Climate Change Research on Transportation Systems: Climate Risks, Adaptation and Planning

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With the occurrence of more frequent and intense climate change events, transportation systems, including their infrastructure and operations become increasingly vulnerable. However, the existing research related to climate risks, adaptation and planning in the transport sector is still at an embryonic stage. Understanding such, this paper presents a critical review on climate risks, adaptation strategies and planning in the context of road and rail transportation systems. It aims to conduct a rigorous survey, to highlight any significant research gaps not addressed in past studies and to analyse current emerging topics to guide future directions. It critically dissects the selected papers by categorising them into several dimensions to reveal the status quo and potential challenges, including climate risk assessment, transport asset management, climate planning and policy, and adaptation of transport infrastructure to climate change. It will provide valuable references for future research and constructive insights and empirical guidance on climate adaptation, risk analysis, transport planning and other important relevant topics.

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1. Introduction

Climate change has been an interdisciplinary frontier study. The transport infrastructure and operations are seriously threatened and challenged by the existing variability in climate. Scholars have proposed adaptation measures and strategies to tackle the climate risks on ports, railways and roads, and applied them to different geographical locations and regions (e.g. Strauch et al., 2015; Dobney et al., 2009; 2010; Ng et al., 2018; Wang et al., 2018a; 2018b; 2019b). It is the time to conduct a rigorous survey on the studies to find the lessons learnt for cross-referencing among different transport modes and explore prominent research challenges to shift the research focus to the most relevant emerging topics. Therefore, this study conducts a comprehensive review on climate adaptation of transportation systems based on relevant prestigious journal papers in the past decade. It aims to elaborate important theories and practise with a new classification method to present climate adaptation research in transportation areas with reference to diverse key topics. Meanwhile, it contributes to reveal the research gaps and guide research directions in future through statistics of the relevant studies and in-depth qualitative analysis.

According to the definition from the Fourth Assessment Report of IPCC (2007), 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, 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, such as the reduction of GHGs from the transport sector to the air (e.g., Kishimoto et al., 2017; Hendricks et al., 2018).

Given that climate change is an irreversible process, posing destructive threats to human well-being (Keohane & Victor, 2010), the relevant strategies in response to climate change tend to combine mitigation and adaptation rather than pure mitigation (Ng et al., 2016). Climate change studies in the context of transportation are not exceptional from such a tendency. Hence, this paper undertakes a systematic investigation by comprehensively analysing the state of art of research, with an emphasis on the impacts of climate change to transportation systems (i.e. road and railway), risk assessment as well as the corresponding adaptation and planning issues. This 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.

This novelty of this work is twofold. First, although a notable few of review studies regarding climate adaptation in transportation sector has been conducted (e.g., Eisenack et al., 2012; Koetse & Rietveld, 2012), the papers were written about 10 year ago and the information does not contain the development of the relevant research in the past decade, which is the fastest development period in terms of the total number of the published papers. More importantly, the existing work in the literature fails to analyse the studies based on critical dimensions, such as climate risk assessment, asset management and other issues during the implementation of adaptation planning. This paper conducts a comprehensively review of the state-of-the-art data of climate adaptation in transport sector. By systematically dissecting the trends of existing research and key research themes, it reveals the research gaps and emerging topics to offer possible research directions and suggestion in future. Second, some systematic reviews in recent years focused on seaport and airport adaptation to climate change (Poo et al., 2018; Becker et al., 2018), there is no comprehensive review on road and rail transport. This paper conducts critical review on climate risks, adaptation strategies and planning in the context of road and railway systems, which will facilitate the collaboration and engagement of diverse stakeholders in the inland and multi-mode transport during the process of adaptation planning.

After this introduction section, Section 2 indicates the approach used to conduct this state-of-the-art survey. Section 3 presents the survey results with respect to the overall trend of research by published years and journals, geographic locations and co-authorship, research methods and themes. Furthermore, in Section 4, we critically analyse the selected papers by categorising them into six dimensions: climate impacts on rail/road transportation, climate risk assessment, climate change and asset management, climate planning and policy, transportation adaptation to climate change and others. The implications suggesting future research directions on climate risk and adaptation planning are described in Sections 5. Finally, Section 6 concludes this paper.

2. Methodology and scope of the review

A systematic assessment on the research papers regarding 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 (Colicchia & Strozzi, 2012; Lau et al., 2013), this review work is conducted inn two steps: 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 identify how the knowledge is generated, transferred and developed.

The systematic literature review consists of three phases, namely, "Question formulation", "Locating studies", and "Study selection and evaluation" (Rousseau et al., 2008). Firstly, the authors defined the scope of this research according to 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 defined as climate change, adaptation and transportation. Initially, through a brainstorming process, the 12 keywords were identified, including climate change, impacts, risks, adaptation, planning, policy, transportation, road, rail, asset management, risk analysis and risk assessment. A team containing three scholars and two practitioners in the transportation field refined these keywords to provide sound validity. To avoid too generic and extensive results, the keywords were combined 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 authors identified the relevant papers by utilising the database of Web of Science as one of the foremost comprehensive academic search platforms (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 their substrings) were chosen as 'keywords'. Then, we combined all the searching results 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 significantly increases. Hence, we took year 2005 as a threshold and surveyed the published articles from 2005 to 2018. In total 192 articles were retrieved from 75 academic journals in subjects of business, management, transportation, economics and engineering. Only papers written in English were collected and reviewed.

Next, we thoroughly reviewed all the 192 articles including some cross referencing which could be traced back to 1990s. To guarantee the quality and relevance of the reviewed papers, we carefully screened them 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, abstracts and keywords 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 a label or subtopics 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 research has been refined to include 100 peer-reviewed journal papers.

At the second stage, we 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 3.3. By examining the research papers by this systematic approach, we seek to investigate the evolving pattern during the period of 1970-2018 to reveal the research gaps and stimulate novel exploration.

3. Trends in Climate Change and Adaptation Research on Transportation Systems

3.1. Evolution of paper numbers and top journals

A critical review has been conducted with regards to the identified 100 papers, addressing a variety of aspects such as climate risks, adaptation planning and policy, 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, and how the research themes have evolved over time in this subject.

The distribution of the reviewed papers based on the timeline 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 2011. The generation rate of these paper was about 3.4 each year before 2012 compared to 12.6 papers per year between 2012 and 2018. The number of papers peaked in 2015 when 16 were published. This is a strong indication of the growing interests in this research topic.

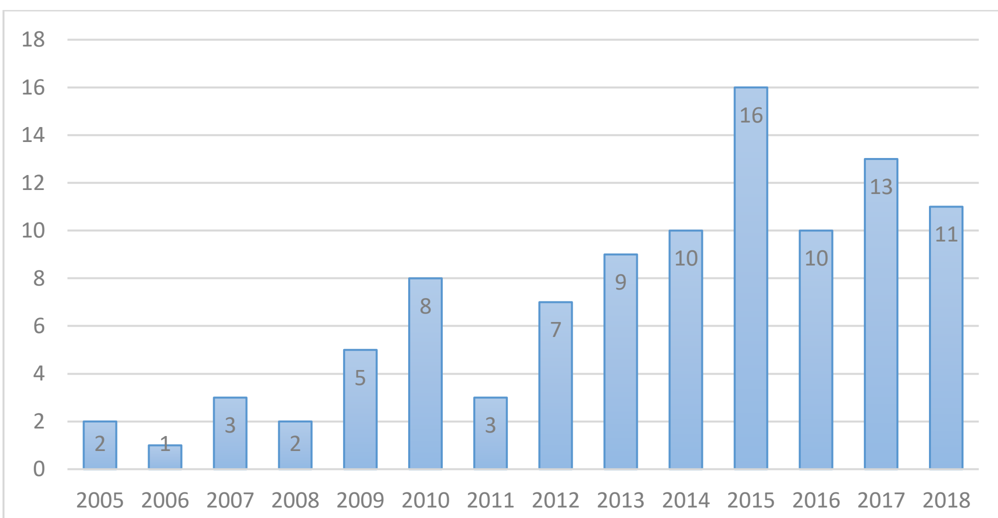


Figure 1. Distribution of papers by published year (January 2005 - December 2018)

The top journals that published most articles in the literature review are listed in Table 1. Among them, the pivotal source of articles is Transportation Research Record, 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 occupied approximately two-thirds of the papers reviewed. It is noticeable that the top journals are multifaceted, involving the subjects of transportation, climate change, risks, policy and geography.

Table 1. Top five journals of climate adaptation research on transportation (January 2005 to December 2018)

No.	Journal Title	No. of Articles
1	Transportation Research Record	11
2	Transportation 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

3.2 Evolution of the geographic location and co-authorship

The popularity of climate change and adaptation research on transportation in a typical country can be interpreted by the number of researchers (i.e. authors) from that country. In the reviewed articles, the researchers were mainly from 13 countries according to the locations of their institutions. Figure 2 elaborates the regional distribution regarding the researcher numbers in each continent over the past decade. Overall, the North American (27%) and European (25%) researchers were the main forces on climate adaptation research in transportation. The unknown category implies some international collaboration or work without geographic features. In particular, before 2012, the relevant research was only conducted in a few countries within North America and Europe, and the number of researchers was meagre. Since then, more papers were generated and geographically extended to Australia, South America, Asia and Africa. It has been observed that European and North American scholars dominated this research field during 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.

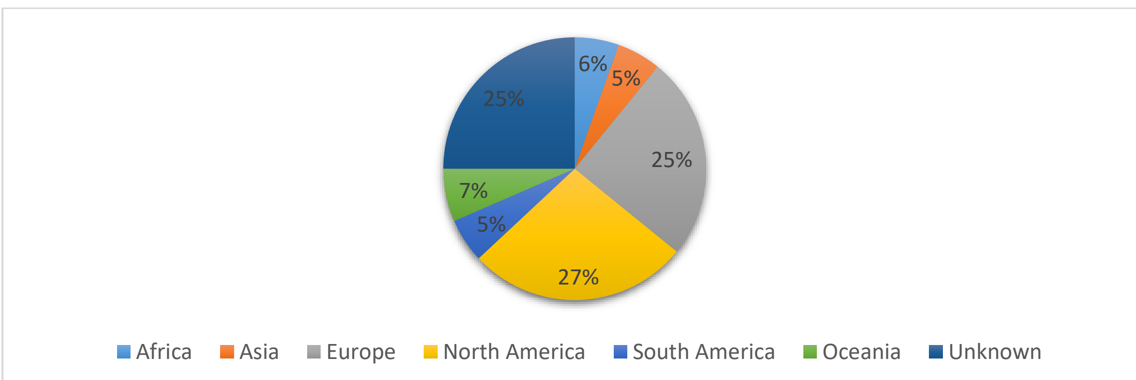
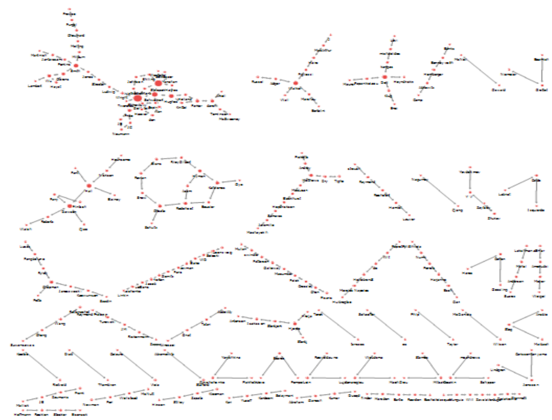


Figure 2. Distribution of articles by geographic location (January 2005 to December 2018)

Furthermore, the co-authorship analysis of scientific collaborations was applied in this paper. It served to extract useful information related to the existence of communities (clusters) of various types in a co-authorship network and investigate their emerging factors (e.g., linguistics, geography, and/or disciplinary proximity)(Newman, 2004), and to reveal the general structure of the collaboration pattern from fragmentation to cohesion (Newman, 2010). Indeed, we measured the scientific collaborations of not only the individual authors but also the authors who write together, ignoring the authors' order or role (e.g., first author or corresponding author), in order to capture the linkages among the researchers. By doing so, the results of co-authorship are illustrated by a mapping graph, in which links (edges) are as the co-occurrence of multi-author in the same paper and graph nodes (vertices) are as authors.

Figure 3(a)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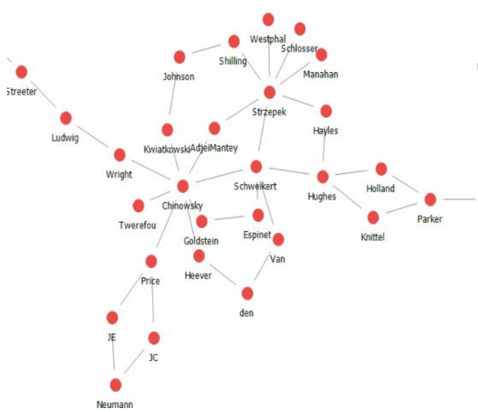

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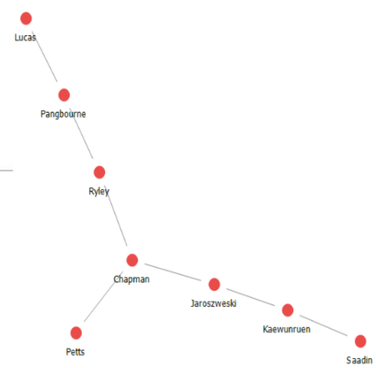

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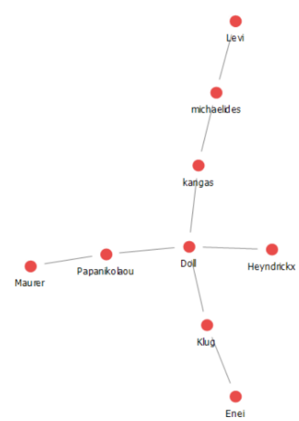

Figure 3(e)

Figure 3(a-e) Key network of the co-authorship in published articles (January 2005 to December 2018)

Figure 3 visualises the network of the co-authorship across the research of climate change and adaptation in the transportation field. The data was manipulated by NetMiner 4.3 (Cyram, 2017), which is an efficient tool in social network analysis for visualising the data's unique feature and level of integration in large-size networks. In Figure 3(a), the size shown by the author's name indicates the total number of the papers he/she has published in the field. Figure 3(b) elaborates the overview of the collaborative network of the co-authorship, while Figure 3 (c-e) enlarges the three key networks to show more detailed relevant information.

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 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 of 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 countries and gradually extended to other regions.

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, simulation, mathematical modelling and others (e.g. Sachan & Datta, 2005). The category of 'others' encompassing descriptive research and perspectives from industries, mainly refers to qualitative methods. Figure 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 39% of the total publications. Together with the review articles and others, the papers using the qualitative research methods made up 68% of the total, while those using the quantitative research methods, including survey, simulation and mathematical modelling, only accounted for 32% of the total publications. Among the 32% quantitative studies, the majority used surveys such as the evaluation of adaptation measures in the transport sector by surveying a group of experts (Stamos et al., 2015). The remained were conducted based on simulation including the CLIMATE-C (Maoh et al., 2008) and mathematical modelling including the general circulation models (Schweikert et al., 2014).

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, we counted twice each categorised method.

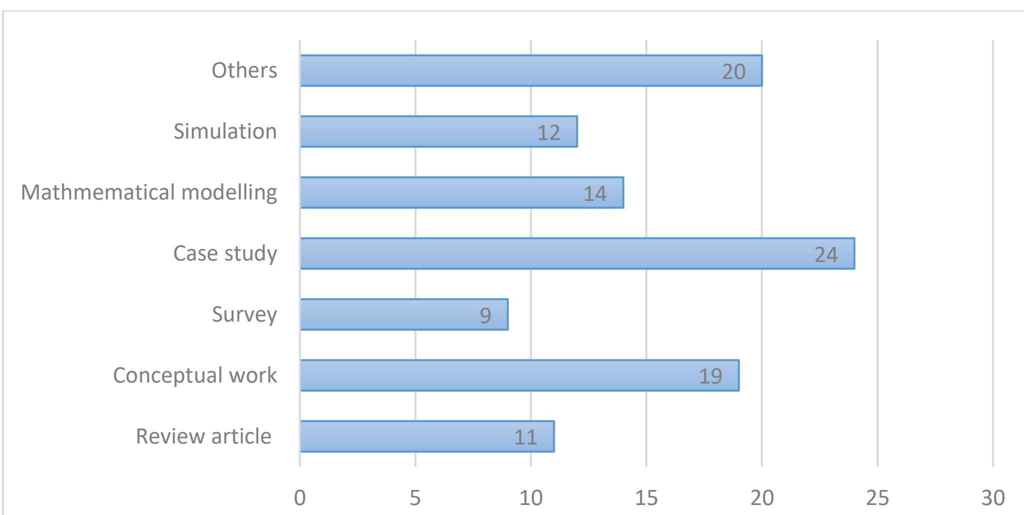

Figure 4. A categorisation of papers based on research methods

The semantics analysis was applied to categorise the selected work based on different themes, by which scholars were searched for emerging ideas and tendency within large corpuses (Knuth, 1993; Ferrer et al., 2001). In this paper, we started analysing the titles and abstracts of the selected papers, as they can best summarise the main themes of the articles through elaborating readers the first information before reaching the rest of the work (Lau et al., 2017). After that, we examined the corpuses through a full-text review. Accordingly, the selected papers were categorised into six dimensions based on diverse subjects of the research: climate risks on rail/road transportation, climate risk assessment, climate change and asset management, climate planning and policy, transportation climate adaptation on transportation, and others. Figure 5 depicts the number of papers in each dimension. A summary of context analysis by research themes is shown in Table 2, while its details are presented in Section 4.

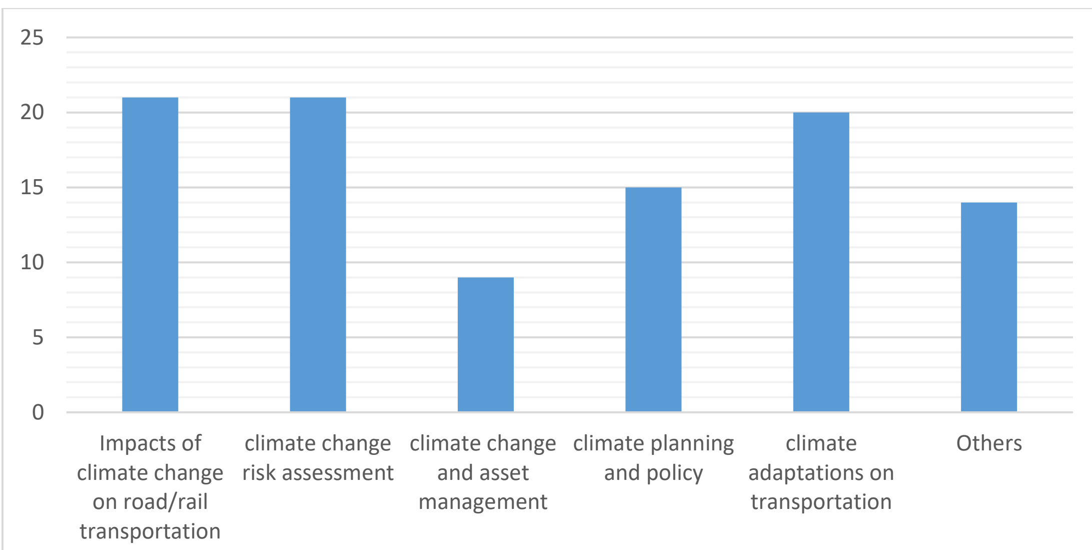

Figure 5. A categorisation of papers based on research themes (January 2005 to December 2018)

Table 2. Critical analysis by research themes

Themes	Context	Gaps
Climate impacts on rail/road transportation	Research has been maturely developed at a national and multi-regional scale (i.e., some developing countries).	Little research appeared in the public domain; the majority of studies was primarily focusing on the specific regions and transport modes.
	The US road system: climate stressors, impacts and adaptation cost analysis	Climate change has not been taken into consideration in all the 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, more attention has been attracted; mainly focusing on road freight.
	Asia: threats posed by climate change on road infrastructure and building infrastructure in Asian countries (e.g. Vietnam)	Research mainly focused on railway infrastructure; how climate would change in the future, especially at a local level remains uncertain; requiring nationwide analysis 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 and institutional dimensions) have not been well addressed; insufficient attention on particular types of climate change events and/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 visualisation techniques; sensitivity matrix; Building Information Modelling (BIM)	Data limitation; inadequate treatment of risk; lack of sufficient financial resources; uncertain demands in future system
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 been sufficiently translated into actions; focusing on the 'proofing' of infrastructure 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: primary focus on physical infrastructure, roadways and railways, a set of case studies and top-down policy pattern	Existing literature is too vague or focuses on general principles and overly detailed technical adaptation measures; much knowledge for adapting to climate change remains unclear; research is relatively scattered, without dominant theories, themes and journals, current transportation investment and planning could not address climate change impacts adequately; lacking of access to financial resources.

4. Critical review results by research themes

4.1. The impacts of climate change on transportation

The transport-related activities are vulnerable to heterogeneous weather extremes, which include but not limited to changes in temperature, winds, rainfalls, sea-level and other-water levels, visibility and fog period, thunderstorms, thaw and frost (e.g., Schweikert et al., 2014; Wang et al., 2019b). The climate change impacts could be further magnified because those 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 categorised in Table 3.

Table 3. Summary of the impacts of climate change on transportation

Climate parameters	Categories	Impacts
Precipitation	Flooding, freezing and liquid precipitation, snow, liquid precipitation, perceptible water vapour, water body depths and soil moisture	Delays and reduced speeds; loss of control and traction; pressures on tyres and components of vehicles; flooding induced road and highway closures; re-routing; wet road surface; uneven or break braking; roadbed scouring; railroad beds softening; smoke or dust reduced visibility due to drought barge shutdowns due to lower water levels
Temperature	Surface and air temperature, heat index, heating and cooling degree periods and the first occurrence of season	Stresses on infrastructure and vehicle components, perishable cargoes, and rail buckling; reduced rail speeds; new routes in northern areas; cost reduction and safety improvement due to the milder winter
Sea Level	Unusual low and high tides, tropical cyclones, storm surge, sea ice of open-water, sea state, hurricane winds, sea and wind wave height	Road and railway closures; disruptions of whole supply chain; diverse damage to vehicles and infrastructure; obstructions on blocked rails; extreme water levels owing to sea level rise (SLR); changing shipments; risk and damage to infrastructure; opening of a possible commercial pathway

Thunderstorm	Lightning, severe storm cell tracks and hail	Infrastructure damage; railroads blocking; loss of control induced fast changing conditions with different threats of damage and collisions ; visibility influences; rock slides induced threats of collisions and delays
Winds	Wind speed	Vehicle instability, loss of control and re-routing; blow-overs
Visibility	Restrictions due to fog, dust, haze, sun glare and smog, and upper atmosphere restrictions due to desert dust and volcanic	Risk of damage and collisions; reduced speed; re-routing; schedule delays

Source: Adopted and processed from the analysis of multiple articles (e.g., Peterson et al., 2008; McGuirk et al., 2009; Love et al., 2010)

Climate impacts have widespread implications for transport design, planning, operations, material specifications, maintenance, network and vehicle function, with several studies in the public domain (i.e., Taylor & Philp, 2010; Hooper, 2013; Meyer et al., 2014; Chinowsky et al., 2015a; Olmsted et al., 2017). There has been relevant research conducted at a national and multi-regional scale. Meanwhile, the majority of research papers about the climate impacts on transportation are primarily focusing on the specific transport modes, typically on the road, rail and ports. In reality, climate impacts on transport infrastructure vary on the different transportation modes, geographic locations and conditions of event occurrence (Suarez et al. 2005).

4.2. The risk assessment for climate change

A considerable number of methods and practices have been developed in recent years for identifying 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 climate threats on bridges, roads and coastal development as well as urban drainage infrastructure. Four models were synthesised to assess vulnerabilities and the efficiency of corresponding measures. A regional travel demand model was proposed by Kim et al (2018) to evaluate the risks of flooding affecting an urban transportation system 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 SLR on the eight beaches in Australia. Alirezaei et al. (2017) focused on road safety, using a system dynamics method to model the economy nexus between climate change and road safety and investigated the interactions amongst these essential areas. Five sub-models were then generated to test each dimension of the 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, concerned on climate impacts on winter roads. Mullan et al. (2016) stated that there was a tendency towards thinner lake ice and a less time window when lake ice was thick enough to support trucks on the Tibbitt to Contwoyto Winter Road (TCWR). Assessed by three climate models, a clear trend towards winter warming effects on TCWR required decision-makers to consider future climate conditions in annual haulage planning. 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 meteorological stations and maintenance records and the WSI model, users can better interpret how winter weather is 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 threats on road pavement performance (Qiao et al., 2015). The binary non-linear programming was utilised to optimise intervention strategies to minimise the associated costs (i.e. agency costs/total costs). Accordingly, the differences in road maintenance planning and LCC under diverse 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 over 50 potential climate futures by general circulation models, Schweikert et al. (2014) assessed the cost caused by climate change in South Africa. Similarly, Twerefou et al. (2015) estimated the economic impact of climate change on road infrastructure in Ghana. Such analysis reveals that 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 at an initial planning stage.

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. 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 impacts on infrastructure, macroeconomic models are suggested to 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).

4.3. Climate change planning and policy

The principles and practice of planning are essential factors in adapting to climate change impacts complementary to the design, operations and maintenance of transport infrastructure (Taylor & Philp, 2010). Climate change has been considered from the perspectives of national and regional transportation planning and policy-making. However, the existing references are relatively scattered and tend to only 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, while the results revealed the existence of institutional barriers in several case studies (e.g., Taylor & Philp, 2010; Bache et al., 2015; Hrelja et al., 2015).

One of the key perspectives 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 polices for transportation sector, namely, ethanol subsidies, cap and trade, as well as low-carbon and renewable fuel standards. Boarnet (2010) stated that combining pricing and land use regulation could effectively minimise the GHG emissions, with relationship between land use and travel behaviour or distance being identified in the past decade (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 other energy tax, on the both economy and transport sector in Malaysia. Climate change also requires re-orientation of spatial planning, shifting attention to potential pathways (Wilson & Piper, 2010). However, existing planning in climate policy seems to play a limited role for transitions of climate change. In other words, the expected goals and capacity of policy for climate change have not been sufficiently translated into actions (e.g., Biesbroek, et al 2009; Preston et al., 2011; Romero-Lankao, 2012). For instance, Hrelja et al. (2015) analysed the ability of spatial planning in supporting local transitions of climate change to realise sustainable transportation by utilising two Swedish cases. Bache et al. (2015) examined how the UK government's headline on climate change targets were translated into action in the regional transport sector. The symbolic meta-policy led to little action on the ground and only served political goals with insufficient practical values.

Newman et al. (2013) stressed the concept of policy capacity, which reflected the officers' ability to provide and deliver practical advice to political decision-makers effectively. Policy capacity has received a renewed interest in recent years, as a pivotal element in the policy cycle on transportation sectors (e.g., Edwards, 2009). However, there are incompatible matches between the established goals of transportation sector and current goals of climate action, leading to a particular administrative constraint called policy layering (Kern & Howlett, 2009). To enhance the policy capacity, they suggested to give politicians more institutional support to generate viable climate strategies, and appropriate solutions to help counter these institutionalised constraints.

In the latest decade, market-based mechanism is increasingly attracting much attention in climate adaptation planning and policy making. The market-based climate policies have been recognised as efficient approaches for regarding GHG emissions (e.g., carbon taxes, emission-trading systems, cap and trade, and standards of clean energy) in the case of the US (Aldy & Stavins, 2012). Nevertheless, this circumstance may not fit other markets (e.g., small countries) as argued by Ergas

(2012). This is because that the successful implementation of the market-based mechanism is on the basis of a series of premises, including long-term commitments on technological innovation, legal updating and international agreement. In the absence of these premises, the profits of investment of these instruments cannot be guaranteed. Meckling & Jenner (2016) discussed the two types of market-based environmental policies, where price and quantity instruments were usually utilised by European and American governors respectively. A hybrid policy mixes, however, is the mainstream in policy making of climate change, blending the two varieties as a consequence of global diffusion driven by changing national government alliances. Furthermore, Shrivastava & Bhaduri (2019) linked the market-based mechanisms (e.g., promoted by the Paris Agreement on climate change) to climate justice which has multi-institutional dimensions, and argued that the former could archive some aspects of the latter. Effectively combining the market-based and non-market mechanisms would greatly contribute to the realisation of the goal of climate change planning.

Planning of transportation infrastructure for climate change is always complicated, involving uncertainty and demand for balancing costs and benefits. During the examination of land-based transport in relation to climate change in Australia, Taylor & Philp (2010) emphasised the necessity of local rural networks for emergency evacuation planning as a future research direction. However, the existing policies tend to look at the 'proofing' of transportation infrastructure whilst ignoring other important dimensions (Hearn, 2015). Some management agencies barely integrate climate change into the process of decision making, which partially explains why there are insufficient tools for climate forecasting and planning (Espinet et al., 2016). Vulnerability assessment could be a crucial step in adaptation planning as vulnerability can significantly weaken the efficiency and ability of the transport operation. Hence, the next section reviews the management of transportation infrastructure and assets for climate change.

4.4. Asset management for climate change

Transport infrastructure presents significant components in transportation systems. The damage and economic losses on transport infrastructure posed by climate change could be catastrophic (Huibregtse et al., 2016). The direct costs include those relating to repair, maintenance and replacement of infrastructure. 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 method to support decision making and maintain property effectively in the transportation sector. A significant amount of works has been undertaken in the past decade, especially in developed countries (e.g., the US, 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 (The Federal Highway Administration (FHWA), 2012). The second report published by FHWA of the US transportation agencies examined risk-based approaches in asset management at multiple levels of the transportation sector. The recommended asset risk management method can be embedded in relevant institutions, involving policy innovation, assigning responsibilities, documenting processes and training at each risk level (FHWA, 2012). Wall & Meyer (2013) proposed a risk-based climate adaptation framework for transportation through reviewing two types of adaptation planning: on physical infrastructure and assets, and on operations and maintenance. More recently, Huibregtse et al. (2016) applied a risk-based approach to quantify climate impacts on a road network in the Netherlands. Based on the philosophy of identifying the system's resilience, this method indicated the remaining time before unexpected situations came out, can be employed in climate adaptation planning.

Meyer et al. (2010) utilised an asset management system as a decision-making framework in climate transportation planning. It is evident that the asset management system offered the most robust approach to develop transportation asset planning for 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 to an adaptation pilot project in the US. Thus, the 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 investigate sensitivity indicators and important thresholds for specific projects. The matrix synthesised the information from empirical studies of damage, historical climate data and engineering analyses 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, providing planners with an approach to balance the trade-offs among governments, businesses and their communities, and to address the challenges in climate adaptation. These techniques have been extensively applied in the construction of infrastructure in cities and also offered valuable sources in developing a useful sustainability framework in transportation asset management. Afterwards, Sanchez et al. (2014) applied BIM into asset management of a transportation system in Australia. BIM enabled the integration of information from different disciplines and measured sustainability performance of asset management projects. It assisted transport agencies to be more cost-effective through analysis of alternative designs, as well as monitoring and optimising 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 the establishment of an asset inventory, recognition of the disaster types, and conduction of quantitative evaluations for potential asset damage.

The analysis of economic losses due to climate change is a critical component in asset management as well. The International Institute for Sustainable Development developed a guide to help transportation practitioners to interpret the economic implications of not only the infrastructure damages but also the investment benefits by strengthening infrastructure resiliency (Sawyer, 2014). This guidance provided a general framework to conceptualise economic effects posed by climate change, and link asset vulnerability, economic outcomes with climate change together.

Minimising the uncertainty in climate adaptation is a critical issue waived to be addressed for both risk analysis and asset investment. The primary difficulty attributes to the uncertain natural of climate change itself. As it is challenging to collect precise data by an objective approach, a group of researchers (e.g., Yang et al., 2018; Wang et al., 2019b; 2020) have conducted a series of climate risk studies by using uncertainty methods, which combines fuzzy set (e.g. Lavasani et al., 2012), Bayesian networks (e.g. Zhang et al., 2014; Wang et al., 2019) with evidential reasoning (e.g. Wang et al., 2019) approaches, to model subjective input data (Baksh et al., 2018). Such methods allow modelling subjective linguistic variables extracting from the stakeholders' opinions by surveys. Accordingly, climate risks were assessed based on their timeframes of climate threats, occurrence frequencies, the severity of consequences, and resilience of infrastructure to climate change with minimum uncertainty and loss of objective information (Wang et al., 2020).

Meanwhile, the uncertainty issues on climate change had been addressed by another group of scholars (e.g., Wang & Zhang, 2018; Randrianarisoa & Zhang, 2019; Wang et al, 2020), in recent years, by studying the scale and timing of investment and relevant issues in climate adaptation in a competitive port market. Through establishing a two-period real options game model, it was found that the probability of climate threat occurrence, and the level of competition the information obtained could influence the timing of investment (Randrianarisoa & Zhang, 2019). Considering the inter-and intra-port coopetition in the market of terminal operator companies (TOCs), Wang & Zhang (2018) found that inter-port competition encouraged adaptation investments while the free-riding effect existed among terminal operator and port authority within a port. Furthermore, Wang et al. (2019a) investigated that the TOC market structure could moderate the effect of climate threat uncertainty on port adaptation.

However, it is only very recently that climate change has been 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 limitation, inadequate financial resources and treatment of risk, and uncertainty in future system demand. Hence, more professional and resilient asset management methods are called to quantitatively analyse the effects of climate change on transportation infrastructure. They could be supported by investigating multiple parameters, reviewing models and adding extra functionality (Huibregtse et al., 2016). To better implement asset planning in future climate adaptation, it suggested 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 to each case and to enlarge benefits for the entire transportation sector (Wall & Meyer, 2013; Sawyer, 2014).

4.5. Climate adaptation in transportation systems

4.5.1. Climate change strategies

To effectively address the threats posed by climate change on transportation, climate strategies must be adopted. From the mitigation perspective, there have been numerous research works concerning measuring, managing and minimising carbon dioxide and GHG emissions (Patterson et al., 2008), and 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 and introducing novel technologies into engine design for more efficient operations (Love et al., 2010). Compared to the mainstream of carbon emission studies in climate change, unfortunately, it is quite recently that climate adaptation on transportation sector has started to be developed (Hooper & Chapman, 2012). It has been recognised that adaptation is more cost-effective compared to mitigation strategies (e.g., Pielke, 2007). 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 adaptation and mitigation. The optimal investment levels of the two strategies mainly depend upon cost-benefit analysis. The high efficiency of a mix of both measures can be achieved in the case of maximum damage reduction and minimal marginal social costs (Koetse & Rietveld., 2012). Likewise, neglecting or delaying adaptations in decision-making can not only exacerbate consequences due to climate change but also degrade the welfares of mitigation (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 often takes place at regional and local levels (Koetse & Rietveld, 2012).

4.5.2. Adaptation strategies in transportation systems

The current research in adapting to climate change impacts mainly focuses on physical infrastructure (e.g., pavements, bridges and drainage systems) (e.g., De Bruin et al., 2009). Dobney et al. (2009; 2010) quantified the impacts of increasing summer temperatures on the British railways, and suggested two effective adaptation measures, namely, ensuring raising the stress-free rail temperature and maintaining track and track bed appropriately. More adaptation tools and frameworks that can be utilised in transportation are elaborated in Table 4. The framework of climate change usually indicates the process of adaptation planning with specific context of each stage, it is could be either a standardised method (e.g., Blueprinting (Niemeier et al., 2015)) or a project-based solution (e.g., New York City Panel on Climate Change (Rosenzweig et al., 2011)).

Table 4. Climate adaptation tools and frameworks in transportation

Name	Context	References
Blueprinting	A collaborative process that residents can involve in an interactive dialogue regarding the future city development of their urban area	Niemeier et al. (2015)
Dynamic Adaptive Planning	Used to overcome the disadvantages of existing methods by dealing with the deep uncertainty	Wall et al. (2015)
Roadmaps for Adaptation Measures of Transportation to Climate Change	Review adaptation measures and policies for the transport sector and evaluate them through a series of performance indicators	Stamos et al. (2015)

Three-Pillar (Policy-Management-Technology) model	Sensitivity and risk analysis used to identify the key 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 SLR and storm surge	Map the crucial targeted infrastructure, making efficient climate forecasts and develop 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 in the long-term transportation planning	Oswald et al. (2013)
Adaptive Systems Management	Include projecting the potential climate change, identifying vulnerabilities, analysing climate change strategies from the perspective of transportation engineering	Meyer & Weigel (2010)
Spatial Planning	Map the coastal inundation in Indonesia via a GIS model, and analyse changes of land use and estimate damage exposure	Suroso & Firman (2018)

Despite all these pioneering attempts, systematic reviews of literature show that existing research regarding climate adaptation in the transportation sector is still scare (Eisenack et al., 2012; Wang et al., 2019b). 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 (Eisenack et al., 2007).

The factors such as infrastructure age, location, design, maintenance and limited redundancy, could affect the sensitivities of transportation systems and the implementation of adaptation planning (Strauch et al., 2015). Nevertheless, existing research has barely taken into account how to figure out the factors constricting or promoting the implementation of adaptation. It requires more detailed knowledge about the 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 where might be more vulnerable to climate change regarding 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 addressed in the current literature, the primary research emphasis is put 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. 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.

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 do 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 and severe climate events (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).

The first issue is relatively easy to handle by factoring climate change into daily monitoring and maintenance, supported by stricter design parameters in response to various extreme climate events (e.g., TRB, 2008). This strategy is also called proactive or ex-ante adaptation, which applies to significant and long-term investments. It well responds to the fact that major factors among transport infrastructure are expensive, while the mistakes on investments could cause irreversible negative consequences if the infrastructure lifespan exceed the climate thresholds (Koetse & Rietveld, 2012). Embedding adaptation in broader investment or adaptation programmes has been exemplified by the adaptive infrastructure design to SLR and coastal zone management in North America and Europe (Adger et al., 2007).

However, the second issue requires more consideration due to its complexity. In port planning, for example, Becker et al. (2012) noticed that a majority of the surveyed ports planned for a historic 100-year storm period. However, the accelerated rate of climate change would make this preparation inadequate if the return period becomes 30 years instead of 100 years. As a common port infrastructure is designed with a 50-year lifespan, new infrastructure put in place nowadays should fit a new climate regime. Hence, balancing the investments in infrastructure with the planning cycle, especially under financial constraints, should be considered in adaptation planning (Wang, 2015). Regarding 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 to address the issue by postponing the decision-making and infrastructure updating until key parameters of climate change are given with a relatively confident certainty, in particular 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, in which case the costs of overinvestment are relatively low while 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).

5. Implications and future research agenda

Research surveying the impacts of climate change on the transport sectors has been conducted at a national and multi-regional scale in several developed countries (Pant et al., 2016; Wang et al., 2016; NRCNA, 2008). A considerable number of studies identifying the risks of climate change on the transportation system have been conducted to quantify the economic consequences of the environmental impacts based on the diverse transport modes via multiple decision models. However, the literature on Asian studies is relatively underdeveloped, calling for nationwide analyses and strengthening the infrastructure resilience by quantifications of climate impacts and adaptation costs (Chinowsky et al., 2015b). 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 associated planning and policy in climate risk assessment.

Transport resilience (Wan et al., 2018) has become an important concept in risk assessment for climate change in recent studies. It has been applied into multiple transport projects, such as the risk evaluation of the impacts of sea level rise and flooding in New York (Beheshtian et al, 2018) and climate change impacts on the road and rail systems in the UK (Wang et al., 2019b, 2020). Hence, future studies calls for more comprehensive and in-depth investigation on how to enhance transport resilience could contribute to the adaptation of climate change impacts.

Multiple vulnerability studies on climate adaptation are still at a relatively 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 the existing literature is between too vague or general principles and too detailed technical adaptation measures. It is suggested to make the adaptation instruments to be more generic for facilitating the requirement of adopting concrete organisational or technical measures (e.g., Koetse & Rietveld, 2012).

In this process, a significant challenge for transportation planners is the shortage of data both in precise climate prediction and the cost-benefit analysis owing to the high uncertainty of climate change (De Bruin et al., 2009). The knowledge gaps regarding direction, magnitude and severity also lead to the failure of adaptation strategies (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). Owing to the high-level uncertainty towards the future climate change, adaptation planning is encouraged to be robust. Among the literature reviewed, Espinet et al. (2017) proposed a robust prioritisation framework for adaptation investments of transport infrastructure under such uncertainty, which offered a new decision-making process and practical guidance on how to realise low-regret adaptation solutions for flexible design of road infrastructure. More practical and robust adaptation frameworks on climate change are desired to assist in more accurate climate projections, transparent information and innovative applications to minimise the vulnerability of the transport systems for expected shifts in extreme weather patterns (Pilli-Sihvola et al., 2016).

From the perspective of adaptation planning, it is noted that many adaptation plans (e.g. those in the UK) are not explicitly constructed to address the climate threats 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. In general, a proper infrastructure planning should be based on a systematic procedure. It includes identification of climate threats, categorisation of the most vulnerable infrastructure and opportunities for adaptation measures, examination of the existing institutional mechanism, as well as identification of regulatory and network constraints related to disruptions or degradation (Espinet et al., 2016). Additionally, as adaptation strategies are significant and could be costly, infrastructure sectors should be embedded to the future planning optimisation in advance (e.g., Neumann & Price, 2009). In Europe, the cost analysis based on WEATHER and EVENT projects implies a high uncertainty together with the financial burden on the 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).

Generally speaking, most adaptation initiatives have an organisational or planning nature that refers to a top-down policy pattern (Eisenack et al., 2012; Koetse & Rietveld, 2012). It was explained that public stakeholders were responsible for obliging or enabling transport providers to adapt to climate risks for transport users (Koetse & Rietveld, 2012). 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 researchers and argued 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 should be considered in future research.

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 choice among ex-ante disaster prevention, insurance and ex-post aid was discussed in recent years. The investigating results via experiment in floodplain areas of the Netherlands, for example, proved the efficiency of premium discounts to facilitate investment for both private and public stakeholders (Mol et al., 2018). The public sector (e.g., government) in general has stronger ability to initiate insurances and raise funds for post-disaster issues, while the motivations vary in different countries due to unstable financial and other factors (McAneney et al., 2016). McAneney et al (2016) argued that insurance cannot be taken as a social political instrument, and meanwhile, the incentives of insurance relies on transparency and accuracy in pricing risks.

The decision-making processes of investment are complex, related to diverse elements (e.g., probability of disaster occurrence, effect of information accumulation, mode capacity and coordination of government) and can vary at different stages of adaptation planning (Xiao et al., 2015; Gong et al., 2020). The 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). Some adaptation practices in transportation design have revealed that not all communities are incapable of incorporating climate impacts into infrastructure planning and management. Some questions are therefore deferred for future consideration, such as how academics can cooperate with local practitioners to implement adaptation, how to balance the roles of central and local governments, and how to tackle the barriers faced by communities in responding 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. Furthermore, more systemic economic modelling studies on investment by integrating multiple factors will continually help planners making decisions on each phase of adaptation planning with minimum uncertainties and costs.

In summary, the issues on developing appropriate adaptation tools for climate change remain. Firstly, many adaptation methodologies and tools are not explicitly designed for the transportation sector. Secondly, adaptation measures are either conceptual or lack of specific models for climate change, they could not provide a one-for-all solution for decision makers. Therefore, a comprehensive climate adaptation framework with systematic risk analysis on the transportation sector could provide significant contributions in the future. Typically, the establishment and development of such a framework 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. Nevertheless, it calls for more integrated methods in managing 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 closely knitted transport systems. These all indicate the needs for better cooperation among multiple organisations and information sharing in intermodal transportation systems.

6. Conclusion

This paper presents a state-of-the-art survey on climate adaptation of transportation systems based on 100 relevant journal papers featured in 65 internationally recognised journals in a period between 2005 and 2018. 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 forces, 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 68% of the total, in which case study and conceptual work were the dominant ones. Though the existing research was relatively scattered, lacking in dominant journals, researchers 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..

By semantics analysis, we categorised the corpuses based on different research themes and analysed them with respect to the climate change impacts on road/rail transportation, climate change risk assessment and asset management, climate planning and policy and climate adaptations on transportation. Despite much effort on investigating climate risks and developing appropriate adaptation tools for climate change, a few gaps were still revealed:

1) Current studies mainly focus on short-term impacts and climate adaptation for the transport sector are relatively presented in piecemeal;

2) Many adaptation tools or frameworks are not explicitly designed for the transportation sector;

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

4) The high uncertainty in adaptation for climate change risks poses a significant challenge for planners.

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. 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.

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.

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.

Overcoming these gaps firstly 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. A systematic analysis for developing long-term climate change adaptation planning in transportation systems can be further optimised by both quantitative and qualitative methods, such as a developed Fuzzy Bayesian Reasoning model, real surveys, and in-depth interviews with associated transport stakeholders. Future studies in climate adaptation planning calls for profound investigation on emerging topics, including but not limited to, the improvement of transport resilience, reducing climate uncertainties in adaptation investment, and the rational selection of adaptation strategies in planning and policy making.

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, contributing to yield an archive of the associated publications on the researched themes and present the state quo of climate adaptation studies to strike the new exploration in a right track. By doing so, it sets a future research agenda by indicating directions on how the research community should move forward to and providing transport planners and decision-makers with valuable insights and guidance on understanding the status quo and potential challenges in for climate risk analysis and implementation of adaptation planning in transportation. Moreover, the revealed gaps in current literature and potential suggestions discussed in this study will enlighten researchers and practitioners cause a paradigm shift regarding existing adaptation planning and management.

Although it aims to be a comprehensive review to dissect all significant research gaps and current emerging topics in the context of climate adaptation on transportation systems, unexceptionally, this work has its limitations. First, transport systems in this work mainly refer to road and rail transport, wider implications on other modes should be conducted in future for cross-referencing purposes. Second, to ensure the quality and relevance of the reviewed papers, we screened them using two strict constraints. Inevitably, some non-journal articles (e.g. government reports) that might contain useful implications are not included in the current work. Accordingly, we encourage continuous investigation to widen the research scope with latest data in the future study.

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References

Abkowitz, M., Jones, A., Dundon, L., & Camp, J. (2017). Performing a regional transportation asset extreme weather vulnerability assessment. *Transportation research procedia*, *25*, 4422-4437.

Adger, W. N., Agrawala, S., Mirza, M. M. Q., Conde, C., O'Brien, K., Pulhin, J., & Takahashi, K. (2007). Assessment of adaptation practices, options, constraints and capacity. *Climate change*, 717-743. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York: Cambridge University Press.

Aguiar, F. C., Bentz, J., Silva, J. M., Fonseca, A. L., Swart, R., Santos, F. D., & Penha-Lopes, G. (2018). Adaptation to climate change at local level in Europe: an overview. *Environmental Science & Policy*, *86*, 38-63.

Aldy, J. E., & Stavins, R. N. (2011). Using the market to address climate change: Insights from theory and experience. *National Bureau of Economic Research, 141(2),* 45-60.

Alirezaei, M., Onat, N. C., Tatari, O., & Abdel-Aty, M. (2017). The climate change-road safety-economy nexus: A system dynamics approach to understanding complex interdependencies. *Systems, 5(1)*, 6.

Aparicio Mourelo, Á. C. (2017). Transport adaptation policies in Europe: from incremental actions to long-term visions. *Transportation research procedia*, *25*, 3529-3537.

Arnell, N.W. (2010). Adapting to climate change: an evolving research programme. *Climate Chang*, *100*, 107-111.

Bache, I., Reardon, L., Bartle, I., Marsden, G., & Flinders, M. (2015). Symbolic meta-policy: (not) tackling climate change in the transport sector. *Political studies, 63(4),* 830-851.

Baksh, A. A., Abbassi, R., Garaniya, V., & Khan, F. (2018). Marine transportation risk assessment using Bayesian Network: Application to Arctic waters. *Ocean Engineering, 159,* 422-436.

Becker, A., Inoue, S., Fischer, M., & Schwegler, B. (2012). Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. *Climatic Change, 110(1-2),* 5-29.

Becker, A., Ng, A. K., Mcevoy, D., & Mullett, J. (2018). Implications of climate change for shipping: Ports and supply chains. *Wiley Interdisciplinary Reviews: Climate Change*, 9(2), 1-18.

Beheshtian, A., Donaghy, K.P., Gao, H.O., Safaie, S., Geddes, R. (2018). Impacts and implications of climatic extremes for resilience planning of transportation energy: A case study of New York city. *Journal of Cleaner Production*, *174,* 1299–1313.

Bergström, J., van Winsen, R. & Henriqson, E. (2015). On the rationale of resilience in the domain of safety: A literature review. *Reliability Engineering and System Safety*, *141*, 131-141.

Biesbroek, G. R., Swart, R. J., & van der Knaap, W. G. M. (2009). The mitigation–adaptation dichotomy and the role of spatial planning. *Habitat International*, *33(3)*, 230-237.

Boarnet, M. G. (2010). Planning, climate change, and transportation: Thoughts on policy analysis. *Transportation Research Part A: Policy and Practice*, *44(8)*, 587-595.

Chinowsky, P. S., Price, J. C., & Neumann, J. E. (2013). Assessment of climate change adaptation costs for the US road network. *Global Environmental Change*, *23(4)*, 764-773.

Chinowsky, P., Schweikert, A., Hughes, G., Hayles, C. S., Strzepek, N., Strzepek, K., & Westphal, M. (2015a). The impact of climate change on road and building infrastructure: A four-country study. *International Journal of Disaster Resilience in the Built Environment*, *6(4)*, 382-396.

Chinowsky, P. S., Schweikert, A. E., Strzepek, N., & Strzepek, K. (2015b). Road infrastructure and climate change in Vietnam. *Sustainability*, *7(5)*, 5452-5470.

Clarivate Analytics (nd). Retrieved on July 9, 2017 from http://clarivate.com/about-us/what-we-do/?product=web-of-science

Colicchia, C., & Strozzi, F. (2012). Supply chain risk management: a new methodology for a systematic literature review. *Supply Chain Management: An International Journal*, *17(4)*, 403-418.

CRED EM-DAT (2015). The OFDA/CRED - International Disaster Database, Université catholique de Louvain Brussels - Belgium. Retrieved on May 30, 2018 from https://www.emdat.be/database

Cyram (2017). NetMiner versión 4.3. Seoul: Cyram Inc. Retrieved on May 10, 2018 from http://www.netminer.com/.

De Bruin, K., Dellink, R., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., . . . Roetter, R. (2009). Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change, 95(1),* 23-45.

Denyer, D. & Tranfield, D. (2009). Producing a systematic review. In *The Sage Handbook of Organizational Research Methods.* Buchanan, D. and Bryman, A. (Eds), Sage Publications, London, 671-89.

Dixit, A.K., & Pindyck, R.S. (1994). *Investment under uncertainty*. Princeton, NJ: Princeton University Press.

Dobney, K., Baker, C.J., Quinn, A.D., & Chapman, L. (2009). Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in South-East United Kingdom. *Meteorological Applications, 16(2),* 245-251.

Dobney, K., Baker, C.J., Chapman, L., & Quinn, A.D. (2010). The future cost to the United Kingdom's railway network of heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change. *Proceedings of the institution of mechanical engineers, Part F: Journal of rail and rapid transit, 224*, 25-34.

Doll, C., Klug, S., & Enei, R. (2014). Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. *Natural Hazards, 72(1),* 211-239.

Doust, K. (2010). Responding to Climate Change in Cities: Techniques for Minimising Risk through Transport System and Urban Form Planning and Asset Management. HKIE Civil Conference.

Edwards, L. (2009). Testing the discourse of declining policy capacity: Rail policy and the Department of Transport. *Australian Journal of Public Administration, 68(3),* 288-302.

Eisenack, K., Tekken, V., & Kropp, J. (2007). Stakeholder Perceptions of Climate Change in the Baltic Sea Region. *Coastline Report, 8,* 245-255

Eisenack, K., Stecker, R., Reckien, D., & Hoffmann, E. (2012). Adaptation to climate change in the transport sector: a review of actions and actors. *Mitigation and Adaptation Strategies for Global Change, 17(5),* 451-469.

Emerald Group Publishing (nd). Retrieved on July 9, 2017 from http://www.emeraldgrouppublishing.com/about/index.htm

Ergas, H. (2012). Policy Forum: Designing a carbon price policy: using market-based mechanisms for emission abatement: are the assumptions plausible?. *Australian Economic Review, 45 (1),* 86-95.

Espinet, X., Schweikert, A., van den Heever, N., & Chinowsky, P. (2016). Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico. *Transport Policy, 50,* 78-86.

Espinet, X., Schweikert, A., & Chinowsky, P. (2017). Robust prioritization framework for transport infrastructure adaptation investments under uncertainty of climate change. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 3(1),* E4015001.

Ewing, R., & Cervero, R. (2001). Travel and the built environment: a synthesis. *Transportation research record, 1780(1),* 87-114.

Ferrer, R., Cancho, I. & Sole, R.V. (2001). The small world of human language. *Proceedings of the Royal Society B: Biological Sciences, 268(1482),* 2261-2265.

Geels, F. W. (2012). A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography, 24*, 471-482.

Gong, L., Xiao, Y., Jiang, C., Zheng, S., & Fu, X. (2020) Seaport investments in capacity and natural disaster prevention. *Transportation Research Part D: Transport and Environment*, *85*, 102367.

Handy, S.L. (2005). Smart growth and the transportation – land use connection: what does the research tell us? *International Regional Science Review, 28 (2)*, 146-167.

Hearn, G. (2015). Managing road transport in a world of changing climate and land use. In *Proceedings of the Institution of Civil Engineers-Municipal Engineer, 169 (3),* 146-159.

Hendricks, J., Righi, M., Dahlmann, K., Gottschaldt, K. D., Grewe, V., Ponater, M., & Kampffmeyer, T. (2018). Quantifying the climate impact of emissions from land-based transport in Germany. *Transportation Research Part D: Transport and Environment*, *65*, 825-845.

Holland, S. P., Hughes, J. E., Knittel, C. R., & Parker, N. C. (2015). Some inconvenient truths about climate change policy: The distributional impacts of transportation policies. *Review of Economics and Statistics*, *97(5)*, 1052-1069.

Hooper, E., & Chapman, L. (2012). Chapter 5 The Impacts of Climate Change on National Road and Rail Networks. In *Transport and Climate Change*, 105-136. Emerald Group Publishing Limited.

Hooper, E. J. (2013). *Future resilient transport networks: current and future impacts of precipitation on a UK motorway corridor*. Doctoral dissertation, University of Birmingham.

Hrelja, R., Hjerpe, M., & Storbjörk, S. (2015). Creating transformative force? The role of spatial planning in climate change transitions towards sustainable transportation. *Journal of Environmental Policy & Planning, 17(5),* 617-635.

Huibregtse, E., Morales Napoles, O., Hellebrandt, L., De Wit, S., & Paprotny, D. (2016). Climate change in asset management of infrastructure: A risk-based methodology applied to disruption of traffic on road networks due to the flooding of tunnels. *European Journal of Transport and Infrastructure Research (EJTIR), 16 (1)*, 98-113.

ICF International (2008). *Planning for climate change impacts at US ports.* White paper prepared for the US Environmental Protection Agency, July 2008.

IPCC. (2007). *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Change.* Cambridge, UK and New York: Cambridge University Press.

IPCC (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 .

Jude, S. R., Drew, G. H., Pollard, S. J., Rocks, S. A., Jenkinson, K., & Lamb, R. (2017). Delivering organisational adaptation through legislative mechanisms: evidence from the Adaptation Reporting Power (Climate Change Act 2008). *Science of the Total Environment*, *574*, 858-871.

Keohane, R. O., & Victor, D. G. (2011). The regime complex for climate change. *Perspectives on politics*, *9*(1), 7-23.

Kern, F., & Howlett, M. (2009). Implementing transition management as policy reforms: A case study of the Dutch energy sector. *Policy Sciences, 42(4)*, 391-408.

Kim, K., Pant, P., & Yamashita, E. (2018). Integrating travel demand modeling and flood hazard risk analysis for evacuation and sheltering. *International journal of disaster risk reduction*, *31*, 1177-1186.

Kintisch, E. (2008). Roads, Ports, Rails Aren't Ready for Changing Climate, Says Report. *Science, 319(5871)*, 1744-1745.

Kishimoto, P. N., Karplus, V. J., Zhong, M., Saikawa, E., Zhang, X., & Zhang, X. (2017). The impact of coordinated policies on air pollution emissions from road transportation in China. *Transportation Research Part D: Transport and Environnent, 54,* 30-49.

Klein, R.T., & Huq, S. (2007). Inter-relationships between adaptation and mitigation. In *IPCC Climate change 2007: Impacts, adaptation and vulnerability,* Chapter 18, 745-777. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York.

Knuth, D.E. (1993). *The Stanford Graph Base: A Platform for Combinatorial Computing.* New York, NY: ACM, Vol. 37.

Koetse, M. J., & Rietveld, P. (2012). Adaptation to climate change in the transport sector. *Transport Reviews*, *32(3)*, 267-286.

Lau, Y. Y. , Ng, A. K. Y. , Xiaowen, F. U. , & KEVIN X., L. I. . (2013). Evolution and research trends of container shipping. *Maritime policy and management*, *40(7),* 654-674.

Lau, Y. Y., Ducruet, C., Ng, A. K., & Fu, X. (2017). Across the waves: a bibliometric analysis of container shipping research since the 1960s. *Maritime Policy & Management, 44(6),* 667-684.

Lavasani, S.M.M, Yang, Z., Finlay, J. & Wang J. (2012). Application of MADM in a fuzzy environment for selecting the best barrier for offshore wells. *Expert Systems with Applications, 39*, 2466-2478.

Leviäkangas, P., & Michaelides, S. (2014). Transport system management under extreme weather risks: views to project appraisal, asset value protection and risk-aware system management. *Natural Hazards*, *72(1)*, 263-286.

Love, G., Soares, A., & Püempel, H. (2010). Climate change, climate variability and transportation. *Procedia Environmental Sciences, 1*, 130-145.

Matthews, L., Andrey, J., & Picketts, I. (2017). Planning for Winter Road Maintenance in the Context of Climate Change. *Weather, Climate, and Society*, *9 (3),* 521–532.

McAneney, J., McAneney, D., Musulin, R., Walker, G., & Crompton, R. (2016). Government-sponsored natural disaster insurance pools: A view from down-under. *International Journal of Disaster Risk Reduction*, *15*, 1-9.

McGuirk, M., Shuford, S., Peterson, T.C., & Pisano, P. (2009). Weather and climate change implications for surface transportation in the USA, *WMO Bulletin. 58(2)*, 85.

Meckling, J., & Jenner, S. (2016). Varieties of market-based policy: Instrument choice in climate policy. *Environmental Politics*, 25(5), 853-874.

Miao, Q., Feeney, M. K., Zhang, F., Welch, E. W., & Sriraj, P. S. (2018). Through the storm: Transit agency management in response to climate change. *Transportation Research Part D: Transport and Environment*, *63*, 421-432.

Mol, J. M. , Botzen, W. J. W. , & Blasch, J. E. . (2018). Behavioral motivations for self-insurance under different disaster risk insurance schemes. *Journal of Economic Behavior & Organization*. In press doi.org/10.1016/j.jebo.2018.12.007

Mullan, D., Swindles, G., Patterson, T., Galloway, J., Macumber, A., Falck, H., ... & Pisaric, M. (2016). Climate change and the long-term viability of the World's busiest heavy haul ice road. *Theoretical and Applied Climatology*, *129*, 1089-1108.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources*, *32*, 395-419.

Neumann, J.E., & Price, J.C. (2009). Adapting To Climate Change: The Public Policy Response: Public Infrastructure. Final report prepared for Resources for the Future. Retrieved on July 9, 2017 from http://www.rff.org/News/ ClimateAdaptation/Pages/domestic_publications.aspx

Neumann, J. E., Price, J., Chinowsky, P., Wright, L., Ludwig, L., Streeter, R., ... & Martinich, J. (2015). Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change, 131(1)*, 97-109.

Newman, M.E.J. (2004). Co-authorship networks and patterns of scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 5200-5205.

Newman, M.E.J. (2010). Networks: An Introduction. Oxford: Oxford University Press.

Newman, J., Perl, A., Wellstead, A., & McNutt, K. (2013). Policy Capacity for Climate Change in Canada's Transportation Sector. *Review of Policy Research, 30(1)*, 19-41.

Meyer, M. D., Amekudzi, A., & O'Har, J. P. (2010). Transportation asset management systems and climate change: adaptive systems management approach. *Transportation research record*, *2160*(1), 12-20.

Meyer, M., Flood, M., Keller, J., Lennon, J., McVoy, G., Dorney, C., ... & Smith, J. (2014). *Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report*, *5,* 20-83.

Ng, A. K., Becker, A., Cahoon, S., Chen, S. L., Earl, P., & Yang, Z. (2016). Time to act: The criticality of ports in adapting to the impacts posed by climate change. In Climate change and adaptation planning for ports, Routledge, pp., 265-267.

Ng, A.K., Wang, T., Yang, Z., Li, K. X., & Jiang, C. (2018). How is Business Adapting to Climate Change Impacts Appropriately? Insight from the Commercial Port Sector. *Journal of Business Ethics, 150(4),* 1029-1047.

National Research Council of the National Academies (NRCNA) (2008). *Potential impacts of climate change in US transportation, Vol 290.* Transport Research Board, Washington, DC.

Olmsted, S., O'Connor, A., Samaras, C., Cook, L. M., & Martinez-Pastor, B. (2017). *A Climate Engineering Assessment for Transportation Assets–Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering 2* (No. 17-05677).

Osthorst, W., & Mänz, C. (2012). Types of cluster adaptation to climate change. Lessons from the port and logistics sector of Northwest Germany. *Maritime Policy & Management, 39(2)*, 227-248.

Oswald, M. R. (2011). *Development of a decision support tool for transportation adaptation practices in response to climate change*, University of Delaware.

Oswald, M. R., & McNeil, S. (2013). Climate change adaptation tool for transportation: Mid-Atlantic region case study. *Journal of transportation engineering*, *139*(4), 407-415.

Pant R., Hall, J. W. & Blainey, S. P. (2016). Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. *European Journal of Transport & Infrastructure Research*, *16*(1), 174-194.

Patterson, Z., Ewing, G. O., and Haider, M. (2008). The potential for premium-intermodal services to reduce freight CO 2 emissions in the Quebec City–Windsor Corridor. *Transportation Research Part D: Transport and Environment*, *13(1),* 1-9.

Peterson, T. C., McGuirk, M., Houston, T. G., Horvitz, A. H., & Wehner, M. F. (2008). Climate variability and change with implications for transportation. *Transportation Research Board*, *90*.

Picketts, I. M., Andrey, J., Matthews, L., Déry, S. J., & Tighe, S. (2016). Climate change adaptation strategies for transportation infrastructure in Prince George, Canada. *Regional environmental change*, *16(4),* 1109-1120.

Pielke, R. A. (2007). Future economic damage from tropical cyclones: sensitivities to societal and climate changes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1860),* 2717-2729.

Pilli-Sihvola, K., Nurmi, V., Perrels, A., Harjanne, A., Bösch, P., & Ciari, F. (2016). Innovations in weather services as a crucial building block for climate change adaptation in road transport. *European Journal of Transport & Infrastructure Research, 16(1),* 150-173.

Poo, M. C., Yang, Z., Dimitriu, D., & Qu, Z. (2018). Review on Seaport and Airport Adaptation to Climate Change: A Case on Sea Level Rise and Flooding. *Marine Technology Society Journal, 52(2)*, 23-33.

Preston, B. L.,Westaway, R. M., & Yuen, E. J. (2011). Climate adaptation planning in practice: An evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change, 16(4)*, 407-438.

Qiao, Y., Dawson, A. R., Parry, T., & Flintsch, G. W. (2015). Evaluating the effects of climate change on road maintenance intervention strategies and Life-Cycle Costs. *Transportation Research Part D: Transport and Environment*, *41*, 492-503.

Randrianarisoa, L. M., & Zhang, A. (2019). Adaptation to climate change effects and competition between ports: Invest now or later?. *Transportation Research Part B: Methodological*, *123*, 279-322.

Reilly, J.,& Schimmelpfennig, D. (2000). Irreversibility, uncertainty, and learning: Portraits of adaptation to long-term climate change. *Climatic Change, 45(1)*, 253-278.

Romero-Lankao, P. (2012). Governing carbon and climate in the cities. *European Planning Studies, 20(1)*, 7-26.

Rousseau, D.M., Manning, J. & Denyer, D. (2008). Evidence in management and organizational science: assembling the field's full weight of scientific knowledge through syntheses. *The Academy of Management Annals*, *2 (1)*, 475-515.

Rowan, E., Evans, C., Riley-Gilbert, M., Hyman, R., Kafalenos, R., Beucler, B., & Schultz, P. (2013). Assessing the sensitivity of transportation assets to extreme weather events and climate change. *Transportation Research Record, (2326),* 16-23.

RVW (2009). Witte Zwanen, Zwarte Zwanen: Advies over Proactieve Adaptatie aan Klimaatverandering. White Swans, Black Swans: Advice on Proactive Adaptation to Climate Change, Advisory Council for Transport, Public Works and Water Management, Den Haag, The Netherlands.

Sachan, A. & Datta, S. (2005). Review of supply chain management and logistics research. *International Journal of Physical Distribution & Logistics Management, 35(9)*, 664-705.

Sanchez, A., Kraatz, J. A., Hampson, K. D., & Loganathan, S. (2014). BIM for sustainable whole-of-life transport infrastructure asset management. In *Proceedings of the 2014 IPWEA Sustainability in Public Works Conference:* The Institute of Public Works Engineering Australasia (IPWEA), Australia, pp. 1-7.

Sawyer, D. (2014). The Economic implications of climate change on transportation assets: an analysis framework. *The International Institute for Sustainable Development, IISD Report.* Retrieved on July 9, 2017 from https://www.iisd.org/sites/default/files/publications/climate_change_transportation_assets.pdf

Schwanen, T., Banister, D., & Anable, J. (2012). Rethinking habits and their role in behaviour change: the case of low-carbon mobility. *Journal of Transport Geography, 24*, 522-532.

Schweikert, A., Chinowsky, P., Kwiatkowski, K., Johnson, A., Shilling, E., Strzepek, K., & Strzepek, N. (2014). Road infrastructure and climate change: Impacts and adaptations for South Africa. *Journal of Infrastructure Systems, 21(3)*, 0401-4046.

Shrivastava, M. K., & Bhaduri, S. (2019). Market-based mechanism and 'climate justice': reframing the debate for a way forward. *International Environmental Agreements-politics Law and Economics*, *19(4)*, 497-513.

Solaymani, S., Kardooni, R., Yusoff, S. B., & Kari, F. (2015). The impacts of climate change policies on the transportation sector. *Energy*, *81*, 719-728.

Stamos, I., Mitsakis, E., & Grau, J. M. (2015). Roadmaps for Adaptation Measures of Transportation to Climate Change. *Transportation Research Record*, *2532*, 1-12.

Strauch, R., Raymond, C., Rochefort, R., Hamlet, A., & Lauver, C. (2015). Adapting transportation to climate change on federal lands in Washington State, USA. *Climatic Change, 130(2),* 185-199.

Suarez, P, Anderson, W, Mahal, V & Lakshmanan, T. (2005). Impacts of flooding and climate change on urban transportation: a system wide performance assessment of the Boston Metro Area. *Transportation Research Part D, 10,* 231-244.

Suroso, D. S. A., & Firman, T. (2018). The role of spatial planning in reducing exposure towards impacts of global sea level rise case study: Northern coast of Java, Indonesia. *Ocean & Coastal Management*, *153*, 84-97.

Taylor, M. A., & Philp, M. (2010). Adapting to climate change-implications for transport infrastructure, transport systems and travel behaviour. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice*, *19(4),* 66.

The Federal Highway Administration (2012). Risk-Based Asset Management: Examining Risk-based Approaches to Transportation Asset Management. Report 2: managing asset risks at multiple levels in a transportation agency. US Department of Transportation. Retrieved on July 9, 2017 from http://www.fhwa.dot.gov/asset/pubs/hif12050.pdf.

Tompkins, E.L., Adger, W.M., Boyd, E., Nicholson-Cole, S., Weatherhead, K.& Arnell, N. (2010). Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environment Change. 20,* 627–635.

Tonmoy, F. N., & El-Zein, A. (2018). Vulnerability to sea level rise: A novel local-scale indicator-based assessment methodology and application to eight beaches in Shoalhaven, Australia. *Ecological Indicators*, *85*, 295-307.

TRB (2008). *Potential impacts of climate change on US transportation.* TRB Special Report 290, Transportation Research Board, Washington, DC.

Twerefou, D. K., Chinowsky, P., Adjei-Mantey, K., & Strzepek, N. L. (2015). The economic impact of climate change on road infrastructure in Ghana. *Sustainability, 7(9),* 11949-11966.

UNEP (2010). United Nations Environment Program. UNEP strategy for the UNEP programme of work 2010-2011, 12-16. Retrieved on April 30, 2015 from http://ccsl.iccip.net/unep_cc_strategy.pdf

Walker, L., Figliozzi, M., Haire, A., & MacArthur, J. (2011). Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities under Climate Change: Case Study in Portland, Oregon. *Transportation Research Record, (2244),* 41-49.

Wall, T. A., & Meyer, M. D. (2013). Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector. A Synthesis of Practice. *Transportation Research Circular*, (E-C181). Paper presented at the Transportation Research Board 92nd Annual Meeting.

Wall, T. A., Walker, W. E., Marchau, V. A., & Bertolini, L. (2015). Dynamic Adaptive Approach to Transportation-Infrastructure Planning for Climate Change: San-Francisco-Bay-Area Case Study. *Journal of Infrastructure Systems, 21(4),* 05015004.

Wan, C., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in transportation systems: a systematic review and future directions. *Transport Reviews, 38(4),* 479-498.

Wang, K., & Zhang, A. (2018). Climate change, natural disasters and adaptation investments: Inter- and intra-port competition and cooperation. *Transportation Research Part B: Methodological*, *117*, 158-189.

Wang, K., Yang, H. & Zhang, A. (2019a). Seaport adaptation to climate change-related disasters: impact of multiple terminal operators. Working Paper, University of International Business and Economics, Beijing.

Wang, T. (2015). *Adapting to the risks and uncertainties posed by climate change on ports*. Master Thesis. Department of Supply Chain Management, Asper School of Business, University of Manitoba, Winnipeg, MB.

Wang, T., Samsom, S., Ng, A.K.Y. & Earl, P (2016). Climate change and adaptation of remote ports and supply chains in Manitoba, Canada. In: Ng, A.K.Y., Becker, A., Cahoon, S., Chen, S.L., Earl, P. and Yang, Z. (Eds.): Climate Change and Adaptation Planning for Ports, Routledge, London, UK, pp.91-105.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., & Bowden, D. (2018a). Impacts of Climate Change on Rail Systems: A New Climate Risk Analysis Model. In: *Safety and Reliability – Safe Societies in a changing World.* London: CRC Press. Haugen, S., Barros, A., Gulijk, C.V., Kongsvik, T., Vinnem, J. (Eds). The European Safety and Reliability (ESREL) Conference, Norwegian University of Science and Technology, Trondheim, Norway, 17th - 21st June 2018.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., & Bowden, D. (2018b). How Can the UK Road System be Adapted to the Impacts Posed by Climate Change? By Creating a Climate Adaptation Framework. *Proceedings of the International Conference on Project Logistics (PROLOG)*, University of Hull, UK, 28-29 June 2018.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., & Bowden, D (2019b). 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 and Environment, 77*, 403-424.

Wang, T., Qu, Z, Nichol, T., Yang, Z., Dimitriu, D., Clarke, G., & Bowden D. (2020). Impact analysis of climate change on rail systems for adaptation planning: A UK case. *Transportation Research Part D: Transport Environment, 83,* 102324.

Wilson, C., & McDaniels, T. (2007). Structured decision-making to link climate change and sustainable development. *Climate Policy*, *7(4)*, 353-370.

Wilson, E., & Piper, J. (2010). Chapter 1: Spatial planning, climate change and sustainable development. In: *Spatial planning and climate change*. 1st Edition, London, Routledge.

Xiao, Y. Fu, X., Ng, A., & Zhang, A. (2015), Port investments on coastal and marine disasters prevention: economic modeling and implications, *Transportation Research Part B: Methodological, 78,* 202-221.

Yang, Z.L., Ng, A. K., Lee, P. T. W., Wang, T., Qu, Z., Rodrigues, V. S., Pettit, S., Harris, I., Zhang, D., & Lau, Y.Y. (2018). Risk and cost evaluation of port adaptation measures to climate change impacts. *Transportation Research Part D: Transport and Environment, 61,* 444-458.

Zhang, D., Yan, X. Yang, Z. & Wang, J. (2014). An accident data-based approach for congestion risk assessment of inland waterways: A Yangtze River case. *Journal of Risk and Reliability*, *228(2)*, 176-188.