk analysis on A1 by Hugin is found in Figure 7.8.

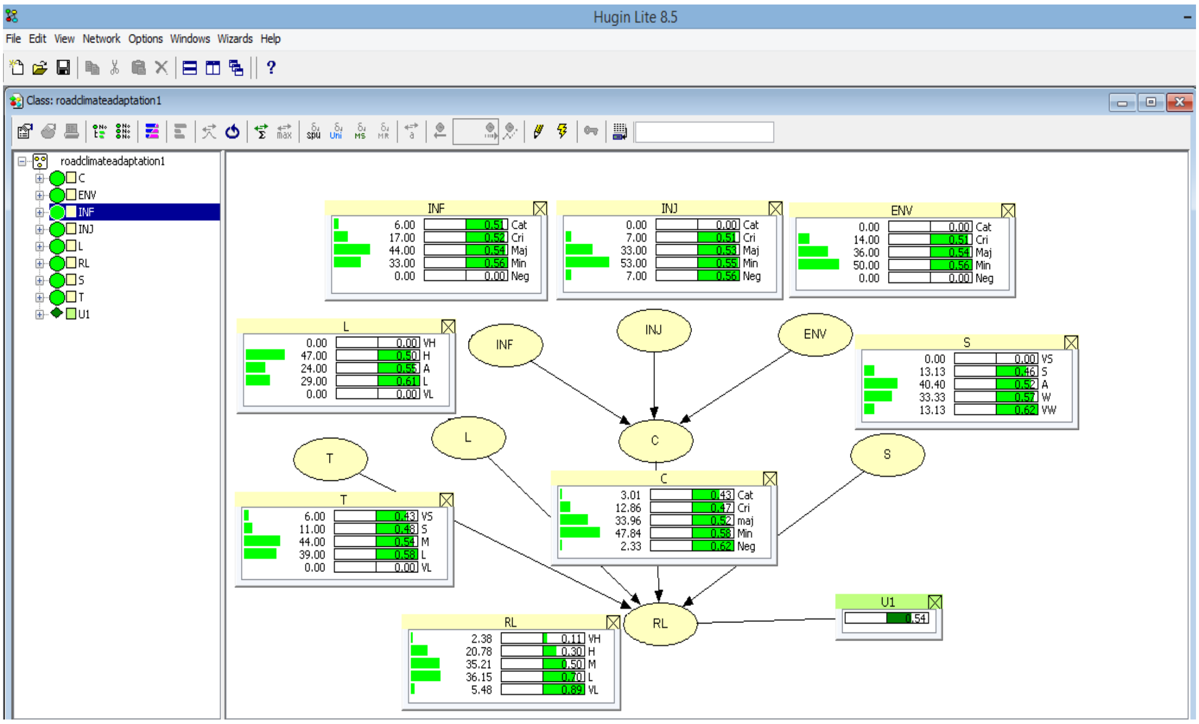


Figure 7.8 Climate risk analysis of "A1. Extended warm weather can cause pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt" using Hugin

Based on the ranking result in Table 7.2, the highest climate risks to the roads in Britain are "A3", "B12" and "B2", which refers to "A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs owing to increased temperature", "B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions", and "B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts", respectively. The threat of the lowest ranking risk level is "(A1) Extended warm weather can cause pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt because of increased temperature". This is probably because the influence of increased temperature on road pavement is a long process where substantial economic losses may not be visualised in a short time.

7.4 Climate Risk Evaluation of the UK Roads in Diverse Groups

To understand the different opinions from diverse groups regarding climate risks on roads, this survey groups the participants into three categories:

1) Engineers (including transport engineers, bridge design leads and freight and logistics technologists); CEOs (including CEO/ transport directors, development/strategy directors, traffic & local road associate directors and policymakers); managers (including transport planners, environmental managers, heads of highways, waste & property, and advanced solution managers), as well as an scholar (a road research fellow) by their positions;

2) Consulting companies, NGOs, transport companies and academia, by the type of their entities; and

3) Large, middle and small companies or organisations by the scale of their entities.

Figure 7.9 describes the percentage distribution of each participants' group. Mangers are the primary respondents occupying 47% of the total. Simultaneously, large and consulting companies take account the significant portion (42%) of the total responses in terms of the scale and type of the participants' entity, respectively.

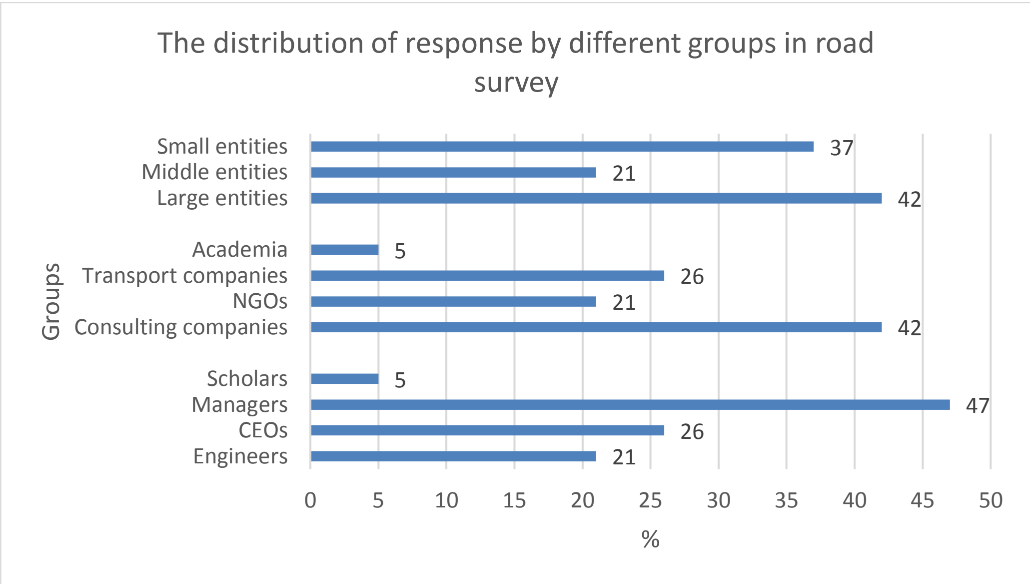


Figure 7.9 Distribution of responses by participants' position, type and scale of their entity

Utilising the FBR method, the utility value and ranking of the risk level of each potential climate threat are calculated (See Tables 6.2-6.4).

In Table 7.3, the assessment takes into account the participants' position. The climate threat "A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs" posed by "temperature increase" is the top concern that three out the four groups of stakeholders evaluate it with the lowest utility values. This is possibly because engineers and managers tend to involve in the day-to-day road operations and evidence the damages to the road infrastructure that they use or are in charge of due to climate change. Interestingly, whilst scholars hold the highest risk views on the impacts of temperature increase (i.e., "A3"), they hold the three lowest risk views on intense rainfall/flooding ("B3" and "B4"), and more intense and/or frequent high winds and/or storms ("C2"). This indicates that the scholar's climate risk perception is quite different from industrialists, triggering new research to better understand the driver behind the difference. It, therefore, raises the research urgency in the field where industrial concerns/needs are higher than academic expectations and possible reactions.

Table 7.3 Questionnaire results of climate risk analysis on UK roads by position

Environmental driver due to climate change	Potential climate threat on the road	Position	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	Engineer	0.56	17
		CEO	0.44	5
		Manager	0.53	14
		Scholar	0.53	14
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	Engineer	0.56	17
		CEO	0.54	15
		Manager	0.49	10
		Scholar	0.50	11
	A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	Engineer	0.40	2
		CEO	0.41	3
		Manager	0.40	2
		Scholar	0.37	1
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	Engineer	0.44	5
		CEO	0.44	5
		Manager	0.41	3
		Scholar	0.43	4
	B2. Rainfall events can cause	Engineer	0.45	6

	rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	**CEO**	**0.48**	**9**
		Manager	**0.41**	**3**
		Scholar	**0.48**	**9**
	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	**Engineer**	**0.48**	**9**
		CEO	**0.45**	**6**
		Manager	**0.40**	**2**
		Scholar	**0.63**	**20**
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	**Engineer**	**0.46**	**7**
		CEO	**0.43**	**4**
		Manager	**0.48**	**9**
		Scholar	**0.66**	**22**
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	**Engineer**	**0.49**	**10**
		CEO	**0.47**	**8**
		Manager	**0.45**	**6**
		Scholar	**0.56**	**17**
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	**Engineer**	**0.47**	**8**
		CEO	**0.46**	**7**
		Manager	**0.51**	**12**
		Scholar	**0.65**	**21**
	C3. High wind and storms can increase traffic accidents and affect road safety	**Engineer**	**0.51**	**12**
		CEO	**0.49**	**10**
		Manager	**0.46**	**7**
		Scholar	**0.50**	**11**
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	**Engineer**	**0.52**	**13**
		CEO	**0.51**	**12**
		Manager	**0.45**	**6**
		Scholar	**0.60**	**18**
	D2. Sea level rise can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	**Engineer**	**0.52**	**13**
		CEO	**0.55**	**16**
		Manager	**0.48**	**9**
		Scholar	**0.61**	**19**

The results in Table 7.4 reflect the ‘type’ of participants. Academia and consulting companies confirm “A3” as the highest-level climate risk. NGO’s identify their highest ranking risk as “B1.The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions” owing to “intense rainfall/flooding”. NGOs and consulting companies have lots of engagements with a variety of projects and stakeholders in the road network; they have a higher chance to provide comprehensive views on climate impact on roads. As in Table 7.3, academia has the three lowest ranking risks ("B3", "B4" and "C2") Again, it reveals variations in understanding the risks posed by climate change between academics and practitioners.

Table 7.4 Questionnaire results of climate risk analysis on UK roads by type of entity

Environmental driver due to climate change	Potential climate threat on the road	Type	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	**Consulting**	**0.59**	**18**
		NGO	**0.42**	**5**
		Transport Company	**0.51**	**14**
		Academia	**0.55**	**16**
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	**Consulting**	**0.50**	**13**
		NGO	**0.44**	**7**
		Transport Company	**0.52**	**15**
		Academia	**0.50**	**13**
	A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	**Consulting**	**0.39**	**2**
		NGO	**0.40**	**3**
		Transport Company	**0.52**	**15**
		Academia	**0.37**	**1**
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	**Consulting**	**0.46**	**9**
		NGO	**0.37**	**1**
		Transport Company	**0.42**	**5**
		Academia	**0.43**	**6**
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	**Consulting**	**0.46**	**9**
		NGO	**0.43**	**6**
		Transport Company	**0.43**	**6**
		Academia	**0.48**	**11**
	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	**Consulting**	**0.45**	**8**
		NGO	**0.46**	**9**
		Transport Company	**0.41**	**4**
		Academia	**0.63**	**20**

	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	**Consulting**	**0.47**	**10**
		NGO	**0.47**	**10**
		Transport Company	**0.48**	**11**
		Academia	**0.68**	**22**
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	**Consulting**	**0.50**	**13**
		NGO	**0.51**	**14**
		Transport Company	**0.49**	**12**
		Academia	**0.57**	**17**
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	**Consulting**	**0.47**	**10**
		NGO	**0.50**	**13**
		Transport Company	**0.55**	**16**
		Academia	**0.65**	**21**
	C3. High wind and storms can increase traffic accidents and affect road safety	**Consulting**	**0.46**	**9**
		NGO	**0.51**	**14**
		Transport Company	**0.52**	**15**
		Academia	**0.50**	**13**
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	**Consulting**	**0.46**	**9**
		NGO	**0.50**	**13**
		Transport Company	**0.46**	**9**
		Academia	**0.60**	**19**
	D2. Sea level rise can deteriorate erosion of road base and bridge supports, cause bridge scour, and pollution under bridges	**Consulting**	**0.52**	**15**
		NGO	**0.45**	**8**
		Transport Company	**0.52**	**15**
		Academia	**0.60**	**19**

Finally, concerning the scale of participants' organisation (Table 7.5), the author divides them into three categories: large (more than 50,000 employees), middle (1,000-50,000 employees) and small (less than 1,000 employees) organisation. Large and middle organisations again confirm “A3” as the highest ranking risk scenario owing to "temperature increase". By contrast, small organisations rated "A3" as one of the lower-ranking risks (14). The middle-sized organisations consider the two lowest-ranking risks to be posed by more intense precipitation ("B4") and/or frequent high wind and/or storms ("C2"). It could be because the larger-scale companies/organisations are more likely to be exposed to the impacts of climate change as their operations usually involve more extensive or more complicated road networks, thus having more concerns on this topic.

Table 7.5 Questionnaire results of climate risk analysis on UK roads by the scale of the entity

Environmental driver due to climate change	Potential climate threat on the roads	Scale	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	**Large**	**0.53**	**13**
		Middle	**0.51**	**11**
		Small	**0.56**	**16**
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	**Large**	**0.46**	**6**
		Middle	**0.50**	**10**
		Small	**0.45**	**5**
	A3. Traffic jams / alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	**Large**	**0.39**	**2**
		Middle	**0.37**	**1**
		Small	**0.54**	**14**
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	**Large**	**0.45**	**5**
		Middle	**0.43**	**3**
		Small	**0.43**	**3**
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	**Large**	**0.45**	**5**
		Middle	**0.43**	**3**
		Small	**0.46**	**6**
	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	**Large**	**0.47**	**7**
		Middle	**0.54**	**14**
		Small	**0.44**	**4**
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	**Large**	**0.45**	**5**
		Middle	**0.58**	**17**
		Small	**0.43**	**3**

More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	**Large**	**0.47**	**7**
		Middle	**0.51**	**11**
		Small	**0.49**	**9**
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	**Large**	**0.48**	**8**
		Middle	**0.58**	**17**
		Small	**0.50**	**10**
	C3. High wind and storms can increase traffic accidents and affect road safety	**Large**	**0.47**	**7**
		Middle	**0.53**	**13**
		Small	**0.53**	**13**
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	**Large**	**0.49**	**9**
		Middle	**0.49**	**9**
		Small	**0.48**	**8**
	D2. Sea level rise can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	**Large**	**0.52**	**12**
		Middle	**0.55**	**15**
		Small	**0.46**	**6**

By averaging the utility values of each category and corresponding group, the overall ranking of risk levels of the investigated climate threats can be found in Table 7.6. Notably, managers from large NGOs hold the highest risk-level views. Meanwhile, according to the above categorisation analyses, the climate threat "A3" is always the top concern. While threats "B4" and "C2" receive the least attention from both academics and middle-size companies/organisations (i.e. "B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable" due to "intense rainfall/flooding" and "C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign" because of "more intense and/or frequent high wind and/or storms").

Table 7.6 Questionnaire results of climate risk analysis on UK roads with respect to the different group

Category		Average Utility value	Overall Ranking of Risk Level
Position	**Engineer**	**0.49**	**3**
	CEO	**0.47**	**2**
	Manager	**0.45**	**1**
	Scholar	**0.54**	**4**
Type	**Consulting**	**0.48**	**2**
	NGO	**0.46**	**1**
	Transport Company	**0.49**	**3**
	Academia	**0.54**	**4**
Scale	**Large**	**0.47**	**1**
	Middle	**0.50**	**3**
	Small	**0.48**	**2**

7.5 Prioritisation of Adaptation Measures for the UK Road System

In this section, the ER approach is used to evaluate the cost-effectiveness of the explored adaptation measures against the climate threats of high risks at the last step of this methodology. For instance, risk reduction with adaptations cost of the n^{th} adaptation measure for tackling the m^{th} climate threat can be synthesised to obtain the cost-effectiveness of the n^{th} adaptation measure against the threat.

The whole process of ER calculations to obtain the final results of the combined degrees of Belief (DoB) β^j ($j=1, 2, 3, 4, 5$) can refer to the latest algorithm pathway.[14]

Furthermore, utilising centroid defuzzification method (Mizumoto, 1995; Yang *et al*., 2009), the linguistic description can then be converted into crisp values {0.11, 0.3, 0.5, 0.7, 0.89} (Yang et al., 2018) so as to obtain a numerical cost-effectiveness index (*CEI*) of each adaptation measure.

The author utilises the Hugin software to simplify the calculations to obtain all of the climate risk levels, with and without the adaptation measures. These are shown in Table 7.7. The evaluation of risk reduction can be illustrated with reference to the potential threat "A2". In this case, the threat of "Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces" due to the "Temperature increase" has a risk index of 0.51. The adaptation measure "(A2a) Prioritise the selection of material, manage expansion joints and

[14] The detailed algorithm has been explained in Chapter 4.

decay protection (i.e., use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)" reduces the risk index to 0.56, a reduction of 0.05. Likewise, the risk results of all potential threats of the environmental driver on the UK roads are elaborated in Table 7.7, in which the adaptation measures receiving no significant risk reduction are eliminated.

Table 7.7 Questionnaire results of risk reduction and adaptation costs on UK roads

Environmental driver due to climate change	**Potential climate threat on the road**	**Adaptation measures**	**Risk Result without adaptations**	**Risk result with adaptations**	**Risk reduction RR_{mn}**	**Risk reduction grades {VE, E, A, SE, I}**	**Cost {VH, H, A, L, VL}**
Temperature increase	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	(A2a) Prioritise the selection of material, manage expansion joints and decay protection (i.e., Use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)	**0.51**	**0.56**	**0.05**	{0, 0, 0.6667, 0.3333, 0}	{0.10, 0.30, 0.40, 0.20, 0}
		(A2b) Design and construct new bridges or replace old ones (i.e., Designs which support the revised specifications in B1 – so that supporting materials have revised specification for performance in line with B1)	**0.51**	**0.53**	**0.02**	{0, 0, 0, 0.6667, 0.3333}	{0.09, 0.36, 0.45, 0.09, 0}
	A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays, and consequential costs	(A3a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	**0.40**	**0.50**	**0.10**	{0.3333, 0.6667, 0, 0, 0}	{0, 0.18, 0.09, 0.55, 0.18}
		(A3b) Provision of timely driver information to 'at risk' routes	**0.40**	**0.52**	**0.12**	{1, 0, 0, 0, 0}	{0, 0.09, 0.09, 0.45, 0.36}
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	(B1a) Consider drain specifications to handle different rain conditions	**0.43**	**0.50**	**0.07**	{0, 0.3333, 0.6667, 0, 0}	{0, 0.38, 0.31, 0.31, 0}
		(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in A1	**0.43**	**0.55**	**0.12**	{1, 0, 0, 0, 0}	{0, 0.33, 0.33, 0.33, 0}
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	(B2a) Improve flood estimation	**0.44**	**0.49**	**0.05**	{0, 0, 0.6667, 0.3333, 0}	{0.08, 0.08, 0.67, 0.08, 0.08}
		(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection	**0.44**	**0.55**	**0.11**	{0.6667, 0.3333, 0, 0, 0}	{0.18, 0.36, 0.45, 0, 0}

	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	(B3a) Consider Slope, drain performance in landslide scenarios	**0.47**	**0.57**	**0.10**	{0.3333, 0.6667, 0, 0, 0}	{0.08, 0.08, 0.50, 0.33, 0}
		(B3b) Design standards for highways which performance to revised standards with different rain events	**0.47**	**0.51**	**0.04**	{0, 0, 0.3333, 0.6667, 0}	{0, 0.15, 0.38, 0.31, 0.15}
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	(B4a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	**0.48**	**0.50**	**0.02**	{0, 0, 0, 0.6667, 0.3333}	{0.08, 0.08, 0.17, 0.50, 0.17}
		(B4b) Provision of timely driver information to 'at risk' routes	**0.48**	**0.50**	**0.02**	{0, 0, 0, 0.6667, 0.3333}	{0, 0.25, 0.17, 0.25, 0.33}
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	(C1b) Consider revised height standards for highways based on scenario modelling in the area	**0.50**	**0.56**	**0.06**	{0, 0, 1, 0, 0}	{0, 0.18, 0.36, 0.36, 0.09}
	C2. Damage to lighting fixtures and supports, traffic boards and information sign	(C2a) Resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology	**0.51**	**0.48**	**0.03**	{0, 0, 0, 1, 0}	{0, 0.18, 0.27, 0.45, 0.09}
	C3. Disrupt traffic safety and emergency evacuation operations, increase traffic accidents	(C3a) Map the highway network and infrastructure asset base	**0.48**	**0.51**	**0.03**	{0, 0, 0, 1, 0}	{0, 0.08, 0.25, 0.50, 0.17}
		(C3b) Identify at risk locations / structures where there are issues as measured under different scenarios	**0.48**	**0.51**	**0.03**	{0, 0, 0, 1, 0}	{0, 0.08, 0.46, 0.31, 0.15}
		(C3c) Provision of timely driver information to 'at risk' routes	**0.48**	**0.50**	**0.02**	{0, 0, 0, 0.6667, 0.3333}	{0, 0.10, 0.30, 0.40, 0.20}
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	(D1a) Revised standards to meet / cope with higher sea levels (i.e. greater time of immersion in water)	**0.49**	**0.55**	**0.06**	{0, 0, 1, 0, 0}	{0, 0.10, 0.10, 0.80, 0}
		(D1b) Revised standards of signage and edge standards, and resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology to higher areas, and edge strengthening	**0.49**	**0.51**	**0.03**	{0, 0, 0, 1, 0}	{0, 0.10, 0.30, 0.50, 0.10}
	D2. Sea level rise can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	{D2a) Revised standards for scour risk caused by higher sea levels	**0.50**	**0.47**	**0.03**	{0, 0, 0, 1, 0}	{0.11, 0.11, 0.22, 0.33, 0.22}
		(D2b) Map bridge structures for the impact of higher levels as to operating performance under normal and extreme scenarios	**0.50**	**0.51**	**0.01**	{0, 0, 0, 0.3333, 0.6667}	{0, 0.30, 0.30, 0.30, 0.10}

Sources: Conference of European Directors of Roads (2012); IPCC (2012b); Regmi & Hanaoka (2011); The Royal Academy of Engineering (2011); UNECE (2012)

In order to transform both climate risk and cost data into the same level, the risk reduction grades are mapped onto the five-level cost-effectiveness, where maximal risk reduction grade is interpreted as to be *"Very Effective"* and minimal risk reduction grade means *"Ineffective"* adaptation measures. The risk reduction values in between are allocated using a linear distribution. Simultaneously, adaptation costs from the survey responses are averaged and then converted into the five-level cost-effectiveness, where *"Very low"* cost is taken as to be *"Very Efficient"* adaptation measure and *"Very High"* cost means *"Ineffective"* measure.

Furthermore, the ER approach (Yang & Xu, 2002) allows us to integrate the results of risk reduction with adaptations costs of the n^{th} adaptation measure for tackling the m^{th} climate threat in order to obtain its cost-effectiveness. The final cost-effectiveness analysis results of all adaptation measures are shown in Table 7.8.

Table 7.8 Questionnaire results of cost-effectiveness of adaptation measures on UK roads

Environmental driver due to climate change	Potential climate threat on the road	Adaptation measures	Cost-effectiveness index of adaptations	Cost effectiveness ranking
Temperature increase	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	(A2a) Prioritise the selection of material, manage expansion joints and decay protection (i.e., Use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)	**0.5090**	**8**
		(A2b) Design and construct new bridges or replace old ones (i.e. Designs which support the revised specifications in B1 – so that supporting materials have revised specification for performance in line with B1)	**0.5912**	**12**
	A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	(A3a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	**0.4325**	**5**
		(A3b) Provision of timely driver information to 'at risk' routes	**0.4097**	**4**
	B1. The road drainage cannot	(B1a) Consider drain specifications to handle different rain conditions	**0.4546**	**6**

Intense rainfall/flooding	efficiently remove water due to heavy rains, which results in poor or dangerous driving conditions	(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a	**0.3040**	**2**
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	(B2a) Improve flood estimation	**0.5293**	**9**
		(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection	**0.2587**	**1**
	B3. Rainfall events result in landslides and mudslides in hilly areas causing roadblocks	(B3a) Consider Slope, drain performance in landslide scenarios	**0.3717**	**3**
		(B3b) Design standards for highways which performance to revised standards with different rain events	**0.5057**	**7**
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	(B4a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	**0.6972**	**19**
		(B4b) Provision of timely driver information to 'at risk' routes	**0.7057**	**20**
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	(C1b) Consider revised height standards for highways based on scenario modelling in the area	**0.5300**	**10**
	C2. Damage to lighting fixtures and supports, traffic boards and information sign	(C2a) Resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology	**0.6549**	**14**
	C3. Disrupt traffic safety and emergency evacuation operations, increase traffic accidents	(C3a) Map the highway network and infrastructure asset base	**0.6801**	**17**
		(C3b) Identify at-risk locations/structures where there are issues as measured under different scenarios	**0.6587**	**15**
		(C3c) Provision of timely driver information to 'at risk' routes	**0.7060**	**21**
Sea level rise	D1. Sea level rise can trigger inundation of coastal roads, extra demands on	(D1a) Revised standards to meet/cope with higher sea levels (i.e. greater time of immersion in water)	**0.5667**	**11**

	infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	(D1b) Revised standards of signage and edge standards, and resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology to higher areas, and edge strengthening	**0.6676**	**16**
	D2. Sea level rise can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	{D2a) Revised standards for scour risk caused by higher sea levels	**0.6517**	**13**
		(D2b) Map bridge structures for the impact of higher levels as to operating performance under normal and extreme scenarios	**0.69**	**18**

The most cost-effective adaptation measure is "(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection" to address the potential threat "B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts". The other top two adaptation measures "(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a" and "(B3a) Consider Slope, drain performance in landslide scenarios" are also aimed to address "Intense rainfall/flooding" issues. The adaptation measure which is assessed to be least effective is "(C3c) Provision of timely driver information to 'at risk' routes" to cope with the potential threat "C3". Disrupt traffic safety and emergency evacuation operations, increase traffic accidents" due to the "more intense and/or frequent high wind and/or storms".

7.6 Discussion and Conclusion

To test the feasibility of the extended FBR model, a large-scale survey was conducted to collect primary data through examining the perceptions of road stakeholders on the impacts of climate change, and effects of adaptation for climate change. This survey aims to illustrate the general situation of climate risks in the UK road system and further justify the necessity of adaptation planning.

The findings from the survey of 19 experts in this study offer a broad overview of how roads can be adapted to climate change impacts in the UK. Before the assessment of climate risks by the FBR model, the author asked the respondents to rank the diverse type of risks that they have witnessed or experienced posed by climate change on the UK roads. Overall, temperature increase, precipitations change/flooding and extreme weather are considered as the top three environmental drivers, followed by snow, flooding and high wind, with varying effects on the roads in different regions. By vertically comparing the results of the primary climate risks in different regions, it is noticed that temperature increase is the common threats for the UK as a whole, especially evident in Northern Ireland. Although precipitation change/flooding is ranked as a critical risk in Scotland, Northern Ireland and England, it occurs unsteadily expect from England. The roads in Wales and England, likewise, are vulnerable to the impacts posed by Extreme weather without a stable occurrence. Additionally, extreme weather is the second top issue for the UK, which poses common impacts for Wales and England but without a stable occurrence. Although snow is a significant threat for the British rails in overall, it is not the case for England.

Regarding the four climate threats identified by literature review, unsurprisingly, the modelling results show that the highest potential climate threats to the roads in Britain fall into “A3. Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs owing to increased temperature”, followed by “B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions”, and “B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts”, respectively. Interestingly, among the top concerned risks owing to increased temperature, the impacts including traffic jams, alternative routing, accidents and delivery delays are highly related to the public’s daily life. While increasing fuel consumption, CO_2 emissions and consequential costs are also visible and widespread issues, in recent decades, their impacts on the lives of the general public are less direct.

These findings are also consistent with the current priorities of tackling flooding and increased temperature issues in climate change adaptation in the UK, but they are more specific so as to assist the further development of practical adaptation measures. For instance, the most cost-effective adaptation measures in most categories are associated with tackling the most significant threats "B1" and "B2" due to intense rainfall and flooding. In other words, some measures can be successfully adapted to the threats of intense rainfall and flooding on the UK roads. However, cost-effective adaptation measures have not been developed for another high-risk area, related to temperature increase (i.e. "A3"). This indicates that more resources are required for dealing with diverse climate change threats through effective adaptation planning.

The perceptions from 19 domain experts, such as CEOs/transport directors, transport planners, transport engineers and road academics, reveal the overall situation with regard to the impacts of climate change and adaptations in the UK roads. By dividing participants into three categories in terms of their position, and type and scale of their organisations, managers from large NGOs hold the most concerns on climate risks and their impacts on the UK road system. The threat "A3" has the highest ranking among all the groups. By contrast, "B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable" posed by "intense rainfall/flooding" and "C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign" posed by "more intense and/or frequent high wind and/or storms" are regarded as the least risky threats from the perspectives of academia and middle-size organisations.

Notably, almost all the respondents who have experienced climate impacts in the past ten years, emphasise flooding. Similarly, the modelling results indicate that the most cost-effective adaptation measures are all relevant to the risks posed by intense rainfall/flooding, namely "(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection", "(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a" and "(B3a) Consider Slope, drain performance in landslide scenarios". Therefore, it can be interpreted that there are two cost-effective measures, "(B1b)" and "(B2b)" to address the top risk threat "(B1)" and "(B2)" respectively regarding the top flooding issue on roads; "(B3a)" is an effective measure to deal landslides and mudslides issues "(B3)" in hilly areas. Our society has more experience and mature measures (or less uncertain knowledge) on tackling flooding, compared to other climate risks. However, for temperature increase, the current adaptation measures, such as "(A3a)" and "(A3b)", are still insufficient to tackle the significant climate risk "(A3)".

Although existing adaptation plans for climate change were recognised to be at an initial stage, 28% of total respondents have implemented an adaptation plan, and 33% have shown a positive intention to make a specific adaptation plan for climate change impacts in the future. As for the adaptation planning horizon, HE is required to report every five years under the Adaptation Reporting Power in the Climate Change Act, which is also in line with the official climate projects (last used UKCP09). The current time horizon of road asset life/activity is evaluated by two general categories: short-term (<30 years) and longer-term (≥ 30 years). However, the time horizon for climate change effects can be divided into short-term (present-

2020), mid-long term (2020-2080) and long-term (beyond 2080) (Highways England, 2016). Owing to the uncertainties of climate change itself, adaptation plans should require a longer time horizon for addressing climate change issues in the future. One interviewee suggested that this time horizon could be linked to asset lifecycles of up to 120 years. In the meantime, the project-based nature of road planning produces variable time horizons depending upon complex conditions affecting a route (e.g., geography, severity and likelihood of climate change, and adaptation budgets). Accordingly, establishing a reasonable time horizon for adaptation planning in the future requires consideration of multiple factors including road asset lifecycle, climate projects and route characteristics etc.

In summary, this chapter presents an innovative conceptual framework of adaptation planning for climate change and how it fits the UK road network. It performs a comprehensive risks analysis, through applying a mathematical FBR model to quantify the climate risks posed by climate change and prioritise the cost-effective adaptation measures when objective data is unavailable or incomplete in reality. The utilisation of mix-methods, including literature review, survey and interview not only offers primary data for modelling requirements but also lays an essential foundation to trigger a broader discussion about adaptation planning in road systems.

However, owing to the sampling limit (e.g., most of the responses are from England, large and consulting companies), the results may not be convincing, hence, future works might continuously refine the findings via case studies (e.g., interviews) with relevant bodies, such as the Environment Agency, Transport for London and other local transport authorities. Therefore, next chapter (Chapter 8) conducts a qualitative analysis of multi-case studies within the UK transport systems to compare the results of the rail and road survey and reveal more in-depth investigations in terms of adaptation planning issues.

Chapter 8 A Multi-Case Study of Climate Adaptation in the UK Road and Railway Networks[15]

The failure of implementing adaptation plans in the transport systems may potentially be attributed to the deficiency of precise data on climate change impacts and cost-benefit analysis of adaptation planning (e.g., Koetse & Rietveld, 2012). Accordingly, there have been considerable studies assessing climate risks and cost-effectiveness of adaptation measures in diverse transport modes (e.g., ports, roads, railways) (Ng et al., 2018; Yang et al., 2018; Wang et al., 2018b; 2019). Nevertheless, current published reports rarely cover the "hidden" problems in climate adaptation planning, such as planning methods, procedure, time horizon, and public participants. Understanding such, in this chapter, the author conducts a comparative study on the UK road and railway networks to reveal the state-of-the-art understanding on how the two transport systems adapt to the risks of climate change, including the primary climate risks, adaptation options, and the implementation and development of adaptation plans.

This chapter performs an analysis of multi-case studies via in-depth interviews with affiliated senior experts in the UK transport systems. The outcomes provide researchers, transport planners, and decision-makers an innovative thinking pattern from the identification of climate hazards to implementation of climate adaptation planning and bridge the research gaps and facilitate climate adaptation in the inland transport industries.

8.1 Highways England

Formerly known as the Highways Agency, Highways England (HE) became a new government company in 2015 responsible for the operation, maintenance and improvement of England's strategic road network covering more than 4300 of miles motorways and major A-class roads (Highways England, 2018a; 2018b).

[15] The modified version of this chapter has been published in the book Maritime Transportation and Regional Sustainability: Chapter 7 How Does the UK Transport System Respond to the Risks Posed by Climate Change? An Analysis from the Perspective of Adaptation Planning, by Wang, T., Qu, Z., Yang, Z. & Ng, A.K.Y.

The Highways Agency initiated its first *Climate Change Adaptation Strategy and Framework* in 2009, aiming to recognise and assess the impacts posed by climate change on the road network to generate preferred adaptation options (Highways Agency, 2009). Through a comprehensive review, the *Highways Agency's Adaptation Framework Model (HAAFM)* was developed by setting up a detailed seven-stage adaptation process from *"define objectives and decision making criteria"* to *"adaptation programme review"*. By 2014, a variety of climate risk assessment and adaptation action plans had been produced, with specific reports on flooding and winter adaptation, but few gaps in climate adaptation on roads remained unexplored (Highways England, 2016). The Committee on Climate Change (2014) commented that neither information on resilience spending plans nor reported progress of implementing resilience measures were publicly available. However, the *Transport Resilience Review* (Department for Transport, 2014), contained recommendations for improving climate resilience such as the management of high-sided vehicles due to high winds, drainage management for flooding and roadside infrastructure for winter driving, *etc*.

The latest *Climate Adaptation Risk Assessment Progress Update* (Highways England, 2016) set up an overview of climate adaptation in the 2015-2020 (Road Investment Strategy 1) period. HE identified the existing primary climate change hazards in its 2016 report. The trend of climate change included increased average and maximum temperature, more frequent and intense rainfalls in summer, high winds and SLR. For instance, the variations in precipitation, such as flooding, storm surges and groundwater level changes, could pollute and deteriorate transport asset as well as influence the design, operation and maintenance of drainage, foundations and skid. High temperature may modify bearings' layout and expansion joints. In addition, high winds may slightly affect structure and gantries but could result in severe disruption of construction work. Cascade failure risk is being talked about in infrastructure circles and will potentially be an issue in the future (Interviewee 1, January 26th 2018).

Still using the *HAAFM* methodology, HE's 2016 report highlighted current adaptation action plans. The existing climate risk evaluation takes account of four main factors, including the rate of climate change, the severity of disruption, uncertainties, and the extent of disruption (Conference of European Programme of Roads, 2010). The management of drainage, road pavements and structures are still the primary focus, with the highest risk scores, which is the same as the results in the risk assessment 2011 (Highways Agency, 2011), whereas other potential climate vulnerabilities will be continuously monitored by HE.

Under the Adaptation Reporting Power in the Climate Change Act, HE is required to report to the British government on a five-year basis. Current time horizons of road asset life/activity are assessed against two broad categories: short-term (less than 30 years) and longer-term (more than 30 years). However, HE (Highways England, 2016) considers that the time horizon for climate change effects to become material can be divided into short-term (present-2020), mid-longer term (2020-2080) and longer-term (beyond 2080).

Due to the uncertain nature of climate change, a longer time horizon might be required in future adaptation planning. This planning horizon can be referred to asset lifecycles up to 120 years (Interviewee 1, January 26th 2018). Road planning is a complicated procedure that involves geography, asset condition and financial budgets. Also, different routes might have diverse time horizon because of its project-based feature. Hence, an appropriate time horizon for climate adaptation planning needs to be set up on a multi-faceted basis (e.g., asset lifecycle, likelihood, frequency, severity of climate change and infrastructure resilience, route conditions, and adaptation costs, *et*c.).

In future adaptation planning, one of the critical challenges, as an interviewee mentioned ((Interviewee 1, January 26th 2018), is how to find an approach to embed climate change in standards. This might start with reviewing relevant road technical specifications (e.g., Design Manual for Roads and Bridges). A long-term plan with specific adaptation actions will be carried out, but how to deliver it to all the staff is yet to be addressed (Highways England, 2016). With the publication of UKCP18, a new-round review of derived products within the British road sector is required (Interviewee 1, January 26th 2018). Moreover, other mitigation measures should be supplementary with adaptation measures to reduce CO_2 emission owing to high temperature, which is a primary concern as stressed in *Highways England Delivery Plan (2015-2020)* (Highways England, 2015) and from our interviews. Still, risk analysis should be a significant component of road planning for climate adaptation. It will benefit from a standardised mechanism constructed by diverse road stakeholders, such as from the UKCP18 Government User Group.

8.2 Network Rail

Network Rail (NR) owns and operates the national railway infrastructure covering 20,000 miles of track, 30,000 bridges and viaducts, as well as thousands of tunnels, signals, level crossings and points across England, Wales and Scotland (Network Rail, 2018a). Its strategic national network has been divided into nine routes, including Anglia, Freight and National Passenger Operations, London North Eastern and East Midlands, London North Western, Scotland, South East, Wales, Wessex and Western line since 2015. Although local train and freight operators run each route, they are supported by NR's national services and functions to maintain its safety and efficiency (Network Rail, 2018b).

Climate change adaptation and weather resilience are two mainstreams in environmental development in NR. Though climate adaptation and weather resilience initiatives have been prepared since 2012, an official *Climate Change Adaptation Report* was not published until 2015. Afterwards, *Route Weather Resilience Plans* specialised for each route were produced in 2016 (Network Rail, 2018c; 2018d). In the Western Route Plan, for instance, flooding, wind and landslips were considered to be the highest priority risk and likely to cost a lot to repair.

The 2015 Adaptation Report (Network Rail, 2015) summarised the understanding of NR as to the existing and potential impacts posed by climate change on its rail performance and safety and the implementation of adaptation actions to deal with them. This included the identification of climate risks, thresholds and uncertainties, knowledge sharing, existing adaptation barriers and opportunities, and planned actions. A few significant climate hazards on rail infrastructure were recognised through an internal risk analysis supported by METeorological data EXplorer (METEX) and geographic information system (GIS) tools. These included changes in temperature and precipitation, increased flooding, high winds, SLR, extreme weather, lightning and seasonal changes. For example, cold weather, such as snow and ice, would threaten overhead line equipment and block rail lines; heat may increase rail bucking and derailment risk; heavy rainfall and flooding could cause scour of embankment material and damage electricity equipment (Interviewee 2, April 6th 2018). Furthermore, *Tomorrow's Railway and Climate Change Adaptation Report*, as a part of the T1009 programme funded by the Rail Safety and Standards Board (RSSB), established an adaptation framework containing four action steps for the management of summer conditions, winter conditions and flooding risk by drawing on the experiences of other countries in weather resilience and climate change adaptation (RSSB, 2016).

In the meantime, NR has been responding to the challenges of extreme weather in its daily operation (Network Rail, 2018c). The latest published *Weather Resilience & Climate Change*

(WRCC) Adaptation Policy and *Weather Resilience and Climate Change Adaptation Strategy 2017-2019* (Network Rail, 2017a; 2017b) laid solid foundation for the delivery of resilience plans of each route through setting up the context and funding values of specific adaptation actions. The *WRCC* reports (Network Rail, 2017a; 2017b) set out NR's approach to creating a safer and more resilient network for future weather impacts. A four-pillared method included these components, 'analysis risk and costs', 'integrate into business as usual', 'streamline operational weather management', and 'proactive investment' in its *2020 Review and Revise Strategy*.

Overall, NR has constructed a relatively comprehensive framework for adapting to climate change and extreme weather, with supplementary specific route plans and a professional resilience steering group (e.g., RSSB, 2016). The current adaptation report runs on a five-year basis. However, the time horizon for rail adaptation planning may look at the next 30 years and beyond 2100 in a longer-term depending upon the lifespan of specific assets and geographical conditions. There are four primary steps in real adaptation implementation, including risk assessment in place, data analysis, asset investment, and influence and discussion with stakeholders (Interviewee 2, April 6th 2018). Nevertheless, owing to the uncertainties of long-term climate change impacts and insufficiency of precise data on climate change rate and extreme events (Network Rail, 2015), the existing plan still focuses on the identification of several climate thresholds and selection of the best risk scenario (Interviewee 2, April 6th 2018). The quantification of climate risks and costs is still at an embryonic phase (Network Rail, 2017a).

Several gaps have been investigated in the last five years, including weather and climate-related thresholds, management of wet weather, and standards' design of upper-temperature thresholds (RSSB, 2016). Meanwhile, the need for asset investment funding to take account of the whole-life cycle of the rail network, as well as the cost-benefit analysis was mentioned in the interview (Interviewee 2, April 6th 2018). As part of the process of preparing its climate adaptation strategy, NR has researched exceptional experience and suggestions from local transport authorities, such as TfL, as well as data analysis from EA, consultants and scholars. To be successful, further plans should also incorporate stakeholder views, including public engagement. Besides, NR should continuously receive legislative and regulatory support from the Office of Road and Rail (ORR) and Department for Transport (DfT), and other relevant government bodies. Successful climate adaptation planning might mean that climate adaptation can be finally written into every business plan and become 'business as usual' (Interviewee 2, April 6th 2018).

8.3 London (Transport for London & Environment Agency)

8.3.1 Transport for London

Transport for London (TfL), as a local transport authority, is responsible for the daily operations of the capital's public transport and road system (Transport for London, 2018a). Through delivering the transport strategy and policies from the Mayor of London, it commits to develop and maintain integrated, secure, efficient and economical transportation infrastructure and various services mainly covering London Underground, Surface Transport, London Rail and Emirates Air Line Cable Car (Transport for London, 2018a; 2018b).

TfL started its climate risk assessment on London's transport networks based on the UK Climate Impact Programme's projections of the potential climate risks and opportunities due to flooding, drought and overheating. It possesses mechanisms in managing extreme weather events and identifying the requirement to replace critical assets to make them more resilient to climate change (Greater London Authority, 2011). *Managing Extreme Weather at Transport for London* (Woolston, 2014) reviewed a series of local documents in climate adaptation in London, such as the London Underground's comprehensive flood risk review and EA's Thames Estuary 2100 Project, and attempted to establish a long-term flood risk management plan by a flexible 'threshold' planning approach.

The recently published report *Providing Transport Service Resilience to Extreme Weather and Climate Change* (Transport for London, 2015) updated the findings in the 2011 report and provided an overview of existing risk assessment by TfL regarding operation and services. According to this report, the primary trend of climate change impacts to Greater London included the increased temperature in summer, flooding and more frequent and intensive winter storms by 2080s. Flooding, high winds and heating were deemed to be the main risks that affect the delays on the road network, the safety of surrounding buildings and infrastructure, as well as the comfort and health of passengers on trains respectively.

Some extreme weather events were also reviewed by TfL, exemplified by a lightning strike at Docklands Light Railway Crossharbour in 2012, a hail storm at the Fore Street tunnel in 2013, cloudburst flooding and localised rainfall in several spots in summer 2014 (Transport for London, 2015). Combined with the discussion results from an interviewee, the summary is that roads are less vulnerable to climate risk as they have alternative routes and modes to adapt to climate change; but rail and underground are usually more vulnerable due to lack of flexibility in asset construction. The wind is considered as one of the critical threats at present, while the published UKCP18 has changed the status quo by integrating additional factors, such as SLR (Interviewee 3, January 17th 2018; UK Climate Projections, 2018).

A critical scoring risk assessment method has been developed by TfL. The TfL Board initially develops a ‘top-down' risk appetite factor before each business area (London Rail, London Underground and Surface Transport) produces its own scoring scheme to reflect the local differences (‘the bottom up factor') (Transport for London, 2015). The strategic risk map primarily considers the likelihood and impacts of climate change. For instance, in London Underground, overheating was expected to pose ‘very high’ impacts to key track, signals and communications assets, as well as the comfort of staff and passengers. Current risk management of TfL is based on its day-to-day operations, asset management plans and also infrastructure design and scheme planning in the long term. The forecast bulletins and daily real-time monitoring help identify temperature and precipitation changes to enable the corresponding adaptation options. For example, TfL would apply salt and grit to the road surface, bus station approaches and platforms if cold weather and icy conditions are being forecasted. Meanwhile, its asset management framework sets out the high-level principles and specific strategies for every asset group with regards to required asset performance, conditions and maintenance.

Established in 2003, the London Climate Change Partnership (LCCP) Transport Group committed to raising the awareness of the risks of climate change in the transport sector via the development of guidance and adaptation measures. Several projects, such as London Underground's cooling the tube and ‘Drain London', has offered pioneering trials in climate adaptation (Woolston, n.d.). Nevertheless, existing adaptation methods to climate change are still at an embryonic stage, and no comprehensive adaptation plans have been proposed to TfL. This could partially be due to uncertainties in forecasting and insufficient understanding of climate vulnerabilities and thresholds. Current risk assessment tends to rely on qualitative evidence rather than a systematic quantitative method. Hence, priorities should be given to how to best utilise scientific data, as well as how to translate climate forecasts into meaningful scenarios.

As an integrated transport provider with financial support from the government, TfL has advantages in developing a holistic adaptation plan to make a resilient network in the future. Even so, gaining political interest is still a potential barrier. This would require TfL to continually provide substantial evidence on the level of risks alongside other factors to enable decision-making. In future adaptation plans, appropriate time horizons will vary for each project and different transport mode and its asset strategy. The plan would be led by TfL but draw on the adapting experiences of NR and LCCP, and attract the engagement of transport providers and utility providers (e.g., Thames Water, Environment Agency and Met Office) to further increase the likelihood of success of adaptation planning (Interviewee 3, January 17th 2018).

8.3.2 Environment Agency

In water transport, the Thames Barrier in London is one of the few moveable flood barriers in the world, which is run and maintained by the Environment Agency (EA). EA examines the barrier monthly and tests it at a high spring tide each year. Supported by its internal computer models and data from Met Office and the UK National Tidegauge Network, it forecasts the risks up to 36 hours in advance to inform a decision on when the barrier should be closed. The closure of the Thames Barrier happens under a storm surge condition in order to protect London from the sea, depending upon the height of the tide and the tidal surge as well as the river flow entering the tidal Thames. Since 1982, the barrier has been closed over 170 times to protect against tidal and fluvial flooding (Environment Agency, 2014).

The Thames Estuary 2100 (TE2100) Project, established by EA in 2002, is the first primary flood risk project in the UK to put climate change adaptation at its core. The plan mainly looked at tidal flooding, though other sources of flooding including high river flow as a result of heavy rainfall, and surface water flooding are simultaneously considered. Based on the prediction of SLR from 90cm up to 2.7m by 2100, the plan was designed to provide strategic guidance for adapting to flooding in the Thames Estuary over the next 100 years. A key driver is to consider how the tidal flood is likely to change in response to future change in climate, and how this would impact on people and property in the floodplain. Additionally, there is a consensus that many existing flood walls, embankments and barriers are getting older and would need to be raised or replaced to manage SLR (Interviewee 4, February 1st 2018).

The *Safeguarding London Transport* (Environment Agency, 2008) comprehensively evaluated the risks that potential flooding poses to the London transport system and the Thames Estuary. Combining with GIS information, it assessed the vulnerability of different assets by using Key Performance Indicators (KPIs) in several transport networks (e.g. age of station, elevation, flood warning and distance from the defences). Generally, London Underground was the most vulnerable to the risks of flooding as it was widely located in tunnels underneath the ground, though roads, generally at ground level, can also be extensively affected. However, the rail network had the lowest level of vulnerability because stations and rail tracks were usually located above the ground. Adaptation costs and network resilience were considered in responding to flooding risks. A typical cost of installing a set of points and their related signals could be expected to be between British pounds (£) 175,000 and £250,000 (Environmental Agency, 2008). The resilience was measured by the recovery capacity of the transport network, including the scope to use other alternative routes or modes to bypass the partial closure of this system. London Underground, owing to its natural underground location and interconnected tunnels with a high possibility for water ingress, might be the least resilient to climate risks. In the worst flood risk scenario, a majority of the sections could be closed for an extended period, and the repair cost could be massive. With an updating requirement of a five-year short-term review and a 10-year full review, the latest *TE2100 5-year review*, used historical data and report analysis to examine the results of ten indicators (e.g., sea level, peak surge level, asset condition, barrier operation, habitat and public attitudes to flood risk, etc.) (Environment Agency, 2016).

One of the significant challenges is the mismatch of ageing flooding barrier infrastructure and a higher SLR rate where many flood defences were built 30 years ago when SLR was 8 mm per year but now becomes 11mm per year (Environment Agency, 2017). Existing data is incapable of measuring wave conditions at a peak surge level and the amount of intertidal habitat in the Estuary. Meanwhile, the asset condition has declined in recent years in some areas, especially the outer Estuary. More funding is needed for asset improvement and maintenance and increasing the proportion of assets rating as fair and reasonable (Environment Agency, 2016).

Nevertheless, the TE2100 Plan is believed to be on the right track with a broad range of stakeholders and public engagement, as an interviewee stated. Having had two earlier consultations in 2005 and 2008 on the critical findings of the project supported by a programme of public meetings and a web-based consultation, EA undertook its public consultation on the draft TE2100 Plan in 2009. These included 15 local workshops and public meetings across the Estuary, over 50 meetings with key organisations, to provide stakeholders (e.g., Greater Local Authority) with an opportunity to feedback and ask questions on any aspect of the Plan or its recommendations, as well as receiving 120 written responses (Interviewee 4, February 1st 2018). In future planning, it is expected to have more new and cost-effective barriers further downstream and tidal flood defences for tackling more severe SLR and storm surges (Environment Agency, 2017).

8.4 Devon County Council

Flooding is one of the critical issues for UK transport systems. A significant number of heavy storms in recent years have broken historical records since 2000 in the UK, and there are more frequent events projected in the future (Devon County Council, 2014a).

Dawlish Warren is a coastal spit on the south Devon coast of England. The cumulative effect of the rapid succession of over significant storms in winter 2012/2014 had the most severe impacts in the UK since the 1950s (Devon Maritime Forum, 2014). The South West main rail network was mainly affected with the collapse of the multi-sectional seawall at Dawlish, as well as a significant impact on transport resilience and the local economy of the South West Peninsula due to extreme weather (Devon County Council, 2014a; Devon Maritime Forum, 2014). Up to 46m of railway track was swept away with part of the seawall in early February 2014, restricting the service linking Cornwall and much of Devon with the rest of the UK. Dawlish station was damaged, and the main rail line from Exeter to Newton Abbot was closed. In total, the storms had resulted in the two-month closure of the mainline and over 7,000 services cancelled (Devon Maritime Forum, 2014).

NR estimated that the damage would take ‘at least' six weeks to recover, and an extra £100m was provided for flood repairs across the country (BBC News, 2014a; 2015c). A storm occurred again in early 2017, crashed into trains and over flood barriers as 50ft waves smashed the coasts. Boats, lighthouses and seafront rail track were impaired by surges, and the gales caused temporary cancellation of some trains at Plymouth and between Newton Abbot and Exeter St Davids (The Sun, 2017).

Devon County Council (DCC) is responsible for the maintenance and repair of 12,800km of the public road network (not including Strategic Road Network) in Devon. On the basis of the

UK Climate Impact Programme's projections, the potential impacts on Devon's roads include increased temperature, SLR and the changes in rainfall patterns and humidity variations. DCC initiated its Weather Impacts Assessment in 2010 and introduced an Impact Assessment Tool (IAT) in 2011. The risks posed by climate change were evaluated through the 'Devon Way for Risk Management' matrix, where the impact and likelihood of risks were identified as three scenarios ('low', 'medium' and 'high') in different timescales (the 2020s, 2050s and 2080s).

In the *Extreme Weather Resilience Report* (Devon County Council, 2014a), a few risks on highways maintenance and connectivity posed by extreme weather events were documented after the 2013/2014 storm. These mainly contributed to the collapse the sea wall at Dawlish, severe road deterioration and road closures in multiple sections of "A" road, backlog in the carriageway, increases in potholes, fallen trees and branches (Devon County Council, 2014a). £3m initial clear-up was followed by more than £700m for climate risk maintenance.

In April 2014, the main railway line through Dawlish in Devon was reopened, rebuilt by a 300-strong team from NR at a cost at £35m (BBC News, 2014b). By Dec 2016, the government had commissioned NR to make a further £10m plan to protect coastal lines from storms, which included moving the line and strengthening the cliffs above the line connecting Devon and Cornwall with the rest of the UK (BBC News, 2016). NR has outlined the ongoing maintenance for the regional rail network in Control Period 6 of its five-year plan (2019 – 2024) (Devon Live, 2018).

Led by DCC, the Flood Recovery Coordination Group was established to provide operational and financial support for the affected communities threatened by flooding (Devon Maritime Forum, 2014). Since 2012, DCC has spent over £12m on the storm-related emergency plan for highways, together with extensive drainage works implemented due to the 2013 storms. Nevertheless, a continual modification for existing design and operation and maintenance are required to adapt against further climate change (Devon County Council, 2014b).

More recently, an assessment of the risks posed by climate change to DCC's Highways Management Service was completed in April 2014 in coordination with Highways Agency and DEFRA. DCC, as a part of the South West partnership, including Somerset County Council and Wiltshire Council, has campaigned for government investment to enhance the strategic resilience of the A303/A30/A358 corridor (Devon County Council, 2014b). Meanwhile, the South West Peninsula Rail Task Force, made up of local authorities, enterprise and academia, provided cross-sector support for guaranteeing a £7m investment to develop a more resilient rail network (Devon Maritime Forum, 2014). Therefore, further collaboration between roads and railways is expected to deal with the potential risks posed by storms and other extreme weather events.

The modal shift solution from the road to rail may not fit the case of DCC, as pointed out by an interviewee (Interviewee 5, February 8th 2018). First, rail is more vulnerable to the variation of weather, as it is easier to identify alternative routes for an affected road. Second, the capacity of trains cannot meet the demand for emergency evacuation of cars on the road. For instance, the capacity of a train that can carry 500 people is only equivalent to 250 cars. Alternatively, as an emergency plan, the National Express provided five new 'rail replacement' coach services, and Flybe had put on three extra flights from Newquay to Gatwick each day during that period (Transport Committee, 2014). Most importantly, since 2014, a solution proposed by NR to tackle storms is the reinstatement of the old Tavistock line, along the Great Western Railway Teign Valley route, and a new railway with five alternative routes to avoid the coastal section through Dawlish (BBC News, 2014c; 2014d). More recently, the Peninsula Rail Task Force implemented the Dawlish Additional Line as a long-term priority in the 20-year plan, by reconnecting Okehampton to Plymouth route to make the network more resilient to extreme weather (Devon Live, 2018).

Although NR's efforts in storm adaptation are remarkable concerning rapid repairing capacity and replacement services, the condition of the coastlines and their connectivity to the diverse region is still inexplicit in the long-term with the occurrence of more frequent and intense extreme weather events (Devon Maritime Forum, 2014). Overall, there is no comprehensive adaptation strategy for climate change at DCC, which may be associated with the kaleidoscopic nature of climate change itself. Currently, climate adaptation has been integrated into the risk management, by which DCC is primarily identifying the risks posed by climate change and working closely with NR to make specific adaptation measures for each risk. With more than £10m being put into drainage management, a near-sight plan (the 2020s) is to alleviate flooding and keep the water level as low as possible. One of the advantages in developing a holistic adaptation strategy in the future is that DCC is well aware of the risks of climate change *via* a bottom-up mechanism to collect local information and a top-down mechanism to deliver the governmental policy. Even so, a long-term adaptation plan still needs enough financial support and cross-party engagement to ensure its effective implementation (Interviewee 5, February 8th 2018).

8.5 Qualitative Comparative Analysis (QCA) on the Climate Adaptation Planning of the UK Road and Rail System

Based on the above descriptive analyses of five cases of climate adaptation planning in the UK rail and road system, this section performs a systematic qualitative comparative analysis. It is achieved by firstly detecting all relevant factors influencing the development of a climate adaptation plan from literature review and then qualitatively compare these variables so as to answer the second research questions: "What are the potential challenges in adapting to climate change in the UK rail and road system?"

As an effective analysis approach for case studies, QCA is utilised in this section to figure out which combinations of conditions/ causal configurations justify the implementation of an adaptation plan. In QCA, explanations are formulated in the form of multiple equations. The dependent variable is on the left side of the equation sign, namely explained or outcome condition, and different independent variables are on the other side, namely explaining or casual conditions (Rezvani, 2014, pp. 351).

In order to figure out the critical factors influencing the development of a climate adaptation plan in a UK transportation entity, namely an entity in which conditions has an adaptation plan for climate change. It can be interpreted that *having a climate adaptation plan (A)* is the outcome to be explained, and the following seven conditions[16] are identified from the literature review in Chapter 2 together with corresponding hypotheses include:

(1) *Climate Data (D)(*e.g., climate change forecasting): the chance of having a climate adaptation plan is higher in which an entity has climate data than the other entity without climate data.

(2) *Analytical Tool (T)* (e.g., analysis matrix): the chance of having a climate adaptation plan is higher in which an entity has analytical tools for climate risks than the other entity without analytical tools for climate risks.

(3) *Transport Infrastructure (I)* (e.g., infrastructure maintenance): the chance of having a climate adaptation plan is higher in which an entity has transport infrastructure for climate risks than the other entity without transport infrastructure for climate risks.

[16] The explanation of the seven condition can be found in Chapter 9.1.

(4) *Governmental Policy (P)* (e.g., climate adaptation guidance): the chance of having a climate adaptation plan is higher in which an entity has governmental policy for climate adaptation than the other entity without governmental policy for climate adaptation.

(5) *Investment Strategy (S)* (e.g., investment and planning cycle): the chance of having a climate adaptation plan is higher in which an entity has investment strategy for climate adaptation than the other entity without investment strategy for climate adaptation.

(6) *Financial Resources (F)* (e.g., funding policy): the chance of having a climate adaptation plan is higher in which an entity has financial resources for climate adaptation than the other entity without enough financial resources for climate adaptation.

(7) *Collaboration (C)* (e.g., public and cross-party engagement): the chance of having a climate adaptation plan is higher in which an entity has collaboration with other entities or public engagement for climate adaptation than the other entity without collaboration for climate adaptation.

In QCA, it employs letters to explain conditions and outcomes: the presence of a condition or outcome (positive) are presented by upper-case letters and the absence of a condition or outcome (negative) are presented by lower-case letters. A present and an absent outcome are also often called, respectively, a positive and a negative outcome. Meanwhile, asterisk signs (*) and plus signs (+) are used to link all the different conditions together in the equations. Specifically, "*" similar to the meaning of "and" that different condition should be present at the same time, in contrast, "+" similar to the meaning of "or" that one condition should be present where others are absent (Rezvani, 2014, pp.351).

Following these rules, all the conditions and outcome identified in above hypotheses are represented in the data matrix as showed in Table 8.1, where "1" and "0"on behalf of the condition or outcome is absent or absent, respectively.

Table 8.1 Fictive data matrix of a transport entity having or not having a climate adaptation plan

Cases	D	T	I	P	S	F	C	A
HE	1	1	1	1	0	1	0	1
NR	0	1	0	1	0	1	1	1
TfL	0	0	1	0	0	1	0	0

EA	1	1	0	0	0	0	1	1
DCC	0	1	1	0	0	1	0	0

Table 8.2 Truth table of conditions under which a transport entity has a climate adaptation plan

Cases	D	T	I	P	S	F	C	A
HE	1	1	1	1	0	1	0	1
NR	0	1	0	1	0	1	1	1
TfL	0	0	1	0	0	1	0	0
EA	1	1	0	0	0	0	1	1
DCC	0	1	1	0	0	1	0	0

Based on the same system, a truth table can be generated by combining cases, which means a similar combination of absent and present conditions leads to similar outcomes. In this study, there is no same combination of conditions leading to a same outcome.

To be precise, the following equations serve as formulas, justifying why a transport entity has a climate adaptation plan (HE, NR and EA) and why the other has not one (TfL and DCC):

A= D * T * I * P * F * c (HE)

A= d * T * i * P * F * C (NR)

A= D * T * i * p * f * C (EA)

a= d * t * I * p * F * c * (TfL)

a= d * T * I * p * F * c (DCC)

Accordingly, the analysis results can be expressed by exclusive formulas as follow:

A= D * T * I * P * F * c + d * T * i * P * F * C + D * T * i * p * f * C

a= d * t * I * p * F * c * + d * T * I * p * F * c

In the above equation the condition "*Investment Strategy (S)*" does not appear as the value are "0" for all the five cases, which means is a not a key factor affecting the development of a climate adaptation plan.

Furthermore, in the three cases having a climate adaptation plan, having *"Analytical Tool (T)"* is a common condition thus which can be regarded as a most critical element. Besides, "*Governmental Policy (P)"* and *"Financial Resources (F)"* are the two common conditions for HE and NR, *"Climate Data (D)"* is a common condition for HE and EA, and *"Collaboration (C)"* is a common condition for NR and EA.

In terms of the two cases without a climate adaptation plan (TfL and DCC), although both cases have conditions *"Financial Resources (F)" and "Transport Infrastructure (I)" in* adapting to climate risks, lacking of *"Climate Data (D)", ""Governmental Policy (P)"* and *"Collaboration (C)"* commonly involves in the two cases, and therefore the three factors *(D, P* and *C)* partially explain the failure of an adaptation plan.

Understanding such investigation, the importance value of each critical factor (*D*, *T*, *P* and *C*) can be further calculated as below:

Table 8.3 Importance vale of the key conditions under which a transport entity has a climate adaptation plan

Cases	D	T	P	C	A
HE	1	1	1	0	1
NR	0	1	1	1	1
TfL	0	0	0	0	0
EA	1	1	0	1	1
DCC	0	1	0	0	0
Importance Value	2/3	1/2	2/3	2/3	N/A

Therefore, it can be summarised that *"Climate Data (D)", ""Governmental Policy (P)"* and *"Collaboration (C)"*are the top three factors influencing the generation of a climate adaptation plan in a transport entity, which is followed by *"Analytical Tool (T)"*. However, *"Financial Resources (F)"* and *"Transport Infrastructure (I)"*are less significant in differentiating the development of a climate adaptation plan. It is noted that although "*Investment Strategy (S)*" does not appear in all the five cases, it does not mean that it the least import factor, in contrary, it has been mentioned in some cases as ambiguous investment and planning cycle could a barrier for further adaptation planning no matter an existing plan is available or not. Meanwhile, the case of UK it is also consistent with the pressing issues of climate adaptation in literature review that current transportation investment and planning could not address climate change impacts adequately.

8.6 Discussion and Conclusion

This chapter explores the existing adaptation planning in the road and railway systems by exemplifying four typical case studies in the UK. A qualitative research method is utilised, including document review and five in-depth interviews with domain transport experts from HE, NR, EA and TfL, and DCC. By doing so, the evolvement of climate risk assessment and adaptation actions, currents advantages and potential challenges are dissected for each organisation. To compare the similarities and differences of adaptation plans among different organisations, within-case (e.g., London) and cross-cases analyses (e.g., NR and HE) are further explained to strengthen the external and internal validity.

Table 8.4 summarises the primary progress of the UK road and rail sectors in adapting to climate change based on the Committee on Climate Change's latest report (2017b) and the new findings from the studied cases.

Table 8.4 Primary progress of the UK road and rail sectors in climate adaptation[17]

Similarities	Risks to infrastructure	Increased frequency and severity of flooding (will double the number of assets exposed to climate change by 2080s); temperature and precipitation changes; increased maximum wind speeds; other uncertainties such as fog, storms and lightning (Dawson, et al., 2016)
	Vulnerability	Fewer weather-related delays in England in recent years
		Road is less vulnerable to climate risk as having alternative routes and modes to adapt to climate change; rail and underground are more vulnerable due to the limited flexibility and complexity in rail infrastructure construction (e.g., in cases of London and Devon)

[17] Based on 'Progress in preparing for climate change 2017 Report to Parliament' (Committee on Climate Change, June 2017)

	Risk Assessment	*TfL - Providing Transport Service Resilience to Extreme weather and Climate* Change (2015): A scoring risk assessment method considering likelihood and impacts of climate change at each business area in London Rail, London Underground and Surface Transport has been developed
		EA - TE2100 5-Year Review (2016): evaluated the flooding risks based on identified 10 KPIs
	Funding	*The Autumn Statement 2016 transport projects*: announced £150m governmental funding for flood resilience improvement with £10m on roads and £50m on rails (HM Treasury, 2016)
		London: several £million has invested for Docklands Light Railway, and an estimated cost of at least £1m is required to carry out a sustainability assessment for pathways in TfL (Transport for London, 2015); delivering £308m of investment on tidal flood defence improvements across the Tidal Thames for the Thames Estuary Asset Management programme (Institution of Civil Engineering, 2017)
		Devon: Over £12m storm emergency plan in highways from DCC and a further £10m plan for protecting coastal line from storms for NR (BBC News, 2016); £7m investment for establishing a resilient rail network from the South West peninsula Rail task Force (2016)
	Guidance	*The UK Climate Projections (UKCP09)* provided comprehensive evidence for risk assessment; the new *UKCP18* projections may change the level of climate risks
		The second round of the Adaptation Reporting Power (ARP2) for 2015-2020 (2017a): HE and NR's reports
		DfT - Transport Resilience Review: A review of the resilience of the transport network to extreme weather events (2014): provided HE and NR with the specific recommendation for improving climate resilience
Railways		*RRSB - Tomorrow's Railway and Climate Change Adaptation Report (2016)*: established an adaptation framework for climate change
		NR - An internal audit of weather resilience and climate change (2016): recognised the demand for setting up strategic targets, and standardising risk management and decision making.
		NR - Weather Resilience and Climate Change Strategy (2017): covered all national routes (including West of Exeter); risk analysis and site-specific actions (focusing on embankments, bridge stability and coastal defences)
		Implementation: NR has cooperated with the Energy Network Association to investigate the electricity substations; ageing railway infrastructure is a challenge
Roads		*HE - Climate Change Adaptation Strategy and Framework (2009)*: initiated the HHAFM by setting up seven-stage adaptation process
		HE - Climate Adaptation Risk Assessment Progress Update (2016): embarked a flood risk analysis through utilising EA's flood risk maps and other data; recognised high risk and very high-risk hotspots and culverts and reduced floods at 124 flooding hotspots and culverts
		DCC - Service Resilience in a Changing Climate Highways Management (Devon County Council, 2014b): Developed a 'Devon Way for Risk Management' matrix for evaluating the impact and likelihood
		Implementation: HE has improved drainage and flood resilience to climate change on some regional routes; Some local authorities have increased its strategic planning and investment in resilience

In the cases of HE and NR, a series of climate risk and adaptation reports have been published on the basis of the UK Climate Projections (UKCP09) and relevant legal guidance (e.g., Committee on Climate Change 2017a, 2017b; Department for Transport, 2014). Although fewer weather-related delays in England occurred in recent years, regional extremes are still witnessed and will potentially trigger significant costs due to the uncertainties of climate change. In the road and rail sectors, the facilitation of flood resilience is a shared priority with over £100 million funding being allocated by the government (HM Treasury, 2016). Meanwhile, the Committee on Climate Change's ARP2 and DfT's Transport Resilience Review have provided HE, NR and other local authorities with specific guidance for improving climate resilience on their transport networks.

Simultaneously, the road and rail systems face many challenges in adapting to climate change risks. Overall, rail and underground are more vulnerable to the impacts of climate change due to the limited flexibility and complexity in rail infrastructure construction. Compared with roads, a strategic rail adaptation plan covering all the nine national routes (exclude the Freight and National Passenger Operators route but add the West of Exeter route) has been prepared (Network Rail, 2017; Rail Safety and Standards Board, 2016). However, the existing adaptation plan of NR mainly focuses on the identification of various climate thresholds (Network Rail, 2015). Sometimes climate adaptation is regarded as part of risk management, where the attention focuses on risk assessment for the road system with specific extreme weather adapting plans (Interviewee 5, February 8th 2018). The absence of a holistic adaptation strategy might reflect the deficiency of scientific data (e.g., SLR for TE2100), cost-benefit analysis and understanding of climate vulnerabilities and thresholds (Interviewee 3, January 17th 2018), and these gaps reflect the findings in the literature (e.g., Koetse & Rietveld, 2012). Hence, a new set of climate projections (UKCP18) published in November 2018 by the UK government is believed to offer clear guidance for dealing with the challenges of estimation and selection of risk scenarios under various climate conditions.

One of the significant challenges revealed by the case of the TE2100 is that the ageing flooding infrastructure might not be able to catch up with the higher SLR (Environment Agency, 2017), while ageing infrastructure could be a standard issue for the whole railway industry owing to the increasing rate of climate change. Furthermore, there is an ambiguous time horizon for road and rail adaptation planning. For the majority of cases, adaptation reports run on a five-year basis (Interviewee 1, January 26th 2018; Interviewee 2, April 6th 2018; Interviewee 4, February 1st 2018), thereafter, the time horizon for a long-term adaptation plan is undetermined: it may look at next 30 years and beyond 2100 (Interviewee 2, April 6th 2018) or 100 years (Interviewee 3, January 17th 2018) for railways and up to 120 years for roads. It can be linked to the diverse lifespan of specific assets, geographic conditions, climate change prediction, and financial budgets, *etc*. In the future, climate adaptation planning needs to be regularized and written into every business plan (Interviewee 3, January 17th 2018), embedded in technical standards and delivered to all staff seamlessly (Interviewee 1, January 26th 2018). A successful adaptation plan must be aware of budgetary constraints and strike a balance between corporate priorities and technical requirements (Wang *et al.*, 2019).

The establishment of several partnerships, on behalf of the London Climate Change Partnership (LCCP) Transport Group and the South West Peninsula Rail Task Force, has offered a chance to deal with regional climate change issues. However, in practice, owing to the project-based characteristics in most adaptation cases, as per several interviewees, road and rail stakeholders usually only consult each other but undertake projects separately. A modal shift strategy has been successfully applied into practice, for instance, where road traffic was converted to rail by establishing a rail platform and offering a new rail service in Workington, Cumbria in a quick response (Ace Geography, n.d.), and a rail replacement service by increasing buses and flights from Newquay to London due to seawall damage in Dawlish, Devon (Transport Committee, 2014). More extensive and efficient cooperation between roads and railways is expected, but the development of an integrated inland transport system requires the thorough consideration of multiple factors, such as mode capacity, the severity of consequences and geographic conditions, *etc*. The trans-mode and cross-sectoral collaborations in the future should enable planners to create a new blueprint for climate adaptation, effectively facilitated by governmental regulation (e.g., ORR, DfT), broader stakeholder management and public engagement from decision making to adaptation implementation.

In summary, this chapter studies the adaptation experience of UK road and rail systems in managing the risks posed by climate change (e.g., flooding, rising temperature and storm surge). In particular, it explores the current and potential issues in climate adaptation planning through in-depth investigation of four cases, namely Highways England, Network Rail, Transport for London and Environment Agency (London), and Devon County Council. Although considerable adaptation measures and actions have been implemented at both the national and regional levels in the last decade, the road and rail systems in the UK still confront diverse challenges. These include, but are not limited to, insufficient scientific data, ageing infrastructure, unclear planning horizon, and unspecialized climate risk management. Through combining the analysis of the relevant literature, local reports, news, and interviews with domain transport experts, it offers a broad view of adaptation planning in UK roads and railways and valuable insights for creating an integrated inland transport adaptation system. An analysis of road and rail adaptation measures to climate change not only benefits both sectors by cross-reference but also generates new adaptation solutions in terms of using one system to enhance the resilience of the other when climate risks occur.

Chapter 9 Comparative Analysis of Findings and Discussion

This chapter firstly summarises the findings from the literature review, recapping the gaps to justify the necessity of conducting the two nationwide surveys and multi-case studies on the UK rail and road transport systems. Afterwards, a comparative analysis is performed to compare and contrast the similarities and differences between the critical findings from the surveys and interviews and existing literature. By doing so, it attempts to answer the three primary research questions, which is supplemented with a sensitivity analysis to examine the accuracy of the belief structures and reliability of the proposed Fuzzy Bayesian Reasoning (FBR) model as well as Qualitative Comparative Analysis (QCA) in case studies.

9.1 Findings from Literature Review

The research was initiated on the basis of a literature review of 100 papers featured in 65 globally recognised academic journals. The review of publications over the past decade allowed identification of the emerging issues and relevant themes, how these have evolved and what are the challenges to be tackled in the future.

The investigation results indicated an increased publication rate during the most recent 7-year period with an increased rate of 12.6 papers per year. Represented by Transportation Research Record, Transportation Research-Part D, and Climatic Change, the top journals involve multiple disciplines including transportation, climate change, risks and geography. North American and European researchers were the main force, while South American, African and Asian researchers have gradually become involved in the global research team in recent years. Qualitative research methods made up over 70% of the total, in which case study and conceptual work were the dominant research methods. Though the existing research was relatively scattered, lacking in dominant journals, researcher and theories (Eisenack et al., 2012), the co-authorship analysis showed that networking between researchers from many backgrounds had created two main research communities since 2010 with markedly increased numbers of research papers being published.

Semantics analysis categorised the corpora based on various research themes regarding the impacts of climate change on road/rail transportation, climate risk assessment, asset management, climate planning and policy, and climate adaptations on transportation.

Although much effort has been spent on investigating climate risks and developing appropriate adaptation tools for climate change, a few gaps were revealed:

1) Current studies mostly focus on short-term impacts and climate adaptation for the transport sector are relatively piecemeal (e.g., Eisenack et al., 2012)

2) Many adaptation tools or framework are not explicitly designed for the transportation sector (Niemeier et al. 2015);

3) Existing models could not provide a standardised solution for decision-makers (Mutombo, 2014); and

4) The high uncertainty in adaptation for climate change risks poses a significant challenge for planners (Meyer & Weigel, 2010).

Overcoming these gaps requires a comprehensive analysis which can be tailored to use in diverse transportation modes (e.g., rail and road) to quantify the trade-offs between preliminary costs and long-term benefits (Adger et al., 2007; Wall et al. 2015). A systematic analysis for developing long-term climate change adaptation planning in transportation systems was then put forward to evaluate the climate risks on roads and rails and select the cost-effective adaptation options when some data is unavailable or incomplete. This was realised by utilising both quantitative and qualitative methods, namely, a developed FBR model, real surveys, and in-depth interviews with associated transport stakeholders in this thesis.

More precisely, current research on climate-related risk analysis has commentators on interpreting and identifying existing and future threats, estimating the level of risk as well as determining the level of uncertainties (Yang et al., 2015). However, three main issues need to be tackled:

1) Traditional probabilistic risk analysis methods are often unable to tackle the unavailability or incompleteness of climate risk data (Yang et al., 2015;

2) When the expressions of risk and costs are inconsistent, it is challenging to combine risk and cost results to make rational decisions (Yang et al., 2018); and

3) The uncertain nature of climate change itself challenges the estimation and selection of risk scenarios in the future (Wu et al., 2013).

The first two issues have been resolved in this thesis by taking advantages of integrating fuzzy set, BNs with ER methods to render climate risk and adaptation assessment in the British road and rail systems. In terms of the third issue, supplemented with the results of first-hand data from two nationwide surveys on road and rail sectors, a new set of climate projections (UKCP18) published in Nov 2018 by the UK government is expected to offer scientific guidance for dealing with the challenges of estimation and selection of risk scenarios under diverse climate conditions.

From the perspective of adaptation planning, existing research is still at an embryonic stage with inadequate attention to specific transport adaptation planning and nationwide adaptation strategies in most countries (Eisenack et al., 2012). A few dilemmas include:

1) Many adaptation plans (e.g., in the UK) are not explicitly designed for responding to impacts of climate change but for the co-benefits of other activities such as demands of infrastructure investment and cost savings (Tompkins et al., 2010).

2) The relatively irreversible investments in infrastructure might fail to reach their expected effects and profits under the new climate parameters, where predicted short lifetimes of transportation infrastructure might be problematic with the accelerating pace of climate change (Reilly & Schimmelpfennig, 2000).

3) Relatively short planning cycles (typically 5-10 years) do not match infrastructure lifespans (typically more than 50 years), which leads to malfunctioning of transport networks (ICF International, 2008; Kintisch, 2008; Koetse & Rietveld, 2012).

Though some examples of adaptation in transportation design have been revealed, many communities are incapable of incorporating climate change considerations into infrastructure planning and management. An empirical study, through interviewing five domain experts in the UK transport industry (Highways England (HE), Network Rail (NR), Transport for London (TfL) and Environment Agency (EA) in London, and Devon County Council (DCC)), was conducted to further investigate under-reached issues in climate adaptation planning.

9.2 Discussion on Primary Research Questions

This section aims to answer the three primary research questions by summarising and comparing the findings from the literature review, the road and rail surveys and case studies in the context of the UK inland system.

1) What are the primary risks on the UK rail and road networks posed by climate change?

Based on the UK Climate Projections (UKCP09 and UKCP18) (Jenkins et al., 2009) and other works of literature (e.g., Peterson et al., 2008, Jaroszweski et al., 2010; Hooper & Chapman, 2012. Highways England, 2016), the key impacts and estimated tendency of climate change were identified in the British rail and road sector. For railways, these include the effects of an increased number of hot days, a decreased number of cold days, increased heavy precipitation, drought, sea level change, seasonal change, extreme events and wind. The extreme events posed the most devastating impacts (e.g. heat waves and storms) on rail transport. Higher temperatures in summer may cause rail buckling as well as decreased thermal comfort, while heavier precipitation in winter could cause landslips, flooding and bridge scour. For roads, the impacts posed by climate change include the effects of an increased number of hotter and drier days in summer and warmer and wetter days in winter, increased heavy precipitation and extreme weather events, drought, sea level change, seasonal change, high winds, and reduced number of fog days and cloud cover. For example, higher temperatures in summer can cause road damage; more intense precipitation in winter might result in flooding, landslips, and bridge scour.

In particular, flooding has the most significant impacts on UK inland networks (EPA, 2009). In Cumbria, for instance, its unique geographic conditions result in heavy rainfalls and flooding. The mountains of the Lake District rise sharply only 20 miles from the sea to the west creating conditions in which any low-pressure weather systems coming from that direction would drop most of their precipitation (Homewood, 2015). The most catastrophic floods occurred in Cumbria in 2015, for instance, causing roads to be closed in the severely affected areas and damaging or destroying over 100 bridges (BBC News, 2015).

The UK, as one of the windiest countries located in the mid-latitude westerlies, strong winds are considered to be the most dangerous weather type for the UK roadways (Perry, 1990; Edwards, 1994). A destructive wind event in January 2007 swept over major regions of

England, Scotland and Wales (Eden, 2007), leading to the overturning of approximately 50 goods vehicles and £50 million losses of delay across the nation (Highways Agency, 2007). The cumulative result of the rapid succession of 12 significant storms in December 2013 and January-February 2014 in Devon was the worst since the 1950s (Met Office, 2014; Devon Maritime Forum, 2014), which resulted in a 60-day closure of the railway mainline and 7500 service cancellation (Devon Maritime Forum, 2014). Meanwhile, as the sea level rises, 5% of the UK major road network is expected to suffer 'significantly' increased annual levels of coastal flooding (Edwards, 2017).

Regarding the regional and local climate impacts data and consultations from five domain experts in transport and climate adaptations, changes in temperature (temperature increase), precipitation (flooding), high wind and storm are initially screened to be the top concerns with marked medium- to high-level vulnerabilities. More detailed analyses of weather impacts on road and rail transport based on local reports, newspapers and literature were further investigated through surveys and case studies.

The findings from the nationwide survey of 19 road and 20 rail stakeholders in this study offer a broad overview of how British roads and railways can be adapted to the impacts posed by climate change. Overall, temperature increase, extreme weather and precipitations change/flooding, high winds and landslides are ranked as the top threats on the inland transport systems, which are similar to the investigations from the literature review and latest climate projections. While in the evaluation of four climate risks identified from the literature review, temperature increase and precipitations change/flooding are the common primary risks for both roads and railways. These findings are also consistent with the current priorities of tackling flooding and increased temperature issues of climate change adaptation in the UK.

Specifically, for railways, the ranking results of listed climate risks show that and precipitations change/flooding, landslide and extreme weather are the top three impacts, whereas these threats might be varying pose to the rails in different areas. Besides, by comparing the analytical outcomes of the four main regions in the UK, it is observed that flooding and landslide are the common impacts. Similar to the overall ranking, flooding has variable impacts on each area, with severest influences in England. However, the landslide is considered as having a stable occurrence except for Wales. Additionally, extreme weather is a common threat for the rails in Northern Ireland and England, high winds are a common risk for Wales and Scotland, and storm surges are a common one for Wales and England.

Additionally, the four primary environmental drivers due to climate change identified through the literature review were evaluated by the timeframe and likelihood of risks occurrence, the severity of consequences, as well as infrastructure resilience. Unsurprisingly, the top potential climate threats are highly related to the heavier precipitation and floods ("B1. Bridge foundations damaged leading to bridge collapse and derailment risk", "B2. Landslips causing obstruction in increasing derailment risk" and "B4. Track drainage overloaded leading to flooding of tracks"), which coheres with the current priorities of flooding adaptation in the UK. Through dissecting the perception of different groups, engineers from large consulting companies hold the highest risk-level opinions. Simultaneously, "B1" and "B2" posed by intense rainfall/flooding are still the top issues from the perspective of engineers at large consulting companies. By contrast, the invisibility and rescheduling issues ("C2. High winds affect visibility, and scheduled work may have to be rescheduled for safety and welfare reasons" and "B3. Heavy rain affects visibility, and scheduled work may have to be rescheduled for safety and welfare reasons") posed by high winds or storms and heavy rain are considered to pose the lowest risk threats in overall, with lower possibilities leading to catastrophic damages to infrastructure and operations in the short term.

For British roads, temperature increase, precipitations change/flooding and extreme weather are considered as the top three primary threats with varying influences on the roads in different regions. By vertically comparing the results of the primary climate risks in different regions, it is observed that temperature increase is the common threats for the UK as a whole, especially apparent in Northern Ireland. Although precipitation change is ranked as a critical risk in Scotland, Northern Ireland and England, it occurs unsteadily expect from England. The roads in Wales and England, likewise, are vulnerable to the impacts posed by extreme weather without a stable occurrence. Although snow is a significant threat for the British rails in overall, it is not the case for England.

Regarding the four climate threats identified by literature review, unsurprisingly, the modelling results show that the highest potential climate threats to the roads in Britain are triggered by temperature increase and precipitation change/flooding ("A3.Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs owing to increased temperature", "B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions", and "B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts"). Interestingly, these impacts including traffic jams, alternative routing, accidents and delivery delays are highly related to the public's daily life. While increasing fuel consumption, CO_2 emissions and consequential costs are also visible and widespread issues; in recent decades, their impacts on the lives of the general public are less direct. By dividing participants into three categories in terms of their position, and type and scale of their organisations, managers from large NGOs hold the most concerns on climate risks and their impacts on the UK road system. The threat "A3" has the highest ranking among all the groups. By contrast, "B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable" posed by "intense rainfall/flooding" and "C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign" posed by "more intense and/or frequent high wind and/or storms" are regarded as the least risky threats from the perspectives of academia and middle-size organisations.

Furthermore, the results from open questions indicate that almost all the respondents who provided the details about what they experienced or knew climate impacts in the past ten years emphasised the issues of flooding. For example, significant floods caused widespread damage to highway infrastructure, road deterioration and closures, service stoppage, as well as bridges being washed away, on June 2000, November 2006, June 2012, July 2014 and December 2015 affecting many areas, including South Tyneside, Leeds and Greater Manchester. Meanwhile, several rail lines were significantly interrupted due to severe flooding and landslides. There was a particular issue on the East Coast Main Line between Edinburgh and Newcastle and also on the West Coast Main Line between Glasgow and Carlisle. Extreme wet weather caused landslips and embankments slipped on to the rail tracks lines. The flooding in South West England closed railway lines, e.g., the 2013/14 storm in Devon closed the line at Dawlish after the coastal railway fell into the sea. Ayrshire coastlines are electrified and are subject to tripping when sea surges cause power lines to short-circuit.

<u>2) What are the potential challenges in adapting to climate change in the UK rail and road systems?</u>

Although there have been widespread effects on diverse transport modes (e.g., Peterson et al., 2008; Koetse & Rieveld, 2009), it is only recently that companies/organisations responsible for operating British railways and roads start paying more attention to the impacts of climate change (Hooper & Chapman, 2012; Jaroszweski, 2015).

The quantification of climate risks and costs in British railways is still at an embryonic phase (Network Rail, 2017a). Meanwhile, current action plans of the UK roads are still at the stage of internal technical documents within the relevant business areas; a detailed action plan for climate adaptation has not been officially published (Committee on Climate Change, 2014). The existing approach to adaptation for the UK government usually relies on the established network by the UK Climate Impacts Programme; many adaptations are only the by-products of mitigation activity or not initially designed to deal with the impacts of climate changes (Tompkins et al., 2010). Some of the impediments existing in climate adaptations include lack of support from regulation, policies, standards, regulations and design, insufficient knowledge of climate change risks and vulnerabilities guidance, restricted budgets for available adaptation options and inappropriate planning horizons (UK Climate Projections, 2009a).

The most up-to-date UKCP18 projections have made changes regarding the level of climate risks, which require reviews of existing action plans and budgets. The Department for Environment, Food & Rural Affairs (DEFRA) has been looking at a more standardised approach for climate risk assessment. Adaptation strategies are highly necessary to be incorporated into the planning stages of new developments as well as existing maintenance to minimise risks, reduce costs and enhance the resilience of the UK transport network in the future (Jaroszweski, 2015). Therefore, it is highly urgent to figure out the perceptions of transport stakeholders to climate adaptation measures as well as potential planning dilemmas on the British road and rail sectors. To do so, a nationwide survey and interview were then utilised for this investigation.

28% of total survey respondents on roads and 32% on railways have implemented an adaptation plan, whilst 33% road and 47% of rail stakeholders respectively have shown a positive intention to make a specific adaptation plan for climate change impacts in the future. Overall, rail stakeholders hold a relatively more positive view regarding adaptation planning, which might reflect the benefits of comprehensive guidance from NR in recent years. Although the national adaptation framework (e.g., Adaptation Reporting Power) has been established, there is still an urgent and continuous demand for analysing the responses of both road and rail stakeholders to impacts of climate change and their decision-making procedure (Jude, 2017).

To further figure out the critical elements influencing the development of a climate adaptation plan in a UK transportation entity, the author identified the seven conditions from the literature review, including:

(1) *Climate Data (D):* a significant challenge for transportation planners is the shortage of data both in precise climate change prediction and the cost-benefit analysis owing to the high uncertainty posed by climate change (De Bruin et al., 2009; Koetse & Rietveld, 2012).

(2) *Analytical Tool (T):* the existing models could only provide partial information to guide adaptation planning of specific infrastructure and sector. The knowledge gaps regarding direction, magnitude and severity also lead to the failure of adaptation strategies in the transport sector (Koetse & Rietveld, 2012).

(3) *Transport Infrastructure (I):* only a limited number of agencies have considered adaptations in their organisational management practices. Some common barriers include data limitations, inadequate treatment of risk, lack of sufficient financial resources, and uncertainty in future system demand (Wall & Meyer, 2013). The factors such as infrastructure age, location, design, use maintenance and limited redundancy, could affect the sensitivities of transportation systems (Strauch et al., 2015).

(4) *Governmental Policy (P):* some agencies rarely incorporate climate change into the decision –making processes (Espinet et al., 2016). Many adaptation plans (e.g., in the UK) are not explicitly designed for responding to impacts of climate change but for the co-benefits of other activities such as demands of infrastructure investment and cost savings (Tompkins et al., 2010). Most adaptation initiatives have an organisational or planning nature that follows a top-down policy pattern which has been doubted by some researchers who argue that most of the adaptations could be led by the private sector (Eisenack et al., 2012; Koetse & Rietveld, 2012).

(5) *Investment Strategy (S):* relatively short planning cycles (typically 5-10 years) do not match infrastructure lifespans (typically more than 50 years), which leads to malfunctioning of transport networks (ICF International, 2008; Kintisch, 2008; Koetse & Rietveld, 2012). The relatively irreversible investments in infrastructure might fail to reach their expected effects and profits under the new climate parameters, where predicted short lifetimes of transportation infrastructure might be problematic with the accelerating pace of climate change (Reilly & Schimmelpfennig, 2000)

(6) *Financial Resources (F):* lack of access to financial resources could pose a massive challenge for the implementation of an adaptation plan (Miao et al., 2018). Funding policies and management could influence the implementation of adaptation planning (Strauch et al., 2015).

(7) *Collaboration (C):* deficiency of implementation of adaptation plans may also be caused by the fact that they have a stakeholder-oriented focus, involving multiple participants (public, private and households), actions and agencies (Nelson et al., 2007). It is challenging to develop strategies supported by all participants (Klein et al., 2005; Eisenack et al., 2007).

Regarding the above gaps, a multi-case study by interviewing five domain experts was conducted to examine which factors are essential for the implementation of climate adaptation planning in the UK transport systems. Qualitative Comparative Analysis (QCA) approach was used to further investigate under-reached issues and challenges in climate adaptation planning.

The results of QCA indicated that the top factors influencing the generation of a climate adaptation plan in a transport entity are *"Climate Data (D)", "Analytical Tool (T)" "Governmental Policy (P)", "Collaboration (C)"* and *"Investment Strategy (S)",* whereas *"Transport Infrastructure (I)"* and *"Financial Resources (F)"* are partially significant elements for some organisation or sectors..

Climate Data and Analytical Tool:

Climate adaptation is sometimes regarded as a part of risk management, where more attention has been given to risk assessment for the road system with specific extreme weather adapting plans (Interviewee 5, February 8th 2018). For railways, existing adaptation plan of NR mainly focuses on the identification of various climate thresholds (Network Rail, 2015; Interviewee 2, April 6th 2018). Meanwhile, the current climate risk appraisal method "HHAFM" in HE (2016) fails to comprehensively take other critical factors influencing climate impact into account, such as the costs, time and capacity of a transport system to recover from the risks of a climate change event.

The absence of a holistic adaptation strategy might reflect the deficiency of scientific data (e.g., SLR for TE2100 in the case of EA), cost-benefit analysis and understanding of climate vulnerabilities and thresholds (Interviewee 3, January 17th 2018; Interview 5, February 8th 2018). These gaps also reflect the findings in the literature (e.g., Koetse & Rietveld, 2012). A new set of climate projections (UKCP18) published in November 2018 by the UK government is, therefore, believed to offer scientific guidance for dealing with the challenges of estimation and selection of risk scenarios under diverse climate conditions.

Governmental Policy:

At the national level, the UK Climate Projections (UKCP09) and relevant legal documents (e.g., Committee on Climate Change 2017a, 2017b; Department for Transport, 2014) have provided HE and NR with guidance for generating climate risk and adaptation reports. In particular, a strategic rail adaptation plan covering all the nine national routes (exclude the Freight and National Passenger Operators route but add the West of Exeter route) has been prepared (Network Rail, 2017; Rail Safety and Standards Board, 2016). Meanwhile, the Committee on Climate Change's ARP2 and DfT's Transport Resilience Review have provided HE, NR and other local authorities with specific guidance for improving climate resilience on their transport networks. However, local-based (such as TfL, EA and DCC) polices, and planning guidance have not been well developed (at least not mentioned by interviewees).

Collaboration (C):

The birth of several partnerships, on behalf of the London Climate Change Partnership (LCCP) Transport Group and the South West Peninsula Rail Task Force, has offered a chance for dealing with regional climate change issues. A modal shift strategy has been successfully applied into practice, for instance, a rail replacement service by increasing buses and flights from Newquay to London due to seawall damage in Dawlish, Devon (Transport Committee, 2014). However, in reality, owing to the project-based characteristics in most adaptation cases, some interviewees mentioned (Interviewee 1, January 26th 2018; Interviewee 5, February 8th 2018) that road and rail stakeholders usually only consult each other but undertake projects separately.

More extensive and efficient cooperation between roads and railways is therefore expected, but the development of an integrated inland transport system requires the careful consideration of multiple factors, such as mode capacity, the severity of consequences and geographic conditions, etc. The trans-mode and cross-sectoral collaborations in the future should enable planners to create a new blueprint for climate adaptation, effectively facilitated by governmental regulation (e.g., ORR, DfT), broader stakeholder management and public engagement from decision making to adaptation implementation.

Investment Strategy (S)

Investment strategy does not appear in all the five cases; however, it can be regarded as a critical barrier in adaptation planning in the future no matter an existing plan is available or not within a transport entity. This is because many interviewees (e.g., Interviewee 1, January 26th 2018; Interview 2, April 6th 2018) mentioned the investment and planning cycle for climate adaptation is ambiguous. For the majority of cases, adaptation reports run on a five-year basis (Interviewee 1, January 26th 2018; Interviewee 2, April 6th 2018; Interviewee 4, February 1st 2018), thereafter, the time horizon for a long-term adaptation plan is undetermined: it may look at next 30 years and beyond 2100 (Interviewee 2, April 6th 2018) or 100 years (Interviewee 3, January 17th 2018) for railways and up to 120 years for roads. It can be linked to the different lifespan of specific assets, geographic conditions, climate change prediction, and financial budgets, etc. Therefore, it can be deduced that the case of the UK transport system confirm one of the pressing issues of climate adaptation in the literature review that current transportation investment and planning could not address climate change impacts adequately.

Transport Infrastructure and Financial Resources:

Although fewer weather-related delays in England occurred in recent years, regional extremes are still witnessed and will potentially trigger high costs due to the uncertainties of climate change. One of the significant challenges revealed by the case of the TE2100 is that the ageing flooding infrastructure might not be able to catch up with the higher SLR (Environment Agency, 2017), while ageing infrastructure could be a standard issue for the whole railway industry owing to the increasing rate of climate change. Rapid and massive financial supports have been provided in almost all cases after the risk occurs. In the road and rail sectors, facilitation of flood resilience is a shared priority with over £100 million funding being allocated by the government (HM Treasury, 2016). However, it is doubted that if these funding could be adequately adapt to these climate risk before they come.

Besides above factors, interviewing revels that climate adaptation is sometimes regarded as a part of risk management, where more attention has been given to risk assessment for the road system with specific extreme weather adapting plans (Interviewee 5, February 8th 2018).

Simultaneously, the road and rail systems face many challenges in adapting to climate change risks. Overall, rail and underground are more vulnerable to the impacts of climate change due to the limited flexibility and complexity in rail infrastructure construction. In the future, climate adaptation planning needs to be regularised and written into every business plan (Interviewee 3, January 17th 2018), embedded in technical standards and delivered to all staff seamlessly (Interviewee 1, January 26th 2018). A successful adaptation plan must be aware of budgetary constraints and strike a balance between corporate priorities and technical requirements (Wang et al., 2019).

3) What are the most cost-effectiveness measures for the UK rail and road stakeholders to adapt to climate change?

In response to the impacts of climate change on transportation infrastructure, the UK government has recognised adaptations on infrastructure as a high priority. For example, an early report called "Climate Resilient Infrastructure: Preparing for a Changing Climate" was published together with guidance on building infrastructure resilience in 2011 (HMG, 2011; HM Cabinet Office, 2011).

In the rail system, Network Rail has been responding to the challenges of extreme weather in its daily operation (Network Rail, 2018b). A few significant climate hazards on rail infrastructure were recognised through an internal risk analysis supported by METEX and GIS tools (Network Rail, 2015). Aiming to generate a safer and more resilient network to the future weather impacts, Network Rail conducted a four-pillared method in 2020 Review and Revise Strategy (Network Rail, 2017a; 2017b). Furthermore, RSSB (2016) established an adaptation framework containing four action steps for the management of summer conditions, winter conditions and flooding risk by drawing the experiences of other countries in weather resilience and climate change adaptation. Quinn et al. (2017) also reviewed several documents in the context of climate change on railways, including the issues at stake, strategies and toolkits for addressing them. It also offered case studies in the UK by providing techniques and tools drawn from global experiences. For example, Network Rail and Cumbrian County Council implemented a modal shift strategy by converting road traffic to the rail by quickly setting up a new direct rail service and building a rail platform in Workington (Ace Geography, n.d.).

Since 2010, the UK highway industry began developing a holistic asset management plan for climate change (Munslow, 2011). The existing climate risk appraisal considers the rate of climate change, the extent of disruption, the severity of disruption and uncertainties (Highways Agency, 2009; Highways England, 2016). Nevertheless, this method does not take other critical factors influencing climate impact into account, such as the costs, time and capacity of a transport system to recover from the risks of a climate change event. HE's Climate Adaptation Risk Assessment (2016) highlighted a series of current adaptation action plans, mainly focusing on road structures, pavements and drainage management, and will continuously monitor all the potential climate vulnerabilities. Several regional flooding adaptation actions, including the design and constructions of flood defences to protect the people and properties, have been undertaken in severely jeopardised regions. An excellent example of risk management was the success of dealing with the Cockermouth's flooding in 2009. The government allocated approximately £1 million funding to support the clean-up and repairs of damaged roads and bridges within Cumbria.

The modelling results indicate that some measures can efficiently adapt to flooding and other potential threats (e.g., sea level rise posed by climate change. According to the results of rail survey, the most cost-effective adaptation measures in the rail system are "(B1a) Improve scour resilience during routine renewal of scour protection systems", "(B1b) Design future bridges to withstand climate change", and "(B2b) Identify and introduce resilience measures at vulnerable sites, such as shaping to reduce slope angles" which address the top potential threats "(B1)" and "(B2)" due to "Intense rainfall/flooding" respectively. However, there is no effective adaptation listed to address "(B4) Track drainage overloaded leading to flooding of the track" due to "intense rainfall/flooding".

In the road network, the most cost-effective adaptation measures are all highly related to intense rainfall/flooding, namely "(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection", "(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a" and "(B3a) Consider slope, drain performance in landslide scenarios". Therefore, it can be interpreted that there are two cost-effectiveness measures "(B1b)" and "(B2b)" to address the top risk threat "(B1)" and "(B2)" respectively regarding the flooding issue on roads. Meanwhile, "(B3a)" can also effectively cope with landslides and mudslides issues in hilly areas due to flooding. However, for temperature increase, the current adaptation measures, such as "(A3a)" and "(A3b)", are still insufficient to handle the critical climate risk "(A3) Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs".

Chapter 10 Conclusion

This chapter summarises the main findings from the previous chapters. The author further dissects the thesis's theoretical and practical contribution, limitations and implications for future research.

10.1 Summary

This thesis outlines a complete procedure for examining the impacts posed by climate change and reveals potential threats and opportunities for adaptation planning in road and rail transportation systems. It responds to the three primary research questions as proposed in Chapter 1 by synthesising the key findings from the literature review, surveys and interviews. The modelling results indicate the top climate risks ranked by the survey participants (i.e., temperature increase, extreme weather, precipitation change/flooding, high winds and landslips) are consistent with the findings from literature reviews and climate projections (UKCP09 and UKCP18). Meanwhile, the top climate threats posed to rail and road systems are closely related to temperature increase and flooding, whereas less relevant with high winds and sea level rise. Hence, further modelling research might switch to investigate the threats posed by landslide and extreme weather rather than high winds and sea level rise.

Although a few climate adaptation measures have been undertaken in some transport authorities, climate adaptation is still at an embryonic stage as revealed by literature review. Likewise, 28% of total survey respondents on roads and 32% on railways have implemented an adaptation plan, whilst 33% road and 47% of rail stakeholders respectively have shown a positive intention to make a specific adaptation plan for climate change impacts in the future. According to the modelling results, the most cost-effective adaptation measures in the UK rail system are associated with addressing impacts posed by intense rainfall/flooding. However, there is no effective adaptation in railways to address "(B4) Track drainage overloaded leading to flooding of the track" due to "intense rainfall/flooding". Simultaneously, the current adaptation measures in the UK roads are still insufficient to handle the critical climate risk "(A3) Traffic jams/alternative routing /accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs". More reliable and efficient measures, therefore, are expected to tackle these issues in the future.

Furthermore, within-case (e.g., London), cross-cases analyses (e.g., NR and HE) were undertaken to strengthen the external and internal validity of the multi-case study. At the national level, a series of climate risk and adaptation reports have been published supported by the UK Climate Projections and relevant legal guidance, risk assessment tools and funding. However, some local authorities relatively lack such abundant resources for improving climate resilience on their transport networks. Rail and underground in overall are more vulnerable to the impacts of climate change due to the limited flexibility and complexity in rail infrastructure construction. The effects of risk reduction and cost of an adaptation measure can both influence its cost-effectiveness, whereas risk reduction has a stronger influence in particular for the road system. Therefore, how to maximally reduce climate risks will still be a core question for adaptation planning in the future. Although road and rail systems confront diverse challenges in adapting to climate change risks, based on the findings from QCA, the generation of a climate adaptation plan in a transport entity mainly relies on some common factors. These include scientific climate data and analytical tool, instructive governmental policy and collaboration between diverse stakeholders and public engagement. Other factors identified from the literature review (e.g., transport infrastructure and financial resources), might be pivotal for certain entities but not such vital for the UK inland system as a whole.

Hence, to what extent has this thesis achieved the four objectives as proposed in Chapter 1? Specifically, the literature review highlights the significance of the impacts that climate change poses to rail and road systems and the necessity of climate adaptation planning (Objective 1). The nationwide survey illustrates an overview of existing significant threats posed by climate change and cost-effective adaptation measures for British inland transport systems (Objective 2). Meanwhile, a systematic procedure for developing long-term climate change adaptation planning for transportation systems is established in this thesis. Using the FBR method to construct a model, and data collections from the survey, the framework systematically evaluates the climate risks and selects the cost-effective adaptation options when objective risk and cost data are incomplete or unavailable. It offers a significant contribution to innovate climate adaptation methods and to facilitate economic development and investment within the context of transportation planning (Objective 3). Furthermore, from the consultations with interviewees in the case studies and the answers to the open-ended questions in the survey, the author summaries the current achievement and barriers of climate adaptation planning for both road and rail systems. A few practical suggestions have been proposed in Chapters 9, while the full implications for future research will be provided in Chapter 10 (Objective 4).

10.2 Theoretical and Practical Contributions

The thesis is intended to be an innovative study of climate risks assessment and adaptation planning on both road and railway systems, with particular attention in the UK, to fill existing research gaps. Both theoretical and practical contributions are considered. Firstly, a comprehensive literature review concerning journal articles published over the past decade allowed researchers to identify emerging issues and associated themes; how these concerns and themes have evolved over time; and what are the challenges to be addressed in future. Also, a relatively new area of research, semantics analysis based on the categorisation of five research themes, provides researchers with an innovative thinking pattern in future climate adaptation research.

Secondly, in light of the previous climate adaptation research on ports, this thesis reiterates the reliability and validity of the utilisation of FBR model in the context of transportation systems. From the modelling perspective, this work brings novelty by considering climate resilience and expanding the risk parameters of 'severity of consequence' into three components: economic loss, damage to the environment, and injuries and loss of life. It advances the-state-of-the-art techniques in the current relevant literature from a single to multiple tier structure. The abundant raw data collected from the real world provides the most useful practical insights for rail and road resilience when facing increasingly frequent and severe climate change events.

Thirdly, being a pioneering survey on the British rail and road network, the latest primary data offers a comprehensive overview of the most significant risks posed by climate change and corresponding cost-effectiveness adaptation measures. The survey results have supported the evidence for the existence of several climate threats and adaptation issues identified in the literature review (e.g., temperature increase and flooding).

This thesis also has practical implications for both road and railway industries. The useful adaptation framework for constructing or developing an adaptation plan for climate change offers a new methodology by integrating mathematical modelling and qualitative consultation into decision making. The results are expected to be shared with most of the participants in the survey, including highway authorities, railway operators, transport consulting companies, governments and relevant associations. It calls for more attention from transport planners on the significance of the impacts that climate change poses to road and railway planning. Through illustrating a general situation of climate change and adaptation planning at the UK inland transport systems, the survey results also provide transport planners with a better interpretation of the existing climate risks.

For the participants in the case studies, the all-around interviews and data analysis facilitate interviewees in the cases a better understanding of the impacts posed by climate change in decision making and to recognise their strengths and barriers in future adaptation planning. Also, an integrated thinking pattern concerning roads and railways in an integrated inland transport will enlighten transport planners to consider the consistency and resiliency of diverse modes in a systematic transport network in future planning.

10.3 Research Limitation

All research has its limitations, and this work is no exception. For the survey itself, since questionnaires on the subject were rare and not available during survey design, most of the climate risks and adaptation measures are based on official reports and articles in journals. Although a pilot study had been implemented before the survey was distributed, some of the risks and adaptation measures might not be included in the final assessment. As a result, the validity and reliability of this survey are expected to be confirmed in further research.

Secondly, respondents were mainly chosen from the members of the UK Roads Liaison Group (UKRLG), Railway Industry Association (RIA) and the Rail Freight Group (RFG), the leading organisations associated with road and railway development, which may limit the survey sample. However, this sampling method can, at the same time, guarantee that the 19 road and 21 railway respondents were knowledgeable of the issues. Other main road and rail organisations were invited to participate but could not be reached due to communication barriers and other factors. It also admitted that as the survey on both road and rail systems is heavily weighted to England and senior staff due to sampling limit, it might ignore potential threats in other areas (e.g., snow issues in Scotland) and opinions from other institutions. Therefore, more work is required to verify these findings by consultation with wider stakeholders, including those in under-reached regions.

Thirdly, since the respondents have more concern about, and interest in, climate change issues than non-respondents, the survey results might have exaggerated some of climate change impacts or overstated the effectiveness of adaptation measures. Even so, it is believed that the results reflect common problems on road and rail networks posed by climate change. Finally, as climate change is a complex phenomenon involving diverse departments within an organisation and different stakeholders in an integrated transport system, the survey results might be restricted by individual knowledge and perceptions. Accordingly, a broader and in-depth investigation targeting more extensive participants, for instance, environmental agency, insurance, academia, etc., should be undertaken.

Regarding the four case studies, the results of five interviews might be constrained by the limited number of interviewees and their personal perceptions and experiences. Meanwhile, the person who answered might not be the best representative of his/her organisation. Therefore, future research on these cases should consider extending the number of interviewees and extend the range to external stakeholders (e.g., senior engineers, environmental specialists, climatologist and other academies).

Last but not least, the regional focus in this thesis also is worth noting. Both the survey and case studies only focus on climate change conditions and adaptation issues in the UK. Locating a study within a single country may not reflect the overall situation of road and rail networks globally or a specific system in other areas, thereby restricting those who seek a broader application. Nevertheless, this thesis provides a sound theoretical foundation by creating a pioneering climate adaptation framework for the transport sector, a novel risk assessment and adaptation modelling tool and practical reference for transport planners to adapt to climate change impacts in the future. It will allow further research to draw the experiences from the UK and other best global practice and look at the pivotal elements in developing transport adaptation planning for climate change. These include systematic risk analysis and evaluation of adaptation options, scientific forecasting and transparent information sharing, wise decision making in planning cycle and investment, within-mode and cross-mode collaborations and broad public participation.

10.4 Implications for Future Research

Given that most research has focused on short-term impacts, hitherto, there is insufficient research on how to systematically adapt to the impacts of climate change on transportation. With the occurrence of increasingly frequent severe extreme weather events, an initial and critical step is to motivate transport stakeholders to establish and continually develop a climate adaptation plan. Besides the two factors identified by Wall & Meyer (2013) and Aguiar et al. (2018) (i.e., government acts and or legislation as adaptation planning requirements and self-motivated internal agency initiatives), having scientific climate data, practical analytical tools, wise investment strategy, extensive collaboration among diverse stakeholders and public engagement in a transport entity will significantly facilitate the success of climate adaptation planning.

It is pivotal to refine the FBR model regarding climate risk and adaptation assessment for transportation systems to strengthen its robustness and generalisation. The preliminary analysis of this thesis could be incorporated into the long-term transportation asset management planning, which might need the input from continuous data collection and innovation of advanced models based on the updated local conditions (Walker et al., 2011). Effective index and measurements should be further developed to quantify the impacts of climate change in diverse transport modes with supplementary data from engineering, economic and other disciplines by building a seamless connection between natural scientist and social scientist. Meanwhile, cost rationalisation and positive impacts of climate change could be considered in models and policies on a project basis.

Regarding one of the pressing challenges of current climate adaptation planning, namely an inexplicit time horizon as mentioned in case studies, some solutions have been proposed in the literature review. These include construction of efficient asset management systems (Meyer et al., 2012), consideration of the pro-active or ex-ante strategy and postponement strategy in adaptation investment (Koetse & Rietveld, 2012; RVW, 2009), strengthening regular monitoring and maintenance and designing stricter design parameters in response to various extreme climate events (e.g., TRB, 2008). Government has been playing critical roles in guiding and assisting British road and railway stakeholders to deal with impacts posed by climate change and developing adaptation plans. However, higher-level environmental policies may not be easy to customise to specific climate change issues at an individual organisation level. Besides, proposed goals and policy responses to climate change are sometimes insufficiently translated into action (e.g., Biesbroek, et al. 2009; Preston et al., 2011; Romero-Lankao, 2012). Hence, some strategies such as bottom-up planning (Nordhaus, 1990), spatial planning (Hrelja et al., 2015) and proactive policy planning (Chinowsky et al., 2015a) have been proposed in order to overcome the inflexibility of top-down policies and support local climate change transitions to develop sustainable transportation. Nevertheless, the feasibility and efficiency of all these strategies should be further testified by theoretical research and application of regional practice.

In light of the fact that current research is still at an early stage and that literature is still scattered, lacking in dominant journals, researcher and theories, and much knowledge on adaptation has not been clarified through peer-reviews (Eisenack et al., 2012), a few questions are yet to be addressed. These include, how researchers can engage with local experts to explore adaptation options; how to balance the roles of central and local governments; and how to tackle the barriers faced by communities in adapting to climate change vulnerabilities (Picketts et al., 2016). Further research requires a more comprehensive analysis on adaptation planning in terms of identifying the feasibility, deficiency and resilience in organisations that have already considered and engaged with adaptations as well as motivation and challenges faced by non-engaged organisations (Jude et al., 2017).

The Workshop towards an International Consortium on Climate Change and Adaptation Planning for Ports, Transportation Infrastructures, and the Arctic (CCAPPTIA) took place in May 2018 Canada brought together leading experts and stakeholders from academia, government, industry, and interest groups in the workshop. An integrated Supply Chain Management approach is recommended for stimulating incentives for generating or developing climate adaptation strategies on transportation. Given that many adaptation plans are designed for the co-benefits of other activities rather than impacts of climate change (Tompkins et al., 2010), it is necessary to identify clear drivers as an initial step of planning (e.g., government acts and legislation and self-motivated internal agency initiatives (Wall & Meyer, 2013). With the increasing frequency of climate change and extreme weather events, two issues which require further attention (Wang, 2015) are: 1) how is going to take the mantle of leadership for climate adaptation? and 2) how to guarantee the power of execution and sufficient investment to implement adaptation planning. Additionally, as mentioned in the workshop, it is imperative to re-educate the public, in particular college students in associated disciplines, to better interpret the impacts of climate change instead of scaremongering about it alone.

Last but not least, as per climate adaptation planning for ports implied (Ng et al., 2018), cross-sectoral collaboration and new approaches should continuously be encouraged for triggering motivation and paradigm shift among diverse stakeholders (e.g., senior policymakers, industrial practitioners, economists, scientists and researchers). It will significantly contribute to understanding the dynamics between climate change and adaptation planning of transportation systems through comprehensive guidance, standardised framework, scientific data, advanced models and global experiences. With the increasing number of studies on climate risks management on diverse transportation systems, it is anticipated, therefore, the findings of this thesis will contribute to future regional studies and trigger more in-depth discussions on relevant topics, especially for the multi-mode and comparative research (such as in seaports and airports (Poo et al., 2018; Monioudi et al., 2018).

Appendix A

The Background Information of Transport Experts in Pilot Study (Rail)

Expert 1: Associate Director of Freight and Logistics, AECOM UK

Expert 2: Transport Engineer, AECOM UK

Expert 3: Executive Director, Rail Freight Group

Expert 4: Climate Change Adaptation Strategy Manager, Network Rail

Expert 5: Performance Programme Manager, Rail Delivery Group

Expert 6: Environmental Manager, Arriva Rail North

Expert 7: Principal Technologist of Freight and Logistics, Transport Systems Catapult

Expert 8: Policy Maker, Leeds City Council

The Background Information of Transport Experts in Pilot Study (Road)

Expert 1: Transport planner, AECOM UK

Expert 2: Policy maker, Leeds City Council

Expert 3: Transport planner, South Tyneside Council

Expert 4: Academic, University of Westminster

Expert 5: Head of highways, Ynys Mon Country Council

Expert 6: Transport engineer, North & Mid Wales Trunk Road Agent

Expert 7: Senior manager, Transport for Greater Manchester

Expert 8: Team leader, Transport System Catapult

Appendix B1

Rail Questionnaire

INFORMATION CONSENT

You are cordially invited to participate on the captioned research study conducted by the principal investigator, Tianni Wang, who is a Ph.D. student of Liverpool Business School of Liverpool John Moores University (UK), under the supervision of Dr. Zhuohua Qu. This project will be a significant part of Tianni's thesis. Understanding your experiences and prestige in this area, you are invited to participate in a 20minute online survey.

Prior to your decision to participate, it is important that you understand why the research is being done and what it involves. Please take time to read the following information (the Participant Information Sheet and sign the Participant Consent Form). Please contact - if there is anything that is not clear or if you like some more information.

1. Participant's agreement

□ I understand the information regarding participation in the project and agree to participate in this survey.

2. Date

DD/MM/YYYY ______/____ /_______

BACKGROUD INFORMATION

3. What is the name of your company/organisation? Which geographic areas of the railway are your company/organisation responsible for/operate on?

____

____

4. What is your current position at your company/organisation? (Optional)

☐ CEO or Transport Director

☐ Planner

☐ Transport Engineer

☐ Transport Operator

☐ Environmental Manager

☐ Public Relations Director

☐ Development Director

☐ Safety or Security Director

☐ Environmental Academics

☐ Other (please specify) ________________________________

5. In your view, what types of risks are posed by climate change on the railway your organisation associated with? (Please rank the following items which impacted your company; if not at all, please specify)

( ) High Temperature

( ) Sea Level Rise

( ) Flooding

( ) Precipitation Change

( ) High Winds

( ) Storm Surges

( ) Extreme Weather

( ) Snow

( ) Landslide

( ) Other (please specify) ________________________________

6. If the rail your company/organisation are responsible for has been impacted by climate change in the past 10 years, please details including <u>line name(s)</u>(e.g., east coast main line), <u>happened year</u>(s), and <u>main damages</u>.

____

____

____

7. Has your company/organization made an adaptation plan for climate change?

□ Yes, we have implemented an adaptation plan

□ No, we have not implemented an action plan but will consider doing so in the future

□ No, we have not, nor do we have any plans to implement a climate adaptation plan in the future

ADAPTATION STRATEGIES IN THE FUTURE

- **What climate risks would you expect the railway to be exposed to in the FUTURE if your company/organisation does NOT undertake any ADAPTATION measures?**

Description of Variables

Timeframe *- when you expect to first see this impact:*

1. Very Long (VL)--More than 20 years

2. Long (L)--Approximately 15 years

3. Medium (M)--Approximately 10 years

4. Short (S)--Approximately 5 years

5. Very short (VS)--Less than 1 year

Severity of consequences *of this impact:*

Three subcategories are included— ***damage to property (PRO), damage to injures and loss of lives (INJ) and damage to the environment (ENV)***

The damage to properties (PRO):

1. Catastrophic (Ca) -- the damage committed to property is valued at more than £2 million

2. Critical (Cr) -- the damage committed to property is valued between £1million and £2 million

3. Major (Maj) -- the damage committed to property is valued between £500,000 and £1 million

4. Minor (Min) -- the damage committed to property is valued between £100,000 and £500,000

5. Negligible (Neg) -- the damage committed to property is valued at less than £500,000

The damage to injuries and loss of lives (INJ):

1. Catastrophic (Ca)-- major injures and loss of more than 10 lives

2. Critical (Cr) -- many major injuries or/and loss of 5 to 10 lives

3. Major (Maj) -- major injures and loss of less than 5 lives

4. Minor (Min) -- minor injuries and no loss of life

5. Negligible (Neg)--no injuries and no loss of life

The damage to environment (ENV):

1. Catastrophic (Ca)—the event contributes to over 50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations;

2. Critical (Cr)-- the event contributes to 30-50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

3. Major (Maj)-- the event contributes to 20-30% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

4. Minor (Min)-- the event contributes to 10-20% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

5. Negligible (Neg)-- the event contributes to less than 10% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

***Likelihood** that the effect will occur:*

1. Very High (VH)--It is probable that the stated effect will occur, with a likelihood of around 90%

2. High (H)--It is highly likely that the stated effect will occur, with a probability of around 70%

3. Average (A)--It is likely that the stated effect will occur, with a probability of around 50%

4. Low (L)--It is unlikely that the stated effect will occur, with a probability of around 30%

5. Very low (VL)--It is very unlikely that the stated effect will occur, with a probability of around 10%

***Climate Resilience**: the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (IPCC, 2012)*

1. Very Strong (VS)—Very strong (80% above) capacity of the transportation system to *anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring slight cost of recovery (0-£1,000)*

2. Strong (S)-- Strong (60-80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,000-£100,000)

3. Average (A)—Average (40-60%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring certain length of time (a week) and cost of recovery (£100, 000-£1million)

4. Weak (W)—Weak (20%-60) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)

5. Very Weak (VW)— Very weak (0-20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery(£10millions above)

It can be descried by the following three parameters. The worse-case scenario is applied to assess the system's resilience. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

Please describe each of the SIX items in the following question 8-11.

8. Temperature Increase

	Timeframe	Severity of Consequences PRO INJ ENV	Likelihood	Climate Resilience
(a)Track buckling causing derailment risks & reducing opportunities for track maintenance	______	__ __ __	_____	______
(b) Unreliable signalling and power line side systems & failure of temperature controls and overheating of electronic equipment	______	__ __ __	______	______
(c) Sag of overhead line & risk of dewirement	______	__ __ __	______	______

9. Intense Rainfall /Flooding

Timeframe	Severity of Consequences	Likelihood	Climate Resilience

(a) Bridge foundations become undermined leading PRO INJ ENV
to bridge collapse and derailment risk ______ __ __ __ ______ ______
(b) Landslips causing obstruction in cutting
derailment risk ______ __ __ __ ______ ______

10. More intense and/or frequent high wind and/or storms

	Timeframe	Severity of Consequences PRO INJ ENV	Likelihood	Climate Resilience
(a) Trees being blown on to the line	______	__ __ __	______	______
(b) Dewirement of overhead traction power lines	______	__ __ __	______	______

11. Sea Level Rise

	Timeframe	Severity of Consequences PRO INJ ENV	Likelihood	Climate Resilience
(a) Breach of sea wall, flooding and derailment risk	______	__ __ __	______	_____
(b) Overtopping waves damaging & affecting vehicles	______	__ __ __	______	______

- **If your company/organisation undertakes planned ADAPTATION measures, how do you anticipate the climate risks will change in the FUTURE? (If your company/organisation will not undertake any adaptation measures, please skip this part)**

Description of Variables

***Financial cost** of adaptation:*

1. Very High (VH)--involves a very high financial cost so as to comprehensively address the stated potential effect

2. High (H)--involves a high financial cost so as to comprehensively address the stated potential effect

3. Average (A)--involves a significant financial cost so as to comprehensively address the stated potential effect

4. Low (L)--involves a financial cost (though not that significant) so as to comprehensively address the stated potential effect

5. Very low (VL)--involves a minimal financial cost so as to comprehensively address the stated potential effect

***Timeframe** for when you expect to first see this impact:*

1. Very Long (VL)--More than 20 years
2. Long (L)--Approximately 15 years
3. Medium (M)--Approximately 10 years
4. Short (S)--Approximately 5 years
5. Very short (VS)--Less than 1 year

***Severity of consequences**:*

*Three subcategories are included— **damage to properties (PRO), injuries and loss of life (INJ) and damage to environment (ENV)***

The damage to properties (PRO):

1. Catastrophic (Ca) -- the damage committed to property is valued at more than £2 millions
2. Critical (Cr) -- the damage committed to property is valued at more than £1million and less than £2 millions
3. Major (Maj) -- the damage committed to property is valued at between £500,000 and £1 million
4. Minor (Min) -- the damage committed to property is valued at between £100,000 and £500,000
5. Negligible (Neg) -- the damage committed to property is valued at less than £500,000

The damage to injuries and loss of lives (INJ):

1. Catastrophic (Ca)-- major injures and loss of more than 10 lives
2. Critical (Cr) -- many major injuries or/and loss of 5 to 10 lives
3. Major (Maj) -- major injures and loss of less than 5 lives
4. Minor (Min) -- minor injuries and no loss of life
5. Negligible (Neg)--no injuries and no loss of life

The damage to environment (ENV):

1. Catastrophic (Ca)—the event contributes to over 50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial *operations;*

2. Critical (Cr)-- the event contributes to 30-50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

3. Major (Maj)-- the event contributes to 20-30% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

4. Minor (Min)-- the event contributes to 10-20% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

5. Negligible (Neg)-- the event contributes to less than 10% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

***Likelihood** that the effect will occur:*

1. Very High (VH)--It is very highly likely that the stated effect will occur, with a probability of around 90% of at least one such incident within the indicated timeframe

2. High (H)--It is highly likely that the stated effect will occur, with a probability of around 70% of at least one such incident within the indicated timeframe

3. Average (A)--It is likely that the stated effect will occur, with a probability of around 50% of at least one such incident within the indicated timeframe

4. Low (L)--It is unlikely that the stated effect will occur, with a probability of around 30% of at least one such incident within the indicated timeframe

5. Very low (VL)--It is very unlikely that the stated effect will occur, with a probability of around 10% of at least one such incident within the indicated timeframe

***Climate Resilience**: the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (IPCC, 2012).*

It can be descried by the following three parameters. The worse-case scenario is applied to assess the system's resilience. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

1. Very Strong (VS)—Very strong (80% above) capacity of the transportation system to *anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring slight cost of recovery (0-£1,000)*

2. Strong (S)-- Strong (60-80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,000-£100,000)

3. Average (A)—Average (40-60%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring certain length of time (a week) and cost of recovery (£100, 000-£1million)

4. Weak (W)—Weak (20%-60) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)

5. Very Weak (VW)— Very weak (0-20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery(£10millions above)

It can be descried by the following three parameters. The worse-case scenario is applied to assess the system's resilience. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

Please describe each of the SEVEN items in the following question 12-15.

12. Temperature Increase

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
			PRO INJ ENV		
(a) Track buckling causing derailment risks & reducing opportunities for track maintenance (Adaptation Measure: Maintain tracks to narrower temperature tolerances, such as change to more resistant specifications)	______	______	__ __ __	______	______
(b) Track buckling increasing risk of derailment & reducing opportunities for track maintenance (Adaptation Measure: Impose speed restrictions at 'compromised' sites)	______	______	__ __ __	______	______

(c) Track buckling causing derailment risks

& reducing opportunities for track maintenance
(Adaptation Measure: Restrict ballast disturbance
activity during hot weather) ______ ______ __ __ __ ______ ______

(d) Track buckling causing derailment risks
& reducing opportunities for track maintenance
(Adaptation Measure: Paint rails white at
critical locations) ______ ______ __ __ __ ______ ______

(e) Unreliable signalling and power line side
systems, failure of temperature controls and
overheating of electronic equipment (Adaptation
Measures: Use active or passive cooling of
Equipment cabinets) ______ ______ __ __ __ ______ ______

(f) Unreliable signalling and power line side
systems, failure of temperature controls and
overheating of electronic equipment (Adaptation
Measures: Make use of high thermal inertia
design) ______ ______ ______ ______ ______

(g) Unreliable signalling and Power line side
systems & failure of temperature controls and
overheating of electronic equipment (Adaptation
Measures: Position cabinets in shade) ______ ______ __ __ __ ______ ______

(h) Unreliable signalling and Power line side
systems & failure of temperature controls and
overheating of electronic equipment (Adaptation
Measures: Re-specify and replace equipment)_____ ______ __ __ __ ______ ______

(i) Sag of overhead line & risk of dewirement
(Adaptation Measures: Strengthen mast and
wire system) ______ ______ __ __ __ ______ ______

13. Intense Rainfall /Flooding

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
(a) Bridge foundations become undermined			PRO INJ ENV		

leading to bridge collapse and derailment risk
(Adaptation Measure: Improve scour resilience
during routine renewal of scour protection
systems) ______ ______ __ __ __ ______ ______

(b) Bridge foundations become undermined
leading to bridge collapse and derailment risk
(Adaptation Measure: Design future bridges
to withstand climate change) ______ ______ __ __ __ ______ ______

(c) Bridge foundations become undermined
leading to bridge collapse and derailment risk
(Adaptation Measure: Introduce flood risk
monitoring linked to flood agency forecasts
and monitor river levels) ______ ______ __ __ __ ______ ______

(d) Landslips causing obstruction in cutting
Derailment risk (Adaptation Measure: Map
water concentration locations) ______ ______ __ __ __ ______ ______

(e) Landslips causing obstruction in reducing
Derailment risk (Adaptation Measure: Identify
and introduce resilience measures at vulnerable
sites, such as shaping to reduce slope angles)______ ______ __ __ __ ______ ______

(f) Landslips causing obstruction in cutting
Derailment risk (Adaptation Measure:
Vegetation management) ______ ______ __ __ __ ______ ______

(g) Landslips causing obstruction in cutting
Derailment risk (Adaptation Measure: Improve
earthworks and drainage management)______ ______ __ __ __ ______ ______

14. More intense and/or frequent high wind and/or storms

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
			PRO INJ ENV		
(a) Trees being blown on to the line (Adaptation Measure: Identify at-risk locations)	______	______	__ __ __	______	______

(b) Trees being blown on to the line (Adaptation Measure: Vegetation management) ______ ______ __ __ __ ______ ______

(c) Dewirement of overhead traction power lines (Adaptation Measure: Identify at-risk locations) ______ ______ __ __ __ ______ ______

(d) Dewirement of overhead traction power lines (Adaptation Measure: Strengthen existing equipment, at renewal stage if possible)______ ______ __ __ __ ______ ______

(e) Dewirement of overhead traction power lines (Adaptation Measure: Design new equipment with uncertainty in mind, making provision to retrofit or– if economically sound – build in resilience) ______ ______ __ __ __ ______ ______

15. Sea Level Rise

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences PRO INJ ENV	Likelihood	Climate Resilience
(a) Breach of sea wall, flooding and derailment risk (Adaptation Measure: Rebuild wall to appropriate standards)	______	______	__ __ __	______	______
(b) Breach of sea wall, flooding and derailment risk (Adaptation Measure: Introduce a sea level rise forecasting system)	______	______	__ __ __	______	______
(c) Overtopping waves damaging & affecting vehicles (Adaptation Measure: Rebuild wall to appropriate standards)	______	______	__ __ __	______	______
(d) Overtopping waves damaging & affecting vehicles (Adaptation Measure: Introduce a sea level rise forecasting system)	______	______	__ __ __	______	______

OTHER COMMENTS

16. Additional Comments:

THIS IS THE END OF THE SURVEY. THANK YOU VERY MUCH FOR YOUR TIME AND CONTRIBUTIONS!!

Reference

RSSB (2016). Further research into adapting to climate change - Tomorrow's Railway and Climate Change Adaptation (T1009 TRaCCA)

Dora. J. (2012). A Climate Change Report Card for Infrastructure Working Technical Paper Transport : Rail.

Network Rail (2015). Climate Change Adaptation Report. https://www.networkrail.co.uk/Climate-Change-Adaptation-Report.pdf

United Nations Economic Commission for Europe (2012). Climate change impacts and adaptation for international transport networks. United Nations Economic Commission for Europe Transport Division Experts Group, Annex IV: Questionnaire.

Appendix B2

Road Questionnaire

INFORM CONSENT

You are cordially invited to participate on the captioned research study conducted by the principal investigator, Tianni Wang, who is a Ph.D. student of Liverpool Business School of Liverpool John Moores University (UK), under the supervision of Dr. Zhuohua Qu. This project will be a significant part of Tianni's thesis. Understanding your experiences and prestige in this area, you are invited to participate in an online survey which will last for around 20 minutes.

Prior to your decision to participate, it is important that you understand why the research is being done and what it involves. Please take time to read the following information (the Participant Information Sheet and sign the Participant Consent Form). Please contact me if there is anything that is not clear or if you like some more information.

1. Participant's agreement

□ **I** understand to my satisfaction the information regarding participation in the project and agree to participate in this survey.

2. Date

DD/MM/YYYY ______/____ /_______

BACKGROUD INFORMATION

3. What is the name of your company/organisation? Which geographic areas of the roads are your company/organizations responsible for/operate on?

____

____

4. What is your current position at your company/organisation? (Optional)

☐ CEO or Transport Director

☐ Planner

☐ Transport Engineer

☐ Transport Operator

☐ Environmental Manager

☐ Public Relations Director

☐ Development Director

☐ Safety or Security Director

☐ Environmental Academics

☐ Other (please specify) ________________________________

5. In your view, what types of risks are posed by climate change on the rails your organisation associated with? (Please rank the following items which impacted your company; if not at all, please specify)

( ) High Temperature

( ) Sea Level Rise

( ) Flooding

( ) Precipitation Change

( ) High Winds

( ) Storm Surges

( ) Extreme Weather

( ) Snow

( ) Landslide

( ) Other (please specify) ________________________________

6. If the roads your company/organization are responsible for have been impacted by climate change in the past 10 years, please provide details including <u>road name</u>(s)(e.g., A1), years of occurrence and <u>main impacts.</u>

____

____

____

____

7. Has your company/organization made an adaptation plan for climate change?

□ Yes, we have implemented an adaptation plan

□ No, we have not implemented but we will consider an adaptation plan in the future

□ No, we have not, nor have any plans to implement a climate adaptation plan in the future

ADAPTATION STRATEGIES IN THE FUTURE

- **What climate change risks would you expect the roads be exposed to in the FUTURE if your company/organization does NOT undertake any ADAPTATION measures?**

Description of Variables

Timeframe *- when you expect to first see this impact:*

6. *Very Long (VL)--More than 20 years*

7. *Long (L)--Approximately 15 years*

8. *Medium (M)--Approximately 10 years*

9. *Short (S)--Approximately 5 years*

10. *Very short (VS)--Less than 1 year*

Severity of consequences *of this impact:*

Three subcategories are included— ***damage to properties (PRO), damage to injures and loss of lives (INJ) and damage to environment (ENV)***

The damage to properties (PRO):

1. *Catastrophic (Ca) -- the damage committed to property is valued at more than £2 millions*
2. *Critical (Cr) -- the damage committed to property is valued at more than £1million and less than £2 millions*
3. *Major (Maj) -- the damage committed to property is valued at between £500,000 and £1 million*
4. *Minor (Min) -- the damage committed to property is valued at between £100,000 and £500,000*
5. *Negligible (Neg) -- the damage committed to property is valued at less than £500,000*

The damage to injuries and loss of lives (INJ):

1. Catastrophic (Ca)-- major injures and loss of more than 10 lives

2. Critical (Cr) -- many major injuries or/and loss of 5 to 10 lives

3. Major (Maj) -- major injures and loss of less than 5 lives

4. Minor (Min) -- minor injuries and no loss of life

5. Negligible (Neg)--no injuries and no loss of life

The damage to environment (ENV):

1. Catastrophic (Ca)—the event contribute to over 50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations;

2. Critical (Cr)-- the event contributes to 30-50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

3. Major (Maj)-- the event contributes to 20-30% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

4. Minor (Min)-- the event contributes to 10-20% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

5. Negligible (Neg)-- the event contributes to less than 10% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

***Likelihood** that the effect will occur:*

1. Very High (VH)--It is very highly likely that the stated effect will occur, with a probability of around 90% of at least one such incident within the indicated timeframe

2. High (H)--It is highly likely that the stated effect will occur, with a probability of around 70% of at least one such incident within the indicated timeframe

3. Average (A)--It is likely that the stated effect will occur, with a probability of around 50% of at least one such incident within the indicated timeframe

4. Low (L)--It is unlikely that the stated effect will occur, with a probability of around 30% of at least one such incident within the indicated timeframe

5. Very low (VL)--It is very unlikely that the stated effect will occur, with a probability of around 10% of at least one such incident within the indicated timeframe

Climate Resilience*: the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (IPCC, 2012)*

1. Very Strong (VS)—Very strong (80% above) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring slight cost of recovery (0-£1,000)

2. Strong (S)-- Strong (60-80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,000-£100,000)

3. Average (A)—Average (40-60%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring certain length of time (a week) and cost of recovery (£100, 000-£1million)

4. Weak (W)—Weak (20%-60) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)

5. Very Weak (VW)— Very weak (0-20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery(£10millions above)

It can be descried by the following three parameters. The worse-case scenario is applied to assess the system's resilience. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

Please describe each of the SIX items in the following question 8-11.

8. Temperature Increase

	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
		PRO INJ ENV		
(a) Extended warm weather can cause pavement deterioration due to liquidation of bitumen, heating and thermal expansion of bridges and buckling of joints of steel structure	______	__ __ __	______	______

9. Intense Rainfall /Flooding

	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
(a) Increased intensity of summer and winter precipitation create floods, affects drainage, road pavement, driving condition and visibility.		PRO INJ ENV		
(b) Rainfall can affect bridges, culverts waterways	_______	__ __ __	_______	_______
and clearance, and damages bridges and culverts foundation due to scouring	_______	__ __ __	_______	_______
(b) Rainfall can trigger landslides and mudslides in mountainous roads, and create road blocks	_______	__ __ __	_______	_______

10. More intense and/or frequent high wind and/or storms

	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
(a) Rainfall and winds associated with storm cyclone can create flooding, inundation of embankments, and affect road transport	_______	PRO INJ ENV __ __ __	_______	_______
(b) Disrupt traffic safety and emergency evacuation operations, affect traffic boards and information sign	_______	__ __ __	_______	_______

11. Sea Level Rise

	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
(a) Rise in sea level will affect coastal roads, may be need to realign or abandon roads in affected areas	_______	PRO INJ ENV __ __ __	_______	_______

- **Also, how do you anticipate the climate risks will change in the FUTURE if your company/organisation undertakes the planned ADAPTATION measures? (If your company/organisation will not undertake any adaptation measures, please skip this part)**

Description of Variables

***Financial cost** of adaptation:*

1. <u>Very High (VH)</u>--involves a very high financial cost so as to comprehensively address the stated potential effect

2. <u>High (H)</u>--involves a high financial cost so as to comprehensively address the stated potential effect

3. <u>Average (A)</u>--involves a significant financial cost so as to comprehensively address the stated potential effect

4. <u>Low (L)</u>--involves a financial cost (though not that significant) so as to comprehensively address the stated potential effect

5. <u>Very low (VL)</u>--involves a minimal financial cost so as to comprehensively address the stated potential effect

***Severity of consequences** of this impact:*

*Three subcategories are included— **damage to properties (PRO), damage to injures and loss of lives (INJ) and damage to environment (ENV)***

The damage to properties (PRO):

1. <u>Catastrophic (Ca)</u> -- the damage committed to property is valued at more than £2 millions

2. <u>Critical (Cr)</u> -- the damage committed to property is valued at more than £1million and less than £2 millions

3. <u>Major (Maj)</u> -- the damage committed to property is valued at between £500,000 and £1 million

4. <u>Minor (Min)</u> -- the damage committed to property is valued at between £100,000 and £500,000

5. <u>Negligible (Neg)</u> -- the damage committed to property is valued at less than £500,000

The damage to injuries and loss of lives (INJ):

1. <u>Catastrophic (Ca)</u>-- major injures and loss of more than 10 lives

2. <u>Critical (Cr)</u> -- many major injuries or/and loss of 5 to 10 lives

3. <u>Major (Maj) --</u> major injures and loss of less than 5 lives

4. <u>Minor (Min) --</u> minor injuries and no loss of life

5. <u>Negligible (Neg)</u>--no injuries and no loss of life

The damage to environment (ENV):

1. Catastrophic (Ca)—the event contributes to over 50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations;

2. Critical (Cr)-- the event contributes to 30-50% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

3. Major (Maj)-- the event contributes to 20-30% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

4. Minor (Min)-- the event contributes to 10-20% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

5. Negligible (Neg)-- the event contributes to less than 10% of the total amount of potential damage to be caused to the surrounding environment for whole the period of industrial operations

***Likelihood** that the effect will occur:*

1. Very High (VH)--It is very highly likely that the stated effect will occur, with a probability of around 90% of at least one such incident within the indicated timeframe

2. High (H)--It is highly likely that the stated effect will occur, with a probability of around 70% of at least one such incident within the indicated timeframe

3. Average (A)--It is likely that the stated effect will occur, with a probability of around 50% of at least one such incident within the indicated timeframe

4. Low (L)--It is unlikely that the stated effect will occur, with a probability of around 30% of at least one such incident within the indicated timeframe

5. Very low (VL)--It is very unlikely that the stated effect will occur, with a probability of around 10% of at least one such incident within the indicated timeframe

***Climate Resilience**: the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (IPCC, 2012).*

It can be descried by the following three parameters. The worse-case scenario is applied to assess the system's resilience. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", *then the final assessment result should be "Weak".*

1. <u>Very Strong (VS)</u>—Very strong (80% above) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring slight cost of recovery (0-£1,000)
2. <u>Strong (S)</u>-- Strong (60-80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,000-£100,000)
3. <u>Average (A)</u>—Average (40-60%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring certain length of time (a week) and cost of recovery (£100, 000-£1million)
4. <u>Weak (W)</u>—Weak (20%-60) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)
5. <u>Very Weak (VW)</u>— Very weak (0-20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery(£10millions above)

Please describe each of the SEVEN items in the following question 12-15.

12. Temperature Increase

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences			Likelihood	Climate Resilience
			PRO	INJ	ENV		
(a) Extended warm weather can cause pavement deterioration due to liquidation of bitumen, heating and thermal expansion of bridges and buckling of joints of steel structure (Adaptation Measure--Pavement: use of stiff bitumen to withstand heat in summer, soft and workable bitumen with solvent in winter, control of soil moisture and maintenance planning)	______	______	__	__	__	______	______

(b) Extended warm weather can cause pavement deterioration due to liquidation of bitumen, heating and thermal expansion of

bridges and buckling of joints of steel structure
(Adaptation Measure-- Steel bridges: selection
of material, provision of expansion joints and
corrosion protection) ______ ______ __ __ __ ______ ______

13. Intense Rainfall /Flooding

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences PRO INJ ENV	Likelihood	Climate Resilience
(a) Increased intensity of summer and winter precipitation create floods, affects drainage, road pavement, driving condition and visibility, affects bridges, culverts waterways and clearance, and damages bridges and culverts foundation due to scouring (Adaptation Measure-- Bridges and culverts: flood estimation, return period, design discharge, high flood level, clearance above high flood level, length of waterway, design load, wind load, foundation, river and bank protection, and corrosion protection)	_____	______	__ __ __	______	______
(b) Increased intensity of summer and winter precipitation create floods, affects drainage, road pavement, driving condition and visibility, affects bridges, culverts waterways and clearance, and damages bridges and culverts foundation due to scouring (Adaptation Measure-- Drains: discharge estimation, size and shape of drains, and catch drains)	______	______	__ __ __	______	______
(c) Rainfall can trigger landslides and mudslides in mountainous roads, and create road blocks (Adaptation Measure-- Mountainous road: slope protection work, subsurface drains and catch drains)	______	______	__ __ __	______	______

(d) Rainfall can trigger landslides and mudslides in mountainous roads, and create road blocks (Adaptation Measure-- Pavement: increase road surface camber for quick removal of surface water, frequency of maintenance, design of base and subbase, and material selection) ______ ______ __ __ __ ______ ______

14. More intense and/or frequent high wind and/or storms

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
			PRO INJ ENV		
(a) Rainfall and winds associated with storm cyclone can create flooding, inundation of embankments, and affect road transport (Adaptation Measure--Drains and cross drains: enhance capacity in managing slope)	______	______	__ __ __	______	______
(b) Rainfall and winds associated with storm cyclone can create flooding, inundation of embankments, and affect road transport (Adaptation Measure-- Road embankment: increase the height of embankment)	_____	______	__ __ __	______	______
(c) Disrupt traffic safety and emergency evacuation operations, affect traffic boards and information signs (Adaptation Measure-- Road signs: wind load, structural design, foundation and corrosion protection)	______	______	__ __ __	______	______

15. Sea Level Rise

	Financial Cost Of Adaptation	Timeframe	Severity of Consequences	Likelihood	Climate Resilience
			PRO INJ ENV		
(a) Rise in sea level will affect coastal roads, may be need to realign or abandon roads in affected areas (Adaptation Measure--Coastal road: protection wall, additional warning signs, realignment of road sections to higher areas, and edge strengthening)	______	______	__ __ __	______	______

OTHER COMMENTS

16. Additional Comments:

THIS IS THE END OF THE SURVEY. THANK YOU VERY MUCH FOR YOUR TIME AND CONTRIBUTIONS!!

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Appendix C

Basic Information of Interviewees

Interviewee	Position	Organization	Interview Date
Interviewee 1	Middle	Highways England	January 26th 2018
Interviewee 2	Middle	Network Rail	April 6th 2018
Interviewee 3	Senior	Transport for London	January 17th 2018
Interviewee 4	Middle	Environment Agency	February 1st 2018
Interviewee 5	Senior	Devon County Council	February 8th 2018

Remarks: " Senior" means policy maker, transport planner, etc.

" Middle" means environmental specialist, climate adaptation advisor/manager, etc.

Appendix D

Interview Framework

Part A. Identifying the vulnerabilities of road and rail posed by climate change

A1. There is a variety of vulnerabilities that climate change posed or probably to your company/organisation and relevant stakeholders (e.g., higher temperature, flooding, storm, high winds and sea level rise). What kind of risks are your main concerns in your road/rail planning?

A2. Have you had corresponding adaptation plans to cope with above risks? If so, could you introduce this plan (or these plans) in terms of the time horizon, the participants and the effects of these plans, etc.? If not, are you going to develop one in the future? And why? What are the main factors restrained the implementation of adaptation plan?

A3. Are there any other potential threats or uncertainties on your company/ organisation due to the climate change? Have you considered these uncertainties at all? Will you take adaptation plans to minimise them in the future? If so, what type of resources will you use to identify, forecast and assess these uncertainties? If not, why do you think it is unnecessary and what would be the barriers in an adaptation plan (e.g., the policy, financial budget)?

A4. In coping with these impacts posed by climate change, there are two main methods: adaptation strategies and mitigation strategies. What's the main strategy in your current road/rail planning? Do you think that it is different with the plans of ten years ago? And would it be changed in the future (a long term plan)?

A5. Currently, there are more attentions placed on mitigation strategies than adaptation strategies. What are the possible reasons do you think? And do you think an adaptation plan is urgent from the perspective of global level and local level? Why do (or don't) you think so?

Part B. Risk assessment and planning priority

B1. As a company/organisation already had (or will have) an adaptation plan, what are your main priorities, the most pressing issues should be addressed in a short term? How do you (or will you) define and assess these priorities (e.g., by collecting the scientific data, evaluating the opinions of stakeholders or participants)? Which channel do you think should be put into the priority?

B2. Similarly, what kind of issues do you think are lower priority/risk, which can be coped with in a longer term? Why do you think so? And when do you think that they should be considered and why?

B3. Do you have a risk analysis system in assessing vulnerabilities posed by climate change? If so, could you introduce their applications? (e.g., what are evaluation indicators? Have they achieved your expected effects? Who are the participants in this assessment?) In addition, how did they (or will they) contribute to the adaptation plan?

B4. In an adaptation plan, which principles do you think are fundamental, namely could not be affected by external parties' opinion? Are they consistent with surrounding environment at all (e.g., the public policy, transportation plan, benefits of stakeholders)? If not, why not? And how could you minimise the inconsistences?

Part C. Recognising the characteristics and differences of road/rail's condition

C1. As a relatively new challenge, there is lacking exact planning pattern in adaptation strategies. Thus, for your road/rail planning, do you (or will you) borrow the advanced experiences from other company/ organisation? What are your main accesses to get this information (e.g., journal articles, workshops, websites, and professional consultants)? Also, are there any local references (e.g., local research and consulting reports) can be used to develop your road/rail adaptation plan? If so, what are these local references? Are they accessible and applicable to your road/rail's reality?

C2. Following the above question, do you think there is different research in international, national and regional level on adaptation strategies? If so, what are the differences? Which parts' value do you (or will you) place more importance?

C3. What are strengths and (or) weaknesses of your company/organisation in developing an adaptation plan? How do you (or could you) localise these higher level knowledge into your road/rail's practice?

Part D. The preparation, environment and stakeholders involving an adaptation plan

D1. What attributes do you think facilitate an adaptation plan (e.g., the requirement of government policy, the demand of road/rail's operation)? Do you think that adaptation plan is a practical action or just engaging in idle theorising? Why do you think so? What type of supports would be given to improve or change this situation?

D2. Who does (or will) involve in the adaptation plan (e.g., roadway/railway undertakings, government, local authorities, tax payers, freight users, interest groups, NGOs, consultants, etc.)? Are there trade-offs among different parties? What roles did (or will) they play (e.g., consulting, drafting, decision-making)?

D3. Which parties' opinion do you (or will you) put into the top list? How do you (or will you) balance the various benefits in decision-making?

D4. In implementing an adaptation plan, what kind of supports do you (will you) get from high level of your company/organisation, institutions, and national and international society? And anything else do you think should be added?

Part E. Implementing an adaptation plan and developing adaptation strategies

E1. What is the time horizon do you think for your road/rail's adaptation strategies (e.g., 5, 10, 20, 50, or more)? Are there any specific reasons or reference to design this time-span (e.g., make a reference from your Transportation Plan, the experience of other road/rail plan, financial plan or infrastructural conditions)?

E2. In what conditions do you think adaptation strategies are successful? What factors will affect the achievement of adaptation strategies? Could you list them out and provide a general ranking?

E3. In your opinion, to what extent do "financial constraint", "Transport Plan", "public opinion" and other factors affect the development of adaptation strategies in your adaptation plan? Why do you think so? Could you give me some examples?

E4. Do you make references to your established planning norms, practices and experiences (e.g., existing laws and policies to assess environmental and climate change impacts, existing environmental guidelines, transport, climate change and adaptation related projects in being implemented , and regional transportation and environmental plans)? If so, how will they impact the adaptation strategies of your company/organisation?

E5. Up to now, there is rare rule, regulation and guideline for developing an adaptation plan. How do you think this situation? What could be done to improve it? In addition, there is a relative shortage of public participants, what's the situation of your road/rail adaptation plan? How do you (or will you) ensure a relatively high participant rate and guarantee that your adaptation strategies are acceptable to the staff of your company/organisation and public?

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