Roads to adaptation:

Understanding adaptation planning of urban road infrastructure

Juan Sebastián Cañavera Herrera

Department of Engineering

University of Cambridge

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Declaration

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Abstract

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Urbanisation and growth of the global population places high demand on city administrations to play a leading role in the management of climate change in the 21st century. Additionally, several factors including heavy reliance on interconnected infrastructure, high population densities (together with large numbers of poor and elderly), and the concentration of cultural and economic assets make cities particularly threatened by climate change. Therefore, any actions undertaken in urban contexts will have a crucial role in the management of climate change risks. A recent special report from 2018 from the Intergovernmental Panel on Climate Change of the United Nations (IPCC) confirms that adaptation efforts will be as important as mitigation efforts since we can no longer stop climate change from happening at least to some degree around the globe. Transport infrastructure forms part of the systems on which cities rely most heavily for their efficient functioning. Therefore, the adaptation of these systems to the changing climate is crucial for the success of cities in the future. However, adaptation of urban transport is still not well studied and there is a need for the development of useful adaptation guidelines for applying adaptive actions to transport infrastructure at the local level.

This thesis presents a conceptual framework called the "Expanded Adaptation Action Cycles" (EAAC). This framework conceptualizes adaptation planning in cities as an iterative action-learning cycle. In each iteration of the planning cycle, decision-makers implement adaptation actions based on their current knowledge while, at the same time, they learn how adaptation can be better implemented in their systems in the next iteration. The framework recognises that adaptation can be implemented at different scales (i.e. resistance, incremental adaptation or transformational adaptation) depending on the level of risks expected, the amount of change desired in the system and the resources available. The framework provides an overview of how a city might go through an adaptation planning process. Additionally, this thesis demonstrates the practical application of the EAAC framework by using it as a diagnostic tool to assess where a city is in the adaptation planning cycle, reveal possible future pathways from the current position of a city in the adaptation planning process and identify barriers and opportunities to certain pathways. In this framework, barriers and opportunities are associated with information quality and availability, resources availability and incentives on which decision-makers have to act.

A case study of the decision-making processes for the development and maintenance of road infrastructure in Bogotá, Colombia was conducted to demonstrate the practical utility of the EAAC

framework. Forty semi-structured interviews conducted with key local actors and experts provided insight into Bogotá's governance processes and the extent to which climate change adaptation is considered within the transport sector. The collection of evidence also included a critical analysis of local policy documents and technical reports.

Transport planners in Bogotá are currently trying to increase their understanding of the possible impacts of climate change over its principal road infrastructure through a study called "Red Vial Vital". The main adaptation actions proposed by the city are the use of "green infrastructure" and sustainable urban drainage systems. The analysis indicates that the city is currently at the early stages of its adaptation planning. The adaptation measures being considered suggest that, at most, the city is aiming for implementing incremental adaptation. Additionally, several barriers to effective adaptation planning in the city were identified. The analysis revealed that incomplete or unusable information about climate change and its effects, reduced availability of economic and human resources, and the lack of adequate incentives are hindering the incorporation of adaptation planning into the transport infrastructure planning processes of the city. Furthermore, the most influential underlying factors were associated with the institutional environment. This finding is consistent with what has been proposed by other authors.

The EAAC framework contributes to climate change adaptation literature by providing a relatively simple, yet comprehensive, conceptualisation of adaptation planning. While urban road infrastructure forms the focus of this research, the framework provides the theoretical basis to understand how adaptation can be planned and incorporated into the planning and design processes of any sociotechnical system. The EAAC goes further than other available frameworks as it links together the concept of the adaptation cycle, scales of adaptation and the identification of barriers and opportunities; these are aspects that typically have been separately addressed in the literature. In its practical application, the EAAC framework is expected to be a useful diagnostic tool for transport planners and designers in other cities. This is because it can, first, provide the ability to understand the relative position of a city's approach to adaptation planning within a wider spectrum of possibilities. Second, it can provide insight into future possible planning interventions and their possible impacts, existing barriers to and opportunities for effective adaptation planning, and the necessary steps to follow in the planning process. Finally, there is also the potential for using the EAAC framework to analyse adaptation planning in other sectors facing the challenge of preparing how to deal with the risks associated with climate change.

Keywords: *adaptation planning; urban transport infrastructure planning; climate change; adaptation barriers; adaptation opportunities*

To my parents, Juan Eugenio and Silvia,

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Nomenclature

AAC	Adaptation Action Cycles
ANI	National Infrastructure Agency (Colombia)
CEDR	Conference of European Directors of Roads
EAAC	Expanded Adaptation Action Cycles
ENSO	El Niño Southern Oscillation
FEHRL	Forum of European Highway Research Laboratories
GHG	Green House Gases
IDEAM	Colombia's Institute of Hydrology, Meteorology and Environmental Studies
IDIGER	District Institute for Risk Management and Climate Change
IDU	Urban Development Institute
IDRD	District Institute of Recreation and Sport
INVIAS	National Road Institute (Colombia)
IPCC	Intergovernmental Panel on Climate Change
MRes	Master of Research
PNUD	United Nations Development Programme for Colombia
ROADAPT	Roads for today, adapted for tomorrow
RVV	Vital Road Network
SDGR-CC	District Risk Management and Climate Change System
SUDS	Sustainable Urban Drainage Systems
UMV	Special Attention Rehabilitation and Road Maintenance Unit
UN	United Nations
UNISDR	United Nations Office for Disaster Risk Reduction

Chapter 1

1. Introduction

1.1. Background and need

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2014), the panel's most recent main report, shows the international scientific consensus regarding the existence of anthropogenic climate change. Our planet is reaching Green House Gases (GHG) concentrations in the atmosphere and oceans that present a high risk of affecting adversely the average climatic conditions all around the globe. These changes will have two main forms: gradual changes in the average climate variables such as precipitation, and the increase in the frequency of extreme weather events. These changes will inevitably produce impacts on our societies, especially those most vulnerable in low and middle-income countries, which ironically have contributed the least to GHG emissions (IPCC 2014).

In order to deal with climate change, two types of actions are required from human societies: mitigation and adaptation. Mitigation actions are those related to the active process of combating climate change by reducing GHG emissions from human activities, while adaptation actions are those related to the passive process of dealing with the risks associated with climate change. In practice, so far, mitigation has received more attention than adaptation by decision-makers in policy and business around the globe (Carter et al. 2015; Dhar and Khirfan 2017; Füssel 2007; Di Giulio et al. 2017), but according to the IPCC (2014), mitigation and adaptation should be complementary strategies.

A more recent special report from the IPCC reviews the potential impacts of global warming of 1.5℃ above pre-industrial levels and related GHG emission pathways, and presents the differences between present-day and global warming of 1.5℃, and between 1.5℃ and 2℃ (IPCC 2018). Based on the analysis presented in the report, the IPCC warns that humanity only has 11 years until 2030 to decrease drastically its GHG emissions if catastrophic climate change is to be avoided. The main question is no longer if humanity can stop climate change, but rather what societies are prepared to do to both live with it and limit its effects. This means that adaptation actions will be as vital as mitigation actions since at least some degree of change is expected to happen in weather patterns everywhere.

Cities need to be at the forefront of efforts against climate change. As Carter et al. (2015) state, urban settlements occupy a central position in the adaptation agenda because: 1) continued urbanisation will keep defining and shaping the 21st century; 2) the design of cities creates micro-climates that affect various variables like temperature; and 3) cities are particularly threatened by climate change due to a

range of factors including their heavy reliance on interconnected infrastructure, high population densities (including large numbers of poor and elderly), and the concentration of cultural and economic assets. Because of this, the different elements of urban planning, such as transport infrastructure planning, are likely to be significant instruments for adaptation and mitigation efforts (Carter et al. 2015; Dhar and Khirfan 2017; Hunt et al. 2017; Lehmann et al. 2015).

Transport infrastructure forms part of the systems on which cities rely most heavily for their efficient functioning. The adaptation of these systems to the changing climate is crucial for the success of cities in the future but there is evidence that this is still not well understood. For instance, Dhar and Khirfan (2017) performed a systematic literature review involving a longitudinal study that considered peer-reviewed articles from 30 urban planning and design journals published between 2000-2013. Their review shows that adaptation of urban transport has not been well studied and that there is a need for the development of useful adaptation guidelines for applying adaptive actions to transport infrastructure and other urban issues at the local level. These gaps are still present and will be further discussed in the literature review presented in Chapter 2 of this thesis.

Transport systems in urban settlements have three elements: transport infrastructure, vehicles, and transport users (Eichhorst 2009). Additionally, different types of urban transport infrastructure exist such as roads, rail infrastructure and waterways. This research focuses only on urban road infrastructure, the physical, engineered system, and does not address the adaptation of vehicles or the behaviour of transport users. This research uses the term urban road infrastructure to collectively refer to the roads, bicycle lanes and walkways in a city. Moreover, urban road infrastructure is understood in this thesis as the technical element of a larger and complex sociotechnical system in which interactions exist between social infrastructure, technical infrastructure and the environment (Chappin and van der Lei 2014).

Effective adaptation planning is needed to increase the resilience of urban settlements against the impacts of climate change. Climate adaptation planning can be defined as "social and decision processes that facilitate the implementation of interventions to reduce vulnerability and/or take advantage of potential opportunities associated with climate variability and change" (Preston, Westaway, and Yuen 2011:413). Adaptation planning requires the consideration of different factors other than climate change such as key non-climatic challenges, like social and economic inequality, and economic development plans (Füssel 2007). This type of planning can be seen as a social learning process that should leave room for experimentation and flexibility (Eichhorst 2009; IPCC 2014; McGray et al. 2007; Park et al. 2012; Wise et al. 2014). However, due to the levels of uncertainty associated with climate change, adaptation planning can be a difficult task and there is always the risk of succumbing to maladaptation pathways (Adger and Barnett 2009; Wise et al. 2014). Nevertheless, uncertainty should not be used as a reason for not acting. In other words, as sustainability thinking suggests, the precautionary principle

should be followed. Although there is not an accepted universal definition of the precautionary principle, the United Nations (UN) tried to encapsulate its intent in the Rio Declaration of 1992 by stating that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UN General Assembly 1992:Principle 15).

Aiming to tackle the operationalisation of climate change adaptation planning, road authorities around the world have developed different frameworks that serve as decision-making guidelines for the selection of adaptive actions for the transport networks they manage. Most examples of these frameworks (that can be found through searching publicly available information) have been developed for national highways, such as the ones developed by the World Road Association (2015), the Federal Highways Association (USA) (2017), the UK Highways Agency (2015), National Academy of Sciences (USA) (Wilbanks and National Academies Press (U.S.) 2010), the Ministry of Transport of Colombia (2014), the Federal Highway Research Institute (Germany) (2014) and Rattanachot et al. (2015). There are fewer easily-accessible examples specifically for urban transport networks, such as those developed by Eichhorst (2009) and the Ministry of Transport of Colombia (2016). This suggests that there is a lower level of development of guidelines for planning and implementing adaptive actions to transport infrastructure at the urban level. Because of this gap in knowledge and guidelines, this PhD research project is focused on adaptation planning for urban roads.

Due to the needs presented, this research seeks to contribute to resilience engineering, adaptation planning, transport infrastructure planning and urban planning literature by tackling the problem of how urban transport planners and designers should be able to include considerations of climate change in their decision-making processes and develop effective adaptation strategies for their road networks. For this, this thesis presents a conceptual framework for understanding adaptation planning of urban road infrastructure, called the "Expanded Adaptation Action Cycles", and demonstrates its utility by applying it to a case study of Bogotá, Colombia.

The research was driven by an underlying view that it is a matter of professional ethics for engineers to not only understand decision-making processes for the management of the built environment but also to participate in them. As Fenner et al. (2009:147) state "engineers do not operate in a vacuum but are constantly required to make value judgements. Often these judgements have not been recognised as value-based and we have acted as if they are 'objective science' even when they are not. In order to guide these judgements a system of ethics is essential". Engineers and other built environment professionals have the capacity to comprehend the risks that future challenges like climate change will impose and therefore understand how to prepare for them. This capacity comes together with the ethical responsibility of ensuring that our societies will be safe, especially those that are more vulnerable. Consequently, engineers need to ensure that their technical understanding of how to alleviate damage

to infrastructure, and the human suffering caused by that, is incorporated into planning decisions if they truly want their work to have an ethical impact. Only then will we be able to come closer to having more inclusive, safe, resilient and sustainable cities.

1.2. Previous work (MRes dissertation)

This PhD project is part of the 1+3 – Master of Research and Doctorate (MRes and PhD) in the Future Infrastructure and Built Environment programme of the Department of Engineering of the University of Cambridge. The MRes dissertation component of this research analysed in 2016 four state-of-the-art decision-support tools: The HDM4 Model (Kerali 2004; PIARC 2019), the Infrastructure Planning Support System (IPSS) (Schweikert, Chinowsky, Kwiatkowski, et al. 2014), the ROADAPT Guidelines (CEDR 2015) and the Blue Spot Concept (Axelsen and Larsen 2014; Hansson, Hellman, and Larsen 2010). These tools were analysed on their effectiveness as decision-support tools according to the characteristics presented by Lathrop et al. (2014) and Oswald and McNeil (2012) and on their ability to incorporate the sustainability principles presented by Fenner et al. (2009) into transportation planning. According to Lathrop et al. (2014) and Oswald and McNeil (2012), effective decision-support tools for adaptation should:

- Incorporate information ascertained through scientific research and modelling and specific to a discipline and its processes (in this case, specific to transportation).
- Analyse future climate change scenarios in reference to typical planning horizons.
- Forecast expected habitat and environmental changes, especially the potential loss of habitats important for ecological services.
- Inventory existing infrastructure and facilities within a jurisdiction.
- Evaluate the authorities' adaptive capacity in addition to the community.
- Analyse future developments to address potential at-risk projects.
- Recommend potential adaptation activities or strategies.
- Be easy to translate to decision-makers, and their results should enable easy understanding of potential risks due to climate change to all stakeholders.

The sustainability principles presented by Fenner et al. (2009) are: ethical foundation; justice through participation; efficient provision and co-ordination of infrastructure; maintenance of natural capital; holistic financial accountability; systems context; interlinking scales; and future vision. Sustainability was chosen as a criterion for this analysis because it is a guiding philosophy which aims to help human organisations to cope with complexity, balance trade-offs and manage competing priorities (i.e., decision-making). This allows organisations to deal with risk, resilience and opportunity, crucial dimensions of the adaptation process.

The MRes dissertation had the following conclusions:

- Road authorities globally perceive adaptation to climate change as a risk management strategy. It is suggested by road authorities that by following this approach, political problems regarding the uncertainty of climate change can be avoided. This is because by using the language of risk management it may be possible for transport planners and designers to avoid mentioning climate change directly, which has become a very politicized concept around the globe. This needs to be assessed by further research.

- There will always be a knowledge gap on the potential effectiveness of adaptation measures due to the uncertainty of climate change predictions.

- The currently available decision-support tools analysed exhibit, in general, most of the characteristics of effective tools for adaptation proposed by Lathrop et al. (2014) and Oswald and McNeil (2012). The main characteristic not found in any of the tools is the ability to forecast habitat loss and environmental impacts.

- The currently available decision-support tools analysed present different levels of incorporation of sustainability principles into transportation planning based on Fenner et al.'s (2009) framework. These range from the absence of any sustainability criteria (HDM-4 model and the Blue Spot Concept) to openly using sustainability as decision criteria (ROADAPT project).

- It was found that in the current practice of the road sector the traditional paradigm of balancing quality, cost and time for delivering projects remains as the guiding criterion for managing priorities. More research is needed to understand how to more effectively include non-quantifiable social and environmental aspects in the analysis of alternatives and avoid making decisions based only on economic parameters.

The MRes dissertation component of this research has informed and influenced some of the decisions made for the PhD project presented in this thesis, as described later in Chapter 4. The MRes dissertation demonstrated the existence of several decision-support tools for adaptation planning of road infrastructure. This suggests that proposing a new decision-support tool would not be perhaps a valuable contribution to current knowledge. A more valuable contribution would be investigating the characteristics of the decision-making processes associated with the adaptation planning of road infrastructure and investigating how the existing challenges for transport planners and designers could be identified. By examining these aspects first, it would be easier to reveal later how the principles of adaptation planning could be adopted by transport planners and designers in their decision-making

processes, making these processes potentially more effective in generating resilient infrastructure. Because of this, this PhD project has focused on understanding the adaptation planning process.

1.3. Research questions

Different organisations of the road sector have identified in recent years the necessity to adapt their infrastructure to the future risks of climate change. Various frameworks have been proposed to tackle this necessity, but so far, the inclusion of adaptation in the planning processes and planning guidelines at the urban level has been absent in most parts of the world. This is explored in more detail in Chapter 2. Therefore, the main aim of this PhD research project is to answer the following research question:

How can adaptation be incorporated into the planning and design of road infrastructure in cities?

The answer to this question can be supported by answering the following two sub-questions:

1) What is effective adaptation in the context of road infrastructure?
2) How is the adaptation planning process affected by the local social, political, economic, geographical and environmental context?

Answering the first sub-question allows for the concept of adaptation to be considered in more practical and contextualised terms. The answer to this question allows for the universal concept of adaptation to be brought down to the context of road infrastructure. This permits an understanding of, first, what adaptation means theoretically in the context of road infrastructure, and second, it allows to understand from this conceptualization which are the practical implications of adaptation for road infrastructure planning. This is a crucial step in finding an answer to the main research question, as adaptation cannot be incorporated into planning and design processes of urban road infrastructure if what adaptation entails is not understood first.

Answering the second sub-question is also necessary because engineers, transport planners and designers do not make decisions in a vacuum. These professionals, when planning and designing road infrastructure, make decisions that are affected by the social and environmental processes of their context. This research follows a sociotechnical approach and understands road infrastructure as the technical component of wider sociotechnical systems in which social elements interact with the technical components and the environment. It is necessary to understand how all components of sociotechnical systems interact and influence each other if engineering problems, such as adapting urban road infrastructure, are to be solved in an effective and holistic manner.

This thesis presents an analysis of a case study of Bogotá, Colombia to demonstrate the practical utility of a conceptual framework developed by this research. This conceptual framework provides the

theoretical basis behind the answers to the main research question and its sub-questions. The analysis of this case study contributes to answering the second sub-question and provides the practical element of the answer to the main research question of this PhD project. In order to have a comprehensive understanding of the case study, the following particular questions about Bogotá needed to be answered:

1) Who are the decision-makers and stakeholders involved in the process of deciding the development and maintenance of Bogotá's road infrastructure?
2) What processes do decision-makers in the city follow?
3) How is climate change being considered in the process of deciding the development and maintenance of Bogotá's road infrastructure?
4) What changes are needed in the decision-making process for the development and maintenance of Bogotá's road infrastructure so it can identify and incorporate the most effective adaptation strategies?

1.4. Thesis structure

This doctoral thesis is divided into 8 chapters with the following structure:

Chapter 1 provides an introduction.

Chapter 2 presents a review of existing literature regarding the adaptation of road infrastructure to climate change. The chapter presents, first, a review of the concepts of decision-making, risk and resilience in the context of climate change. This review serves as a basis for understanding the concept of adaptation, how it can be used as a precautionary approach to cope with the risks caused by climate change, and how it is one of several processes of resilience building of sociotechnical systems like those responsible for the development, operation and maintenance of road infrastructure.

Chapter 3 presents the conceptual framework developed to underpin this research, building upon the discussion presented in the previous chapter. The chapter begins by extending the literature review with an examination of the management of change through adaptation planning and the different scales at which adaptation can be implemented. This final element of the literature review is presented separately from the previous chapter as it provides the core theoretical basis for the conceptual framework. Then, the chapter presents the concept of "Adaptation Actions Cycles" (AAC), and finally, a new conceptual framework proposed by this author that expands the AAC concept by including other scales of adaptation and the identification of barriers to and opportunities for effective adaptation planning. This new framework is called the "Expanded Adaptation Action Cycles" (EAAC) framework.

Chapter 4 elaborates on the adopted research methodology. It provides the rationale behind the guiding philosophy and research design, along with the assumptions and limitations of the research methods selected.

Chapter 5 presents a brief review of the geographical context of Colombia and background to the governance and management of climate risk and transport infrastructure in Bogotá. This review of the context serves as a basis for the analysis presented later in this thesis of the adaptation of urban road infrastructure in the city. The first section presents a short overview of the geography, climate, economy, and politics of Bogotá and Colombia. The second section explains the current national and local response to climate change. The third section describes the transport sector of Bogotá and its organisational arrangements. The chapter concludes with an overview of the decision-making processes for road infrastructure planning in the city and its adaptation to climate change. Forming this context is critical for framing the subsequent findings of the research.

Chapter 6 presents a diagnosis of adaptation planning in the transport sector of Bogotá, Colombia using a series of key analytical questions (applying the first main analytical tool of the conceptual framework), which guide the analysis.

Chapter 7 presents how barriers to and opportunities for effective adaptation planning are identified from a sociotechnical perspective in the adaptation planning of road infrastructure in Bogotá, Colombia using the second main analytical tool of the EAAC framework.

Chapter 8 presents the conclusions of this research and suggests directions for future work.

Chapter 2

2. Literature review

This chapter presents a review of existing literature regarding the adaptation of road infrastructure to climate change. The chapter begins by discussing decision-making in the context of climate change in Section 2.1. After this, the concepts of risk in the context of climate change (Section 2.2) and of resilience of engineering systems (Section 2.3) are explored. These concepts are presented as they provide a background for understanding the development of the idea of adaptation to climate change. Subsequently, the concept of adaptation is introduced in Section 2.4. Adaptation is presented as a precautionary approach to cope with the risks created by climate change and as a process of resilience building of sociotechnical systems. After defining adaptation to climate change, the discussion focuses on planned adaptation (i.e., intentional and purposeful actions to cope with the effects of climate change). The chapter presents different approaches to adaptation planning (Section 2.4.1) followed by an examination of adaptation strategies, adaptation actions and barriers to effective adaptation planning (Sections 2.4.2 to 2.4.4). The review offered in this chapter serves as a basis for the introduction of the conceptual framework presented in Chapter 3.

2.1. Decision-making in the context of climate change

A significant level of uncertainty is associated with the planning of infrastructure, especially due to technological and demographic changes, globalisation, as well as climate change. Societies also face resource constraints in environmental and economic terms, for example: depletion of natural resources such as water, forests, land, or construction materials; the need of additional resources to deal with the increase in the frequency of extreme weather events; or competing development needs that must be managed with fewer economic resources. These factors highlight the need for effective decision-making by our political leaders and leading professionals in how to prepare for the future.

Decision-making, as a concept, has been studied by professionals from different disciplines including philosophy, economy, psychology, computer science and statistics, each contributing with their expertise in developing different decision theories (Peterson 2009). Decision theories can be divided into two main types: descriptive theories and normative theories. As Peterson (2009:3) explains, “descriptive decision theories seek to explain and predict how people actually make decisions. This is an empirical discipline, stemming from experimental psychology. Normative theories seek to yield prescriptions about what decision makers are rationally required, or ought, to do”. Most theories include

the notion that decision-makers are faced with two types of decisions: decisions under risk and decisions under uncertainty (Marchau et al. 2019; Peterson 2009). In decisions under risk, the decision-maker can quantify the probability of possible outcomes, while in decisions under uncertainty the probability of the outcomes cannot be reliably established. In recent years, a body of literature has been developed that discusses the concept of decisions under deep uncertainty (Marchau et al. 2019). Understanding how decision-making should work under deep uncertainty circumstances has become more relevant due to the rise in the number of more complex and uncertain processes which decision-makers need to deal with, such as climate change. Also in recent years, the field of behavioural economics has challenged the notions of the rationality of decision-makers when facing uncertainty embedded in other decision theories (see Kahneman (2011) for an introduction to behavioural economics). The previous types of decisions mostly refer to decisions made by individual decision-makers that do not take into account what others are doing. There are also circumstances in which decisions need to be made collectively by a group or in which decision-makers need to take into account what others do. These kinds of decisions are studied by subfields of decision theory such as social choice theory or game theory (Peterson 2009).

Decision-making in any engineering activity, like infrastructure planning, is a complex process since "to make a decision we need to know the problem, the need and purpose of the decision, the criteria of the decision, their sub-criteria, stakeholders and groups affected and the alternative actions to take" (Saaty 2008:84). It is also a complex process because the decisions made can have known and unknown ramifications with different significant impacts on society. For example, decision-making in infrastructure planning often involves the use of significant sums of public spending and can lock in society into certain future development paths. This is why it is a process that should take place "in a wider context of professional debate and public opinion concerning the issues and possibilities at hand" (Lyons and Davidson 2016:109). Another aspect that adds to the complexity of decision-making is that this kind of process depends on subjective judgements (Sarmiento et al. 2015), which are susceptible to multiple decision-making biases (Lyons and Davidson 2016). Therefore, the strengthening of evidence-based decision-making in planning is required to enable more robust decisions. These should be based on information obtained from scientific research but also from traditional and local knowledge to complement it (UNISDR 2015b).

Through an exercise of reviewing general literature on resilience and adaptation to climate change, it was observed that in the context of climate change, two main perspectives concerning the problem of decision-making can be found in the literature, from the disciplines of engineering and from the social sciences and humanities. For this literature review, authors are considered to be part of the engineering or social sciences and humanities disciplines based on their academic background and the reported institutions where they are affiliated. While a systematic literature review of climate change in each of these discipline areas was not conducted, some distinct differences can be identified when reviewing papers themed on decision-making in the context of climate change authored by those with an

engineering background compared to those in the social science and humanities. Engineering authors tend to approach decision-making by recommending the use of decision-support tools as a way of justifying decisions regarding specific interventions in the built environment. On the other hand, the social sciences and humanities research focuses on the analysis and design of climate change policies and climate risk governance. The evidence for this is outlined below.

Engineering literature on decision-making in the context of climate change supports the development and use of decision-support tools. Several authors propose that these tools should be used for providing evidence for the formulation of policies, the design of infrastructure or for the selection of operative actions (Hunt et al. 2017; Lathrop et al. 2014; Oswald and McNeil 2012; Pregnolato et al. 2016; Schweikert, Chinowsky, Kwiatkowski, et al. 2014; Zhou et al. 2012). Most of these decision-support tools rely on economic appraisal methods such as cost-benefit analysis, but these methods are limited as they do not reflect the importance of non-monetizable environmental and social benefits (Lyons and Davidson 2016; Wang 2015). Multi-criteria Decision-making (MCDM) methods have been suggested to be used as alternative decision-support tools so non-monetizable factors are considered in the analysis of alternatives, but determining the criteria and priorities of these methods is a challenging task (Saaty 2008). Velasquez and Hester (2013) review 12 different MCDM methods and outline how their most common areas of application are related to their advantages and disadvantages. According to their review, the most widely used MCDM methods are the Analytical Hierarchy Process[1] and the Multi-attribute Utility Theory. These methods have been commonly used in economics, energy management, public policy and planning (Velasquez and Hester 2013).

The inclusion of environmental and social aspects in decision-making is invoked by sustainability thinking and several efforts have been made in recent years to create sustainability assessment tools that incorporate simultaneously economic, environmental and social considerations. Ness et al. (2007) performed an inventory and categorisation of existing sustainability assessment tools. They also reviewed the degree in which they are able to incorporate the different dimensions of sustainability. They divide sustainability assessment tools into three main categories: indicators and indexes; product-related assessment; and integrated assessment. According to them, the last category focuses principally on prospective analysis. Ness et al., then, argue that tools in this category, like conceptual modelling, system dynamics, risk assessment, uncertainty assessment or vulnerability assessment, are the most adequate for incorporating sustainability in long-term decision making (i.e., decision-making required for climate change action). However, they state that decision-makers can find it difficult to accept the credibility of these forecasting tools due to the presence of subjective aspects in their analysis. Ness et al. also found that only a minority of the tools proposed for sustainability assessment that they reviewed

[1] More about the Analytical Hierarchy Process method can be found in Saaty (2008) and Triantaphyllou and Mann (1995).

actually incorporate an integrated analysis of economic, environmental and social aspects. A final point they make is that the choice of using a sustainable assessment tool is dependent on how this tool reflects the interpretation of sustainability made by decision-makers. As Ness et al. (2007:506) argue "assessment tool practitioners and decision-makers have a choice to use a tool, or specific assessment results that most closely reflect their political viewpoint and their broader interpretation of sustainability. Simply speaking, how one defines sustainability largely determines how one goes about assessing it". This has triggered critiques of these tools and has limited their use as there are still several competing interpretations of sustainability among different decision-makers in engineering, policy and other sectors.

In a more recent work, Morrison-Saunders, Pope, and Bond (2015) present a series of sustainability assessment tools, their applications at different scales and sectors, and some approaches these tools follow. They argue that sustainability is typically presented in sustainability assessment tools in four ways: triple bottom line indicators; composite indicators; systems representations; or articulation of boundaries, limits or systems conditions. Morrison-Saunders, Pope, and Bond, like Ness et al. (2007), show that various interpretations or discourses of sustainability (at least four for them) exist behind available sustainability assessment tools. They explain that there are two problems with this. First, they argue that in many cases, the discourse underpinning sustainability assessment tools is not made explicit which leads to problems with the interpretation of results and with the transparency of the assessment. Second, they state that "the very fact that different discourses can be recognised suggests that sustainability assessment outcomes could be contentious" (Morrison-Saunders et al. 2015:431). This reinforces the point made earlier about why there has been limited use of these kinds of tools due to competing discourses and interpretations.

In contrast to the engineering perspective, social sciences and humanities research on decision-making in the context of climate change focuses on the analysis and design of climate change policies, and the study of climate risk governance. Regarding climate change policy, for example, Lyons and Davidson (2016) suggest that policy design in transport planning should be more flexible in order to cope with future uncertainty. They suggest that a "decide and provide" approach should be embraced in transport planning. This approach proposes that transport planners should decide what the desired future conditions are for their road networks instead of trying to predict the future and that they should act keenly upon reaching that desired goal. For example, when designing a new road, transport planners should not focus on trying to find out what the extreme storm with a return period of 50 years is going to be and when it will more likely happen. Instead, transport planners should decide that they want to have a road that is resilient to a weather event of reasonable magnitude and plan for that weather event without paying too much attention to whether the event occurs or not. Southgate (2013) suggests that integrating science and policy-making is essential and will depend on science being "useful, usable and used". Regarding climate risk governance, Fatti and Patel (2013) present a case study research on

Atlasville, South Africa to discuss how perceptions of risk can influence disaster risk governance. Güiza et al (2016) examine how governance influences the vulnerability to flash-floods of communities in the Cuenca Alta del Río Lerma, Mexico. Zeiderman (2016b, 2016a) discusses how the concept of the "endangered city" can be used to understand how Bogotá and other cities have been governed in recent years. According to him, the feeling of endangerment (i.e., the general condition of feeling threatened) is more relevant than the direct experience of danger to shape experiences in a city. Zeiderman states that endangerment

> *"allows us to understand how the state establishes and maintains its authority and legitimacy, how the government intervenes in the lives of its citizens, how citizens inhabit the city as political subjects, and how subjects position themselves when addressing the state. It offers a way of apprehending the politics of security and the government of risk, and their implications for contemporary cities and urban life"* (Zeiderman 2016b:ix).

He argues that environmental threats like climate change are now part of the feeling of endangerment of the citizens of many cities like Bogotá. Because of this, Zeiderman claims that recent governments in Bogotá, like that of mayor Gustavo Petro [2012-2016][2], have been using climate risk management as a platform to do politics in the city and that the relationship between citizens and state is continuously redrawn through the language of risk. In another paper, Biesbroek et al. (2014) demonstrate the use of four analytical lenses for studying the governance of climate change adaptation (governance as problem solving; governance as competing values and interests; governance as institutional interaction; and governance as dealing with structural constraints) to analyse the results of the National Programme for Spatial Adaptation to Climate Change (ARK) of the Netherlands between 2008 and 2012.

These papers exemplify the focus of social sciences and humanities research on climate change policy and governance. These examples illustrate that literature from these disciplines tends to focus on the description of theories, philosophical principles and conceptual frameworks to understand climate change decision-making, and how different social actors' perceptions of climate risk influence adaptation efforts. However, these examples also suggest that several social sciences and humanities authors tend to focus little on the operationalisation of actions in anticipation of the effects of climate change on socioecological systems. That is, several of these governance papers do not explore how governance arrangements lead to the implementation of certain adaptation projects or programmes of projects. This means that there are still some knowledge gaps in understanding how to implement effective adaptation actions. This implies that there is a potential to integrate both perspectives. For instance, engineering professionals could complement the proposals from social sciences and humanities professionals with their knowledge on how to deploy effectively practical solutions and

[2] Throughout the text, the years in which each mayor was in office will be shown in square brackets like it is presented here.

infrastructure projects. This will prove to be valuable as it will allow overcoming the existing gap regarding the operationalisation of adaptation plans and policies.

The potential of integrating both the engineering and the social sciences and humanities perspectives lies in the field of adaptation planning (adaptation planning is described in more detail in Section 2.4.1). However, the division between these two perspectives is also present in the current literature about adaptation planning. For instance, papers from authors with an engineering background tend to approach the problem of planning climate change adaptation from a technical perspective based on risk management and infrastructure asset management. For example, in their paper, Auerbach and Hermann (2014) describe the adaptation strategy proposed by the German government for its road infrastructure called "AdSVIS - Adaptation of the Road Infrastructure to Climate Change". This strategy uses vulnerability analysis and other risk management tools and aims to integrate adaptation "into a holistic and sustainable asset management system" (Auerbach and Herrmann 2014:3). Bles et al. (2016) present the results of the ROADAPT project ("Road owners adapting to climate change") from the Conference of European Directors of Roads (CEDR) which is described as a risk-based approach to climate change adaptation. In their paper, Rattanachot et al. (2015) propose a methodological framework to develop adaptation strategies of transport infrastructures which relies on risk analysis. Oswald and McNeil (2012) introduce a decision-support tool called "Climate Change Adaptation Tool for Transportation (CCATT)" that utilizes climate change scenario analysis and impact assessment to determine the road infrastructure at risk in a jurisdiction and helps transport planners develop adaptation strategies for their networks. Other examples from the engineering literature that approach climate change adaptation from a risk management and infrastructure asset management perspective can be found in Casello and Towns (2017), FEHRL (2013), Filosa and Oster (2015), Oswald and McNeil (2012), Wilbanks et al. (2010) and World Road Association (2015).

Papers written by authors with a social sciences or humanities background about adaptation, for instance, analyse governance issues behind adaptation planning, analyse climate change policy in different territories, discuss the theoretical relationship between development and adaptation, or critique the philosophical assumptions and foundations of different approaches to adaptation planning. For example, in their paper, Araos et al. (2016) review the adaptation progress of different large cities in the world based on their reported policy documents and policy progress and classify them as extensive adaptors, moderate adaptors, early-stage adaptors or non-reporting. Eriksen et al. (2015) propose a conceptual framework based on social theory called "the politics of adaptation". This framework aims "to capture how politics are embedded in society's management of change" (Eriksen et al. 2015:523). Other examples from the social sciences and humanities literature that look into adaptation planning can be found in Agrawal and Carmen Lemos (2015), Biesbroek et al. (2014), Chu et al. (2016), Dhar and Khirfan (2017), Di Giulio et al. (2017), Haverkamp (2017), Kates et al. (2012), McGray et al. (2007), Pelling et al. (2015), Revi et al. (2014) and Sherman et al. (2016). This chapter later presents a

more detailed review of literature that discusses the relationship between adaptation and development (see Section 2.4).

Adaptation planning, simply put, is the management of climate risk and the management of change. The examples cited in the previous paragraph show that each perspective has traditionally focused more on one singular element of adaptation planning than the other. In other words, engineering authors tend to focus on the management of climate risk, while social sciences and humanities authors tend to focus on the management of change. This demonstrates that these disciplines are not looking at the problem in a holistic manner. The rest of this chapter will focus mainly on the risk management aspect of adaptation. Change management through adaptation planning is discussed in detail in the next chapter.

In parts of the literature, some initial discussions on how to integrate both perspectives are already emerging. For example, in the context of transport planning, Amoaning-Yankson and Amekudzi-Kennedy (2017) review the potential benefits of following a sociotechnical approach in the development of resilient transport systems. They suggest that in order to integrate both perspectives and to expand the benefits of resilient transport systems, transportation planning should move from a largely technical approach to a sociotechnical approach. Inspired by this, this research seeks to contribute to adaptation and transport infrastructure planning literature by demonstrating how decision-makers and policymakers should incorporate a sociotechnical approach into adaptation planning of urban road systems.

2.2. Risks of climate change to roads

As discussed in the previous section, societies require effective and sound decision-making, especially when faced with high levels of uncertainty due to processes such as climate change. These uncertainties provide both risks and opportunities that need to be managed so sociotechnical systems can have their efficient functioning guaranteed over time. This section discusses different interpretations of risk, what kinds of risk are expected in the context of climate change and the potential impacts of climate change on road infrastructure systems. This discussion serves later as a basis to understand which adaptation strategies and actions need to be selected in the adaptation planning process to tackle these risks (see Section 2.4.1).

Risk has different definitions. A common interpretation of risk describes it as a combination of hazard, exposure and vulnerability (Agarwal 2015; Balica et al. 2013; CRED and UNISDR 2015; IPCC 2014; MinTransporte et al. 2014; UNISDR 2015a; Wilbanks and National Academies Press (U.S.) 2010; Wilkinson and Brenes 2014; World Road Association 2015). For example, UNISDR (2015a:27) defines risk as “the combination of the probability of a hazardous event and its consequences which result from interaction(s) between natural or man-made hazard(s), vulnerability, exposure and capacity”. These consequences are usually adverse to human and natural systems, but they also present opportunities

(Dhar and Khirfan 2017; Murillo et al. 2017; World Road Association 2015). This interpretation of risk is followed in this thesis. It has been selected as it is the most widely accepted definition in both academic and non-academic literature reviewed. Another interpretation of the concept of risk suggests that it can be understood as the combination of a scenario, the likelihood of manifestation of that scenario and the consequences of events within that scenario (Francis and Bekera 2014; Mattsson and Jenelius 2015). In this interpretation, a scenario can include the simultaneous occurrence of several hazardous events. This can allow for more complexity in the analysis of risks. It is possible that because of this additional complexity, this interpretation has not been as widely utilised as the first interpretation shown in this paragraph. Additionally, independent of the interpretation of risk that is followed, it should be acknowledged that risks exist and can be created within social systems, so it is important to consider the social contexts in which they might occur (Francis and Bekera 2014; UNISDR 2015a).

In the context of climate change, new climatic conditions produce new hazards. An example of this is occurring in regions where permafrost soils can be found. Structures built over these soils, which have been stable for decades, are now facing new subsidence issues due to the melting of the permafrost produced by the increase in temperatures caused by climate change. Figure 1 shows how the IPCC, the world's leading scientific authority on climate change, conceptually interprets risk in this context. Here, the interaction of climate change hazards with the vulnerability and exposure of a socioecological system generates new risks or increases existing ones (IPCC 2014). This research adopts this interpretation of climate risk. Climate change risks fall into two categories: a) risks due to long-term changes in average climatic conditions, and, b) risks due to extreme weather events. These risks are characterised as non-linear, meaning their consequences can increase rapidly, and as systemic, which means that they "can trigger unexpected large-scale changes of a system, or imply uncontrollable large-scale threats to it" (King et al. 2015:110).

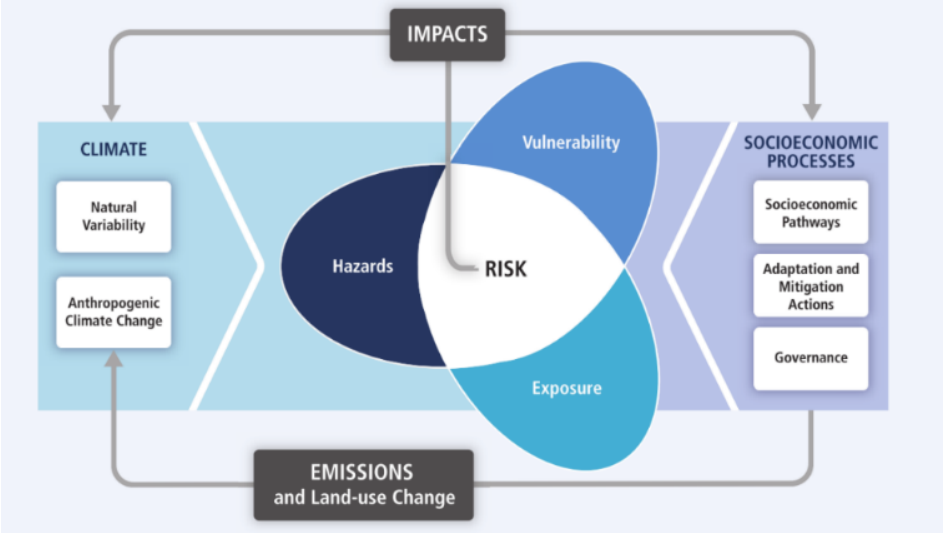

Figure 1. Relationship between vulnerability and risk in the climate change context. Sourced from IPCC (2014) (Figure SPM.1).

In the context of transport infrastructure, climate change threatens to generate new kinds of risks for road systems in the future or increase existing ones. Due to the uncertain nature of climate change, most of the literature provides an estimation of the potential impacts on roads based on current knowledge of weather-related effects on road infrastructure. Most documents, when addressing impacts of climate change on road infrastructure, provide lists of potential impacts with a focus on general descriptions of the hazards and physical damage that road infrastructure could potentially suffer in changing climatic conditions. Two examples of these lists of potential impacts are shown below to illustrate how they are typically presented by a funding body and by a group of road infrastructure asset owners. The Asian Development Bank (2011) provides the following example of such a list of potential impacts:

- *Changes in temperature—both a gradual increase in temperature and an increase in extreme temperatures—are likely to impact road pavements (for example, heat-induced heaving and buckling of joints).*
- *Changes in temperature will also impact the behavior of permafrost and thus the infrastructure lying on permafrost.*
- *Changes in precipitation and water levels will impact road foundations.*
- *Extreme weather events such as stronger and/or more frequent storms will affect the capacity of drainage and overflow systems to deal with stronger or faster velocity of water flows.*
- *Stronger or faster velocity of water flows will also impact bridge foundations.*
- *Increased wind loads and storm strengths will impact long-span bridges, especially suspension and cable-stayed bridges.*
- *Increased storm surges will significantly impact all components of the coastal transportation infrastructure.*
- *Increased salinity levels will reduce the structural strength of pavements and lead to precipitated rusting of the reinforcement in concrete structures.*

The Forum of European Highway Research Laboratories (FEHRL) presents another example in which it highlights potential impacts of climate change to the European highway network (FEHRL 2013):

- *Flooding either through precipitation or potentially rapid snow/ice melt in some regions and some of the associated effects such as:*
    - *Operational disruption, reduced network availability and blockages*
    - *Bridge scour, inundation of tunnels and landslides*
    - *Saturation of the unbound layers, resulting in loss of fine material, settlement and failure*
    - *Saturation of the subgrade causing a reduction in strength*

- *Hotter, drier summers leading to a reduction in sub-surface water, causing shrinkage of the sub-surface and inducing cracking. Increasing changes in sub-surface water can cause soil to shrink and expand significantly, causing the overlying pavement layers to heave and subside.*
- *In periods of hot weather, asphalt surface layers can become susceptible to rutting and deformation. In addition, high temperatures can make newly laid asphalt remain workable for an extended time, making it difficult to maintain profile during compaction.*
- *Thermal gradients can create uneven internal stresses, giving rise to curling or warping in concrete pavements.*
- *Reduction in vegetation due to higher temperatures and drought, and/or higher wind speeds could increase erosion processes on embankments, leading to them becoming unstable.*
- *Intense rainfall events causing erosion or landslips/landslides on embankments. Extreme rainfall events in areas with reduced vegetation, described above, would intensify erosion.*
- *A milder climate could have implications for northern areas of Europe where the ground is currently frozen during winter, through increases in the freeze-thaw process.*
- *Conversely, winter maintenance requirements may decrease in many areas due to a milder climate, whilst changes in springtime snow melt and the proportion of precipitation falling as rain or snow might result in less flooding.*

Both examples offer similar descriptions of the types of potential impacts to road infrastructure generated by climate change showing that there are common perceptions of the threat of climate change amongst stakeholders. Furthermore, these examples suggest that funding bodies and road infrastructure asset owners tend to focus on the physical risks of road infrastructure. They also suggest that in the framework of climate change funding bodies and road infrastructure asset owners do not prioritise the interactions of road networks with the wider societal context. Both examples of lists of potential impacts illustrate that there is a lack of mentioning of the context, especially the social context. As mentioned previously in this section, risks are created and exist inside a social context; this includes climate change risks. Therefore, a more comprehensive understanding of potential impacts would be achieved if the sociotechnical context was included in the analysis. Other examples of lists of potential impacts can be found in Casello and Towns (2017), Clerc and Díaz (Clerc and Díaz 2016), Eichhorst (2009), Federal Highway Administration (2012), Willway et al. (2008) and World Road Association (2015). These lists are not significantly different from the two already presented and that is why they are not reviewed in further detail here.

Diverse strategies have been proposed to deal with the risks of climate change and their potential impacts on road infrastructure. Disaster risk management is one of these suggested strategies to cope with climate change risks (King et al. 2015). According to the UNISDR (2015a:13), disaster risk management is "the application of disaster risk reduction policies, processes and actions to prevent new

risk, reduce existing disaster risk and manage residual risk contributing to the strengthening of resilience". It has formed part of the international development agenda since the end of the 1980s and is now promoted through the Sendai Framework for Disaster Risk Reduction 2015-2030 of the United Nations. The Sendai Framework has 13 guiding principles and 7 global targets, including substantially reducing disaster damage to critical infrastructure and the disruption of basic services (UNISDR 2015b). Additionally, disaster risk reduction can contribute to the achievement of sustainable development, and because of this, the UN has included disaster risk management targets in the global development agenda established by the Sustainable Development Goals (UN General Assembly 2015; UN and United Nations 2015; UNISDR 2015b).

Several authors have discussed the relationship between disaster risk reduction (DRR) and climate change adaptation and there is consensus that climate change adaptation can be considered as a subset of the former (Kelman, Mercer, and Gaillard 2017a). In other words, adaptation can be understood as DRR actions that focus on dealing with climate change-related hazards (for a review of the literature discussing the relationship between DRR and climate change adaptation refer to Kelman et al. (2017b)). Although both concepts are related, disaster risk reduction and climate change adaptation continue being predominantly addressed separately in policies and regulations of the built environment (Chmutina, Jigyasu, and Bosher 2017). Therefore, there is a need to integrate climate change adaptation and disaster risk reduction in practice if the resilience of the built environment to all kinds of risks associated with climatic and non-climatic hazards is to be improved. As has been discussed, this research centres around exploring the management of risks associated with climate change; therefore, the rest of this thesis will focus on reviewing and understanding climate change adaptation. The next section introduces the concept of resilience and how adaptation is one of the processes necessary to improve the resilience of any engineering system.

2.3. Resilience of engineering systems

Resilience was first introduced as a concept in ecology by C.S. Holling in 1973 to explain the behaviour of complex ecological systems when afflicted by shocks (Holling 1973). Since then, it has been adopted by several different disciplines including sustainability, psychology and psychiatry, engineering, sociology and economy (Ayyub 2014; Francis and Bekera 2014; Righi et al. 2015).[3]

In the context of engineering systems, resilience can be understood as "an endowed or enriched property of a system that is capable of effectively combating (absorbing, adapting to or rapidly recover from) disruptive events" (Francis and Bekera 2014:91). This suggests that resilience building is another strategy to cope with risks such as those related to climate change, and that adaptation is one of the

[3] For a comprehensive review of the concept of resilience see Ayyub (2014), Francis and Bekera (2014) and Righi et al. (2015).

processes necessary to improve the resilience of an engineering system. Additionally, resilience is an emergent dynamic property of a system that expresses its ability to cope with disruptive events, and therefore, it cannot be understood without a context (Ayyub 2014; Fatti and Patel 2013; Francis and Bekera 2014).

Some authors propose different definitions of resilience in human systems. The most popular definition of resilience amongst researchers was proposed by Bruneau et al. (2003). According to this definition, resilience has four dimensions (technical, organisational, social and economic), four properties (robustness, rapidity, redundancy and resourcefulness), and three outcomes (increased reliability, faster recovery and lower consequences). Another definition proposes that a resilient system is characterised by having the following capacities: absorptive capacity, adaptive capacity, and, recovery and restorative capacity (Francis and Bekera 2014). In the context of transportation systems, Wang (2015) suggests that a resilient transportation system must have the following qualities: 1) to recover efficiently from disasters, 2) to be reliable in terms of network connectivity and travel time, and 3) to be economically, environmentally and socially sustainable.

Since resilience is a property of a system, the main assumption within resilience engineering is that this property can be incorporated by design into any complex sociotechnical system (Righi et al. 2015). Righi et al. (2015) explain that the main objective of resilience engineering, then, is to design processes for the creation of resilient sociotechnical systems, especially at an organisational level, and develop methods for the scientific investigation of resilience. They indicate that academic research in this area has usually adopted case-study based research designs, due to the highly context-dependent nature of the problem of analysing sociotechnical systems.

Resilience frameworks have been suggested by different authors to provide an understanding of how to increase the resilience of sociotechnical systems. Examples of these frameworks can be found in Chang et al. (2014), Linkov et al. (2014) and Lounis and McAllister (2016), and a review of different resilience frameworks in the transportation sector can be found in Wang (2015). All these frameworks follow a general structure. First, they begin with the assessment of the resilience of the system being studied. A diversity of metrics can be found in the literature that try to quantify this property based on probability methods (Ayyub 2014; Francis and Bekera 2014). After this assessment, frameworks provide suggestions of different resilience measures to be implemented. Resilience-building measures include "the integration of a combination of structural measures …, non-structural measures … and natural and nature-based features" (Linkov et al. 2014:408). Moreover, enhancing social networks is also crucial in resilience building (Linkov et al. 2014). These measures are aimed to increase the absorptive capacity, adaptive capacity, and, recovery and restorative capacity of sociotechnical systems. After implementation, all frameworks suggest a period of evaluation and monitoring.

As discussed previously in this section, adaptation to climate change is part of the processes necessary to improve the resilience of an engineering system. Adaptation measures involve actions that mainly increase the adaptive capacity of engineering systems but also include some actions that may improve the absorptive capacity and the recovery and restorative capacity of the system. The next sections of this chapter discuss in more detail existing research on climate change adaptation planning in the context of road infrastructure.

2.4. Adaptation of road infrastructure to climate change

In order to overcome the future risks outlined in Section 2.2, the adaptive capacity of communities and cities needs to be enhanced to maintain and improve social, economic and environmental conditions in their territories. Infrastructure systems, which form part of societies' sociotechnical systems, need to be adapted in line with societies' efforts to increase resilience.

The concept of adaptation originated in the natural sciences but was first used in the context of human systems by the anthropologist and cultural ecologist Julian Steward in the mid-twentieth century (Smit and Wandel 2006). In the 1980s, the concept of adaptation began to be used in the context of climate change and since then it has been an important part of the global climate change agenda along with mitigation.

In the context of climate change, adaptation is a contested concept and different definitions have been proposed by several organisations and theorists such as Adger et al. (2005), Biagini et al. (2014), Ford and Berrang-Ford (2016), Lampis (2013), McGray et al. (2007), Moser and Ekstrom (2010), Rickards and Howden (2012), Sherman et al. (2016), Smit and Wandel (2006), or UNEP DTU Partnership (2018). A now widely recognised definition of adaptation is that of the IPCC. They define adaptation as

> *"the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects"* (IPCC 2014:5).

However, some critics consider this definition too general and difficult to operationalize, while others criticise the analytical and philosophical approaches promoted by the IPCC. For example, Moser and Ekstrom (2010) argue that they do not follow the definition of the IPCC for three reasons. First, they believe that in contrast to what the definition of the IPCC implies, adaptation must consider climate change but should not be justified by it alone. This means that adaptation may be initiated in the context of non-climatic windows of opportunity (e.g., urban master plan updates, routine infrastructure maintenance or replacement, technical standards updates). Second, they suggest that the IPCC's

definition assumes prematurely the effectiveness of the outcome of adaptation strategies and actions. There are uncertainties on the levels of change in climate conditions and the effectiveness of the actions undertaken (i.e. some adaptation actions could lead to maladaptation). Therefore, flexibility and continuous evaluation and monitoring of the adaptation process are necessary to avoid falling into undesired pathways. Third, their critique highlights that the IPCC's definition separates human and natural systems, but in reality, it is difficult to distinguish between their interactions. Consequently, they should be considered together as socioecological systems. Based on their arguments, Moser and Ekstrom propose the following definition for adaptation:

> *"Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting nonclimatic changes. Adaptation strategies and actions can range from short-term coping to longer-term deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities"* (Moser and Ekstrom 2010:22026)

Throughout the literature, the argument runs that effective adaptation to climate change possesses several characteristics. Adaptation is suggested to be a local process, context-dependent, that requires the involvement of the community and stakeholders (Adger et al. 2005; CEDR 2015; Chappin and van der Lei 2014; Collins 2011; IPCC 2014; Oswald and McNeil 2012; Wilbanks and National Academies Press (U.S.) 2010; World Road Association 2015). It is a passive approach to coping with climate change, in contrast to mitigation, as its purpose is not to influence the climate, but to find ways to reduce the vulnerability of sociotechnical systems (Rattanachot et al. 2015). Adaptation is classified by some authors as a process of resilience building (see Section 2.3).

Some authors have tried to contextualise the definition of adaptation for different sectors so that it can be operationalized. For example, in the more specific context of road infrastructure, Oswald and McNeil (2012) have defined adaptation as

> *"the development, modification, maintenance, and renewal of transportation infrastructure, operations, and policy to moderate the impacts of climate change. This includes infrastructure changes to support mitigation efforts such as the use of alternative fuels"* (Oswald and McNeil 2012:146).

Sharing the critique of the IPCC's definition of adaptation by Moser and Ekstrom (2010), acknowledging their alternative definition and considering the effort of Oswald and McNeil (2012) to contextualize adaptation in the setting of road infrastructure, the following definition of adaptation of transportation infrastructure systems will be adopted in this thesis:

Definition of adaptation of transportation infrastructure systems

Adaptation involves modifications to transportation infrastructure systems in response to actual and expected impacts of climate change which occur in the context of other socioecological changes interacting with them. This may involve the development, modification, maintenance and renewal of physical infrastructure, operations and policies. Adaptation strategies and actions can range from short-term coping to longer-term deeper transformations. Strategies and actions may aim to meet more than climate change goals alone and may or may not succeed in moderating harm or exploiting beneficial opportunities. This includes infrastructure changes to support mitigation efforts.

In this definition, transportation infrastructure systems should be understood as being part of wider complex sociotechnical systems in which complex interactions exist between social infrastructure elements, technical infrastructure elements and the environment. As Franssen and Kroes (2009:223) explain, the prototypical technical artefact is "a single material object designed to be used by a particular person for a particular purpose". Traditionally, engineering has focused on designing and operating all technical artefacts based on this conception. However, there is a class of technical artefacts "that cannot be seen as a single connected material object, nor as having a single user or even a sequence of single but distinct users" (Franssen and Kroes 2009:223). A typical example of this class of technical artefacts is critical infrastructures such as transport infrastructure or energy infrastructure. These artefacts include not only technical/physical components but also social/organizational components that are tightly interconnected. These systems are known as sociotechnical systems. Figure 2 shows a graphical conceptualisation of the components of a sociotechnical infrastructure system and their interactions. In a sociotechnical system, the social infrastructure elements, technical infrastructure elements and the environment continuously interact with each other and their behaviour cannot be fully understood without acknowledging these interactions. It is also worth noting that there are additional interactions with other interconnected sociotechnical infrastructure systems (e.g., transport infrastructure systems interact with water management systems for drainage management purposes) as shown by the layers in Figure 2.

Understanding transportation infrastructure systems as part of wider complex sociotechnical systems has implications for their design and analysis. In terms of design, the "object of design" changes from being just the technical/physical elements, as in traditional engineering practices, to include also social/organisational elements such as institutional arrangements (Franssen and Kroes 2009; Melese, Stikkelman, and Herder 2016). Without taking care to design properly both types of elements, the sociotechnical system will not be able to fulfil its purpose effectively. Additionally, the presence of social/organisational elements implies that the "control paradigm" of classical engineering cannot longer be upheld as these elements do not follow a law-like behaviour that can be anticipated (Franssen and Kroes 2009). Therefore, criteria like flexibility and robustness take a crucial role in the design of these type of systems (Franssen and Kroes 2009; Melese et al. 2016). In terms of analysing these

systems, the "object of study" also changes from being just the technical/physical elements to include as well social/organisational elements. This means that a traditional engineering approach to analysing infrastructure systems, such as transport infrastructure, by modelling the behaviour of the technical elements in isolation will not provide an adequate image of the possible behaviour of the infrastructure system. There is a need to include social infrastructure elements in the analysis of infrastructure systems if these are to be understood properly and holistically. For instance, as Amoaning-Yankson and Amekudzi-Kennedy (2017) suggest, there is evidence that shows that moving from a technical focus to a sociotechnical focus on transportation planning brings large added benefits to the resilience of transportation infrastructure systems and the societies they serve.

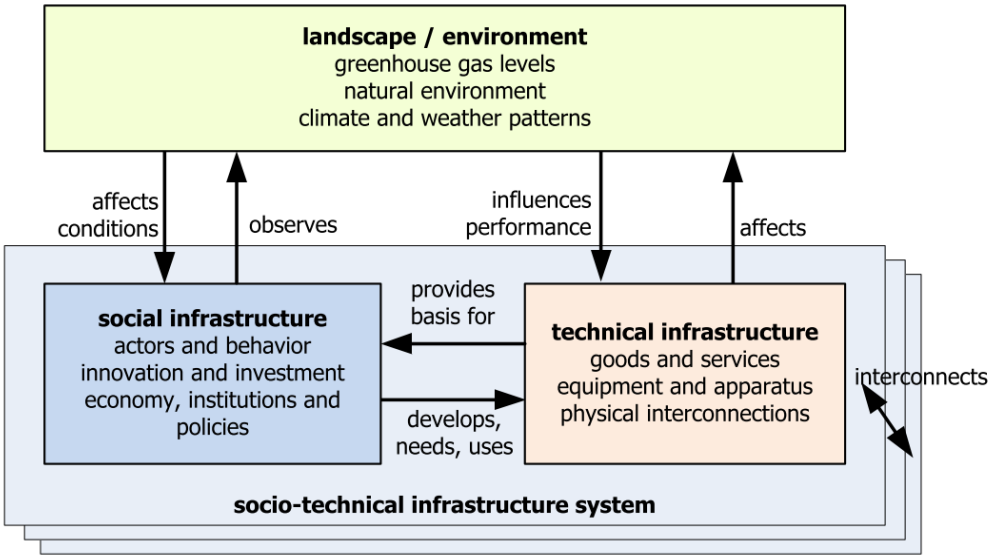

Figure 2. A sociotechnical systems perspective on climate-affected infrastructures. Sourced from Chappin and van der Lei (2014).

Adding to the complexity of the concept, adaptation has also been associated with development. Development and adaptation have no universal definitions, which allows for the relationship between the two concepts to be blurry, especially in practice (Agrawal and Carmen Lemos 2015; Eichhorst 2009; McGray et al. 2007; Pelling et al. 2015; Sherman et al. 2016; Wise et al. 2014). Development is usually associated with "efforts to alleviate poverty, reduce marginalization and inequities, and maintain environmental and social integrity; whereas, others [equate] development with economic growth" (Sherman et al. 2016:712). According to McGray et al. (2007), the relationship between the two concepts is blurry because adaptation and development efforts share many methodological similarities. Additionally, they argue that it is difficult to separate adaptation and development as their objectives can overlap and because anthropogenic climate change has become difficult to dissociate from "normal" climate variability. Some authors have also tried to differentiate between adaptation and development to clarify the relationship. Agrawal and Carmen Lemos (2015), for example, suggest that the two concepts can be separated by how adaptation has a greater focus on risk management than development.

In their literature review, Sherman et al. (2016) show that most of the articles they reviewed in which the relationship between adaptation and development is discussed distinguish between the two concepts in different ways. According to their review, some authors state that adaptation and development operate in different time scales (adaptation efforts focus on long-term planning while development efforts focus on short to medium-term planning). Other authors maintain that adaptation efforts are based more on vulnerability assessments and that there are fewer practical experiences of the implementation of adaptation efforts. Others state that there are specific climate-related objectives that can only be addressed by adaptation and not by common practices of the development sector.

Although the literature identifies several theoretical differences between the two concepts, the division between adaptation and development activities continues to be unclear. Some attempts to frame the relationship between the two concepts can be found in the literature. For example, McGray et al. (2007) propose a framework where adaptation and development are part of a continuum that ranges from "pure" development activities (or vulnerability-oriented adaptation efforts) to "pure" adaptation activities (or impact-oriented adaptation efforts). Agrawal and Carmen Lemos (2015) propose combining adaptation and development in what they call "adaptive development". They define adaptive development as "a form of development that mitigates risks without negatively influencing the well-being of human subjects and ecosystems" (Agrawal and Carmen Lemos 2015:186). Pelling et al. (2015) suggest that adaptation and development only coincide when the objectives of adaptation efforts address the systemic drivers and structural root causes of vulnerability. According to them, this only occurs when societies achieve "transformational adaptation" (see Section 3.1).

Understanding the relationship between adaptation and development has important practical implications, especially in terms of funding allocation. In recent years, different international funding agencies have created adaptation funds that are separate from traditional development funds. This has created pressure to clarify the division between adaptation and development to determine which activities can be considered adaptations and receive financial resources from adaptation budgets. This division can make it difficult for some activities which touch adaptation and development goals, known as "win-win" or "no-regret" solutions, to receive funding since they exist in a grey area between the two efforts (McGray et al. 2007; Sherman et al. 2016).

More work is needed to better frame the relationship of development and adaptation in a way that would allow for efforts in both areas to be effectively operationalized in the practice. Sherman et al. (2016) suggest that most of the academic work discussing the relationship between adaptation and development has been accomplished by professionals with a social science background. This indicates that there is still a gap in terms of investigating this relationship from an engineering perspective. A view from engineering could contribute to the discussion by showing the operational and practical implications of combining adaptation and development efforts. This thesis seeks to contribute to this debate by

discussing how adaptation planning in the context of urban transport infrastructure could achieve transformational effects that achieve both adaptation and development goals (see Chapter 3). The next sections discuss in detail the concepts of adaptation planning, adaptation strategies and actions, and adaptation barriers, continuing to frame the theoretical context for the conceptual framework of this research.

2.4.1. Adaptation planning

Adaptation activities can be classified as autonomous or planned according to their intent (Biagini et al. 2014). Autonomous adaptation can be defined as "'natural or spontaneous adjustments in the face of a changing climate" (Smith, Tol, and Fankhauser 1999). On the other hand, planned adaptation involves intentional and purposeful actions to cope with the effects of climate change. This research focuses on the processes of adaptation planning and planned adaptation activities. Climate adaptation planning can be defined as "social and decision processes that facilitate the implementation of interventions to reduce vulnerability and/or take advantage of potential opportunities associated with climate variability and change" (Preston et al. 2011:413). These processes occur in four stages common to any planning process: "goal-setting", "stock-taking", "decision-making", and "implementation and evaluation" (Preston et al. 2011). Additionally, climate adaptation planning requires the consideration of different factors other than climate change such as current climatic risks, key non-climatic challenges, and economic development plans (Füssel 2007). Adaptation planning is considered by different authors to be a social learning process that should leave room for experimentation and flexibility (Eichhorst 2009; IPCC 2014; McGray et al. 2007; Park et al. 2012; Wise et al. 2014).

Adaptation planning is a complex process that involves managing high degrees of uncertainty about the future (Adger and Barnett 2009; IPCC 2014; Mimura et al. 2014), political and governance issues (Eriksen et al. 2015), inclusivity issues (Chu et al. 2016), technological limitations, and economic challenges (Auerbach and Herrmann 2014; Dhar and Khirfan 2017; IPCC 2014). These levels of uncertainty and the size of the challenges make adaptation planning a complicated task as there is always the risk of succumbing to maladaptation pathways (Adger and Barnett 2009; Wise et al. 2014). Barnett and O'Neill (2010:211) define a maladaptation action as an "action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups". They argue that there are at least five types of maladaptation actions. According to them, these are adaptation actions that, "relative to alternatives: increase emissions of greenhouse gases, disproportionately burden the most vulnerable, have high opportunity costs, reduce incentives to adapt, and set paths that limit the choices available to future generations [path dependency]" (Barnett and O'Neill 2010:211). Nevertheless, the uncertainty associated with adaptation planning should not be used as a justification for inaction (i.e. the precautionary principle).

It is commonly acknowledged in the literature that adaptation planning has been implemented less in practice compared to mitigation efforts since it is a much more complex process (Füssel 2007; Di Giulio et al. 2017). This is mainly due to the fact that the effectiveness of mitigation efforts is much more straightforward to evaluate. For mitigation, the reduction of greenhouse gas emissions can be used as a measure of the effectiveness of efforts, while there are no "off-the-shelf" metrics available for evaluating adaptation initiatives (Araos et al. 2016). Because of this, decision-makers in cities, such as urban planners and transport authorities, are prone to adopting a "mitigation tunnel vision", in which only mitigation efforts are pursued as they provide easy-to-track results (Carter et al. 2015). The position of the IPCC (2014), and other sources on adaptation planning (such as Eichhorst (2009) and Füssel (2007)) is that this should be avoided and ideally, mitigation and adaptation efforts should be complementary in practice.

Existing approaches to adaptation planning have different focal points, such as ecosystem-based adaptation, community-based adaptation and infrastructure-based adaptation (See Box 1 in Appendix 1) (Dhar and Khirfan 2017; DNP 2012; MinTransporte et al. 2014). Sherman et al. (2016) present a set of three alternative approaches to planned adaptation in developing contexts. The three approaches are: a) technocratic risk management, b) pro-poor vulnerability reduction, and c) sustainable adaptation (See Box 2 in Appendix 1). According to Sherman et al. (2016), the most appropriate approach varies depending on the context. They also argue that each approach has its own limitations and they recognize that all may be necessary to a certain extent. This thesis proposes that for transport infrastructure planning, infrastructure-based adaptation and sustainable adaptation are the most appropriate approaches. This is because the main purpose of infrastructure-based adaptation is to "improve the adaptive capacity of infrastructure assets that play a determining role in economic development" (DNP 2012:71), such as transport infrastructure. For its part, a sustainable adaptation approach is consistent with the definition of adaptation of transport infrastructure presented earlier in this chapter, as this approach promotes actions that achieve adaptation, development and mitigation outcomes that are socially and environmentally sustainable.

Road authorities around the world have developed frameworks as a way of operationalising climate change adaptation planning. These frameworks are decision-making guides or roadmaps for the implementation of adaptive actions that organisations can use when confronted with climate uncertainties. Examples of adaptation frameworks include those developed for national highways by the World Road Association (2015), the Federal Highways Association (USA) (2017), the UK Highways Agency (2015), National Academy of Sciences (USA) (Wilbanks and National Academies Press (U.S.) 2010), the Ministry of Transport of Colombia (2014), the Federal Highway Research Institute (Germany) (2014) and Rattanachot et al (2015), and for urban transport networks by Eichhorst (2009) and the Ministry of Transport of Colombia (2016). Some examples of these frameworks are presented schematically from Figure 3 to Figure 7.

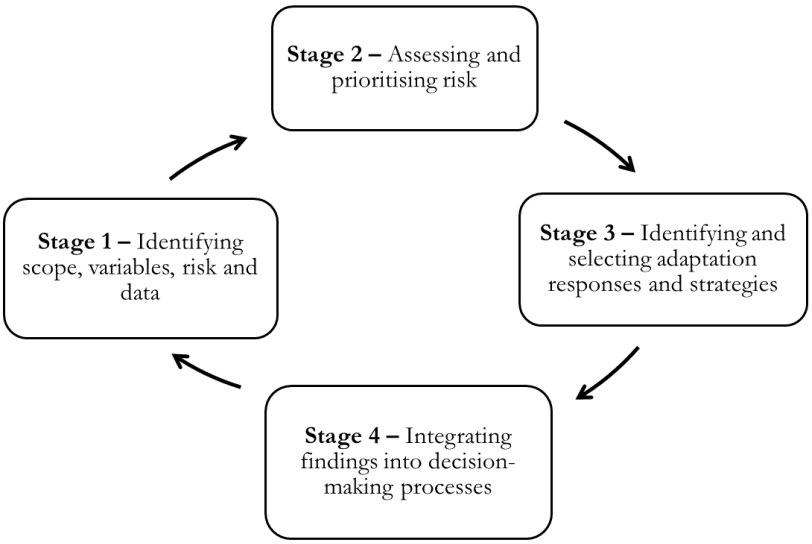

Figure 3. International Climate Change Adaptation Framework for Road Infrastructure (World Road Association). Adapted from World Road Association (2015).

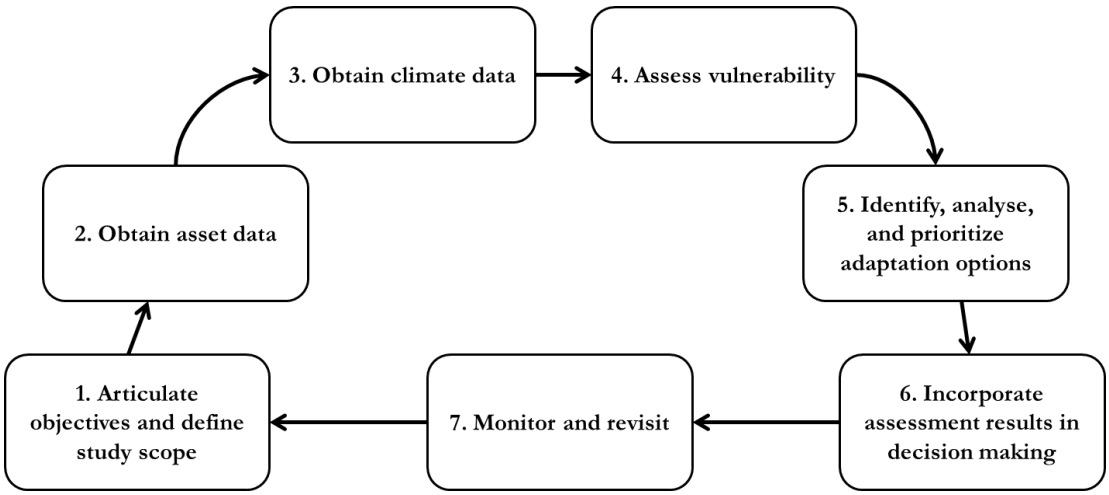

Figure 4. Vulnerability Assessment and Adaptation Framework (Federal Highways Administration (U.S)). Adapted from Filosa et al. (2017).

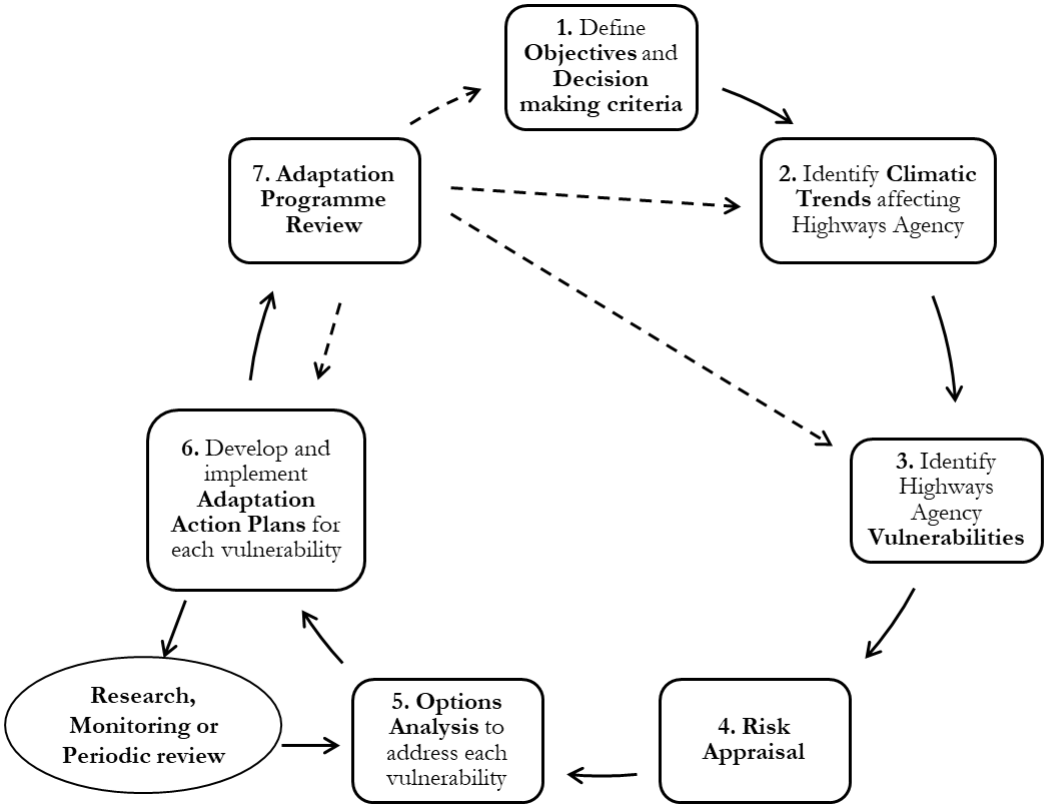

Figure 5. UK Highways Agency Adaptation Framework Model. The dashed lines show which stages are reviewed during the Adaptation Programme Review stage. Adapted from Filosa and Oster (2015).

Redrawing of the diagram presenting the adaptation framework of the National Academy of Sciences (US) removed for copyright reasons. Copyright holder is National Academy of Sciences (US).

Figure 6. National Academy of Sciences (US) adaptation framework. Adapted from Wilbanks and National Academies Press (U.S.) (2010).

Redrawing of diagram representing a framework for developing an adaptation strategy for urban transport development removed for copyright reasons. Copyright holder is Urda Eichhorst and Daniel Bongardt.

Figure 7. A framework for developing an adaptation strategy for urban transport development. Adapted from Eichhorst (2009).

These adaptation frameworks present commonalities. For instance, the first detail that is evident in all these examples is that the adaptation planning process is presented as cycling through similar stages. Some combine the stages into broader ones or divide them further, but in general it could be said that all frameworks coincide in that the adaptation process cycles through the following stages: 1) understanding the problem (i.e., identifying vulnerabilities and risk); 2) selection of an adaptation strategy; 3) implementation of adaptation actions; and, 4) evaluation and monitoring. These are similar to the four stages presented earlier by Preston et al. (2011). This is not surprising as these stages are based on a fairly widely accepted approach for any sort of policy, planning intervention or project. Another common aspect is that the frameworks reviewed show that road authorities around the world are managing the adaptation process from an infrastructure-based approach and a technocratic risk management perspective. This is evident in the language used in the examples and the language used around these frameworks which is directly derived from infrastructure asset management and risk management. For example, it is suggested by the World Road Association (2015), that this approach could help mainstream adaptation[4] by incorporating it into the existing risk management and asset

[4] Pelling (2011:111) defines mainstreaming as "the absorption of innovations into dominant policy and practice".

management programmes of the sector. As is discussed later in Chapters 6 and 7, this might not always be an appropriate approach as is evident in the case study presented by this thesis.

2.4.2. Adaptation strategies

After understanding the implications of climate change on their territories, the first step taken by road authorities in their frameworks is the development of strategies. The selection of any of these strategies depends on various environmental, technical, economic, geographical and social considerations, and on the type of risk (Rattanachot et al. 2015). Several authors suggest different types of strategies that authorities can select to follow. For example, Eichhorst (2009) proposes a general typology in which adaptation strategies can be broadly divided into three categories: retreat (or avoid), protect, and accommodate (Figure 8). Meanwhile, Rattanachot et al. (2015) suggest a similar typology in which adaptation strategies can be broadly divided into three groups: avoidance, improvement and replacement.

Redrawing of figure representing three broad categories of adaptation strategies removed for copyright reasons. Copyright holder is Urda Eichhorst.

Figure 8. Three broad categories of adaptation strategies according to Eichhorst (2009).

More detailed typologies of adaptation strategies for road infrastructure are available. The Conference of European Directors of Roads (CEDR) (2015), for example, suggests six different strategies that road authorities can follow based on the timing relative to the climatic stimuli and the type of adaptation measures implemented. The six strategies are: do minimum and develop contingency plans; future-proof designs; retrofit solutions; update operating procedures; monitor assets; and invest in research. It should be noted that not all of the strategies are mutually exclusive, and the CEDR recommends that authorities seek the combination of strategies that is most cost-effective for their local context (CEDR 2015). The World Road Association (2016) proposes the following general types of strategies: repair and maintenance; relocation; abandonment/disinvestment or avoidance; improving facility redundancy;

and reconstruction/strengthening. Casello and Town (2017) suggest the following five categories of strategies for urban transportation systems:

- *Investing in more resilient materials, infrastructure, and operational practices for transportation infrastructure.*
- *Improving redundancy within transportation networks.*
- *Updating the climate design criteria used in engineering standards to better reflect future conditions.*
- *Improving land use policies and controls.*
- *Enhancing the resilience of communities to extreme weather and climate effects through social adaptations.*

The first typologies presented by Eichhorst and Rattanachot et al. seem to be focused on the management of individual assets rather than in the management of systems. They do not include considerations of, for example, redundancy, which is an important element of adaptation of networks. These considerations are included in the typologies from the World Road Association and Casello and Town. Both the typologies of CEDR and the World Road Association show how these organisations focus heavily on the management of assets in highway networks rather than on urban road networks. This is evident principally in that they do not prioritise the resilience of communities as Casello and Town do. This is because the resilience of communities is perhaps a more pressing matter in urban contexts. These examples show that in general, the perceived available and necessary adaptation strategies will depend on the context and the priorities of the organisations developing the strategies.

The selection of an adaptation strategy or strategies is the first step in adaptation planning. Nevertheless, as this section shows, choosing those strategies that are most effective in a given context is a challenging process for any road authority. This is because road authorities must have a holistic understanding of climate change and its consequences, and of the diversity of possible adaptation pathways to follow. This presents the need for useful frameworks that can aid authorities in navigating these challenges. This is why this thesis presents a conceptual framework in Chapter 3 that aims to help decision-makers and policymakers to reach more informed considerations of the different adaptation pathways available to them and the implementation of these pathways (i.e., which strategy to follow). The next step after selecting an adaptation strategy is determining which actions to implement. This is discussed in the following section.

2.4.3. Adaptation actions

Once authorities select an adequate strategy or strategies, they need to decide which associated adaptation actions to implement. Based on the characteristics of the risks created by climate change (see Section 2.2), adaptation requires two main forms of response: 1) dealing with long-term climatic

changes, and 2) developing resilience to acute and extreme weather events. These responses need to be directed towards reducing the sensitivity of the sociotechnical system, altering its exposure and/or increasing the resilience of the system (Adger et al. 2005). There are a vast number of actions that could be employed and they are not limited just to the improvement of the physical design of transport infrastructure (Pregnolato et al. 2016).

A diverse range of typologies of adaptation actions exist. For example, the ROADAPT project has a database of more than 500 adaptation actions associated with the six types of adaptation strategies suggested by CEDR which are divided into the following categories (CEDR 2015):

- Planning for climate change impacts and extreme weather events.
- Robust construction.
- Legislation and regulations.
- Resilient construction.
- Maintenance and management.
- Traffic management for climate change impacts and extreme weather events.
- Capacity building.
- Monitoring.
- Research.

The World Road Association (2015) presents a list of examples of possible theoretical actions according to the type of weather-related risk. Biagini et al. (2014) propose a typology of adaptation activities based on a review of the implementation of adaptation projects around the world. They divide adaptation activities into ten different categories as presented in Table 1. This research adopts this typology of adaptation actions, as it is the only example found by this review that connects adaptation theory with its practice. This is because Biagini et al. established the categories of their typology by comparing and organizing 92 practical experiences in several countries and later compared these categories with different theoretical constructs of typologies of adaptation actions found in the literature. Through this process, they found that early theoretical ideas of adaptation actions are consistent with the results from the practical experiences they studied. Table 1 presents the definitions of the categories of Biagini et al.'s typology. It is important to note that Biagini et al.'s typology was not developed specifically for road infrastructure projects, but for adaptation projects in general. Because of this, some examples of adaptation actions for each category in the context of road infrastructure have been added by this researcher to the table for illustration purposes. These examples have been provided based on the description made by Biagini et al. of each category.

After implementation, adaptation actions need to be evaluated to determine their success. According to Adger et al. (2005), the success of adaptation measures depends on both the temporal and spatial scale,

and success can be assessed through reference to effectiveness, economic efficiency and the promotion of equity and legitimacy. There is consensus amongst different authors that the most effective and least costly adaptation measures are those implemented in an anticipatory and precautionary way (Dhar and Khirfan 2017; EEA 2014; Schweikert, Chinowsky, Espinet, et al. 2014; UNEP 2016; Wilbanks and National Academies Press (U.S.) 2010). However, if anticipatory adaptation is not well planned, adaptation actions could lead to under- or over-adapted systems to the future climate, thus creating additional unexpected costs (Dittrich, Wreford, and Moran 2016).

Table 1. Adaptation actions categories according to Biagini et al. (2014) with added examples of actions in the context of road infrastructure.

Adaptation actions categories	Description	Examples in the context of road infrastructure
Capacity Building	Developing human resources, institutions, and communities, equipping them with the capability to adapt to climate change	• Training/workshops for knowledge/ skills development. • Public outreach and education. • Dissemination of info to decision-makers/stakeholders in the transport sector. • Identification of best practices, training materials.
Management and Planning	Incorporating understanding of climate science, impacts, vulnerability and risk into government and institutional planning and management.	• Development of new climate change policies, plans and strategies in the road sector. • Better climate data management and future-focused planning in the road sector.
Practice and Behaviour	Revisions or expansion of practices and on the ground behaviour that are directly related to building resilience.	• Review of land use planning legislation and road construction standards. • Reorganisation of the road sector's institutional arrangements in a city. • Major change in the use of roads in a city (i.e. transformation of vehicle roads to pedestrian roads with "green" infrastructure). • Shift in prioritisation methods beyond economic appraisal to more sustainable decision-making methods.
Policy	The creation of new policies or revisions of policies or regulations to allow flexibility to adapt to changing climate.	• Development of new climate change policies and strategies in the road sector. • Review of land use planning legislation and road construction standards.
Information	Systems for communicating climate information to help build resilience towards climate impacts (other than communication for early warning systems).	• Better climate data management and future-focused planning in the road sector. • Creating better information systems.
Physical Infrastructure	Any new or improved hard physical infrastructure aimed at providing direct or indirect protection from climate hazards.	• Use of SUDS in combination with urban roads. • Construction of protective infrastructure like flood barriers next to roads. • New or more resilient road pavement structures.
Warning and Observing systems	Implementation of new or enhanced tools and technologies for communicating weather and climate risks, and for monitoring changes in the climate system.	• Better climate data management. • Monitoring systems along road networks.

"Green" infrastructure	Any new or improved soft, natural infrastructure aimed at providing direct or indirect protection from climate hazards.	• Use of 'green' infrastructure like trees or meadows in combination with urban roads.
Financing	New financing or insurance strategies to prepare for future climate disturbances.	• New financing or insurance options for road projects to prepare for future climate disturbances. • New contingency funds for disasters.
Technology	Develop or expand climate-resilient technologies.	• Novel materials and construction and maintenance techniques.

There are several examples of studies that investigate the effectiveness and costs of particular adaptation measures based on case studies. Most of the studies found in this literature review focus only on economic or monetizable factors and do not include the interdependencies between elements of the sociotechnical system associated with road infrastructure (see Figure 2 in Section 2.4), thus allowing for a part of the problem to be excluded from the analysis. This leaves scope for more to be done to create a more comprehensive evidence base, particularly with respect to studies that take a broader view of adaptation of road infrastructure to climate change. An example of studies that investigate the effectiveness and costs of particular adaptation measures based on case studies is the analysis done by Pregnolato et al. (2016) of the effectiveness of the use of Blue/Green Infrastructure and Sustainable Urban Drainage Systems (SUDS) as adaptation measures to protect the road system from flooding in Newcastle upon Tyne in the UK. Another example can be found in Wang et al. (2015) where the authors analyse the effects of flooding in Hong Kong over flexible pavement road structures. After looking at these effects and different adaptation measures that included increasing the pavement thickness or making drainage systems better, they suggest that the most cost-effective solution in many cases can be implementing strict post-flooding traffic control measures. This is because restricting heavy traffic while the humidity of the road pavement structure is still high after a flooding event has the potential to avoid structural damages to the road. Schweikert et al (2014) present a further example in which they demonstrate the use of an adaptation decision-support tool called the Infrastructure Planning Support System to show that a proactive adaptation approach costs less than a reactive one for ten different countries for projections done both to the year 2050 and the year 2100.

2.4.4. Adaptation barriers

All processes in adaptation planning, from the creation of policies to the implementation and monitoring of these actions, can be hindered by a series of barriers which can be defined “as obstacles that can be overcome with concerted effort, creative management, change of thinking, prioritisation, and related shifts in resources, land uses, institutions, etc” (Moser and Ekstrom 2010).

Different authors have tried to identify barriers to the adaptation planning process in different contexts. Moser and Ekstrom (2010), for example, present a series of lists of common barriers during the phases of understanding, planning, and managing the adaptation process and suggest that the most common

cross-cutting issues exist in leadership, resources, communication and information, and values and beliefs. Wise et al. (2014) identify different reasons for the limited conversion of plans into adaptation action which include behavioural and cognitive aspects, unconducive governance arrangements, the lack of or self-interested leadership, competing planning agendas and the lack of institutional coordination, historical determinacy and path-dependency, and the incorrect or incomplete diagnosis of problems. In the urban context, Dhar and Khirfan (2017) suggest that the success of adaptation measures in human settlements can be hindered by: 1) weak institutions, 2) the lack of financial resources, and 3) inadequate or inappropriate urban planning. Consequently, they recommend that city authorities and engineers find ways to effectively overcome these barriers so cities can cope better with the natural risks generated by climate change. Di Giuilo et al. (2017) describe other barriers at the city level such as the existence of short governing periods for local authorities, the mismatch between the scale of urgent urban issues and the local government authority's limited initiative to address them, and the lack of autonomy to regulate specific sectors and economic agents, amongst others. These examples suggest that most barriers for effective adaptation planning originate from the social infrastructure component of sociotechnical systems and not the technical component, and yet they have significant implications for what will be feasible in the latter (See Figure 2 in Section 2.4). Particularly, these examples show the importance of the institutional environment in how it influences which adaptation actions are considered feasible and preferable by different authorities.

As Wise et al. (2014:329) state, "while identifying potential problems is important, shopping lists are not helpful: a key challenge for adaptation research is to identify which barriers are likely to arise in which kinds of contexts to inform how to address them". Here, when talking about shopping lists, Wise et al. refer to lists of theoretical barriers to the adaptation process disconnected from any context. As a result, some authors have tried to develop analytical frameworks to map the barriers of the adaptation process and determine their causes. For example, Moser and Ekstrom (2010) present a systematic framework to identify barriers to adaptation in a descriptive way. Their framework is actor-based, focuses on intentional, planned adaptation, and has three structural elements (actors, context and object upon which they act). They suggest that barriers arise from all of these structural elements and their interactions and can appear in any of the phases of adaptation planning (which they define as understanding, planning and managing). Eisenack and Stecker (2012) propose a framework that conceptualizes adaptations as actions and helps map barriers to adaptation in a systematic way. Adaptations in this framework are conceptualized as mean-end chains, or a series of actions with a defined purpose. The framework has five main concepts: the stimulus, the exposure unit, the receptor of adaptation, the operator of adaptation and the means (i.e. resources, knowledge, power) (see Figure 9). According to their framework, there are four types of adaptation barriers: "missing operator", "missing means", "unemployed means" and "complex actor relations" (Eisenack and Stecker 2012). Lehmann et al. (2015) present an analytical framework to identify barriers to and opportunities for urban

adaptation planning. In this framework, barriers can appear in relation to information, resources and incentives, and these barriers are dependent on series of underlying factors related to actor-specific characteristics, the institutional environment, and the natural and socio-economic environment. This research integrates the latter framework as one of the analytical tools of the conceptual framework presented in Chapter 3. It is considered that this interpretation of barriers to adaptation is more comprehensive than others as it aims not only to identify what barriers exist but also tries to explain the factors that make them arise in a particular context. Another reason for selecting this framework is its versatility, as has been proven by Lehmann et al (2015) to be useful in identifying barriers and opportunities in both developing and developed countries contexts. This framework and the reasons for selecting it are described in more depth in Chapter 7.

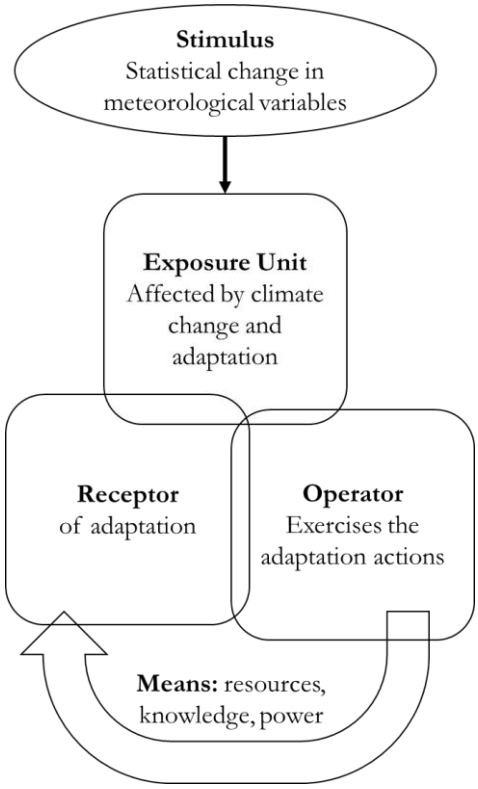

Figure 9. Schematic representation of the core concepts of framework by Eisenack and Stecker (2012). Adapted from Eisenack and Stecker (2012).

2.5. Chapter summary

This chapter first presented a review of the concepts of decision-making, risk and resilience in the context of climate change. This review served as a basis for understanding the concept of adaptation. Adaptation has been presented as a precautionary approach to coping with the risks caused by climate change and as a process of resilience building of sociotechnical systems. It is a process that requires good planning by creating adequate frameworks and strategies that allow for the selection of effective

adaptation actions and the overcoming of different barriers. If implemented effectively with road infrastructure systems, as with the technical components of other sociotechnical systems, it can provide important socio-economic and environmental benefits. This precautionary approach has the potential to be more beneficial in regions of the world where investment possibilities are limited and avoiding the costs of future damages to infrastructure are crucial. Overall, this chapter has focused on presenting the climate risk management aspect of adaptation and the fundamentals of adaptation planning. The next chapter further expands the literature review of this thesis by presenting the change management aspect of adaptation to climate change. This final element of the literature review is presented separately from this chapter as it provides the core theoretical basis for the conceptual framework.

The next chapter builds on the existing definitions and theory of adaptation discussed in this chapter to develop a conceptual framework that holistically captures the processes of adaptation planning and key considerations at each stage of the process. It also introduces the idea of "scales of adaptation" as a way of helping decision makers, such as transport planners, consider how to develop adaptation strategies that are appropriate to the context within which they operate so they are able to manage climate risk in a way that it is appropriate to the pursued level of sociotechnical change.

Chapter 3

3. Conceptual framework

This chapter presents the conceptual framework developed for this thesis, building upon the discussion presented in the previous chapter. The chapter begins by expanding further the literature review with a discussion of the management of change through adaptation planning and the different scales at which adaptation can be implemented. The chapter proceeds by briefly describing a framework proposed by Park et al. (2012) called the "Adaptation Action Cycles" (AAC). This framework conceptualizes adaptation planning as an action-learning process and incorporates the idea that adaptation can be achieved in two different scales (incremental adaptation and transformational adaptation). The chapter concludes with the description of a revised conceptual framework proposed by this author that expands the AAC concept by including other scales of adaptation and the identification of barriers to and opportunities for effective adaptation planning, called the "Expanded Adaptation Action Cycles" (EAAC) framework.

3.1. Adaptation: the management of climate risks and change

Adaptation planning brings together different processes not only for the management of climate risks, but also for the management of change in sociotechnical systems. In order to advance the discussion, this section examines the concept of change and its management through adaptation planning. This final element of the literature review is presented separately from the previous chapter as it provides the core theoretical basis for the conceptual framework.

Adaptation planning, by definition, involves the intentional and purposeful planning of change in sociotechnical systems so these systems are able to cope with climate change. As Park et al. (2012:115) state: "adaptation includes not only the set of actions undertaken to maintain the capacity to deal with current or predicted future change, it also relates to the decision-making process associated with change management itself". This idea of managing change is inherent in the definition of adaptation established in Chapter 2. Change can be managed at different levels or spaces in sociotechnical systems. For example, Pelling et al. (2015) propose a framework called the "adaptation activity space" to identify spaces in which change can occur due to adaptation. According to Pelling et al. (2015), change can occur in seven different activity spheres as a result of internal processes of change or as a response to the interactions with other spheres. These changes can occur at any spatial scale and at different levels

of transformation. The activity spheres are individuals, technology, institutions, livelihoods, the environment, people's behaviour, and society's discourse.

Adaptation can be implemented in different scales depending on the depth of change pursued. Different classifications of the scales of adaptation can be found in the literature, but most coincide in identifying the existence of two principal scales of adaptation: incremental adaptation and transformative (transformational) adaptation (as classified in Kates et al. (2012), Moser and Ekstrom (2010), Park et al. (2012), Pelling et al. (2015), Revi et al. (2014), Rickards and Howden (2012), Sherman et al. (2016) and Wise et al. (2014)).

Incremental adaptation actions are "marginal changes in infrastructure, institutions and practices that foster flexibility and fulfil capacity while not directly threatening systems integrity" (Pelling et al. 2015:117). This scale of adaptation is the most commonly proposed by urban authorities in practice (Pelling et al. 2015; Sherman et al. 2016; Wise et al. 2014). Incremental adaptation is adequate when there are low levels of vulnerability in the socioecological system. That is, for example, when populations have access to sufficient resources and when there is capacity to absorb the expected impacts of climate change (Kates et al. 2012).

Transformational adaptation is a "discrete process that fundamentally […] results in change in the biophysical, social, or economic components of a system from one form, function or location (state) to another, thereby enhancing the capacity for desired values to be achieved given perceived or real changes in the present or future environment" (Park et al. 2012:119). Adaptation can be considered transformational when: 1) actions are adopted in a much larger scale or intensity, 2) adaptation actions are particularly new to a socioecological system, and 3) adaptation actions profoundly change places and shift locations of elements of the system (Kates et al. 2012). Transformational adaptation is a process that occurs less frequently than incremental adaptation; only at specific moments in time. It occurs when the vulnerability of a socioecological system reaches levels in which the execution of large degrees of change is the only way for the system to thrive. This creates ethical and procedural problems with high stakes for decision-makers since transformational processes bring into focus questions such as "what needs to be changed?" and "who decides these changes?" (Pelling et al. 2015).

The large-scale changes required by transformational processes imply high uncertainty of results, meaning that both negative and beneficial outcomes can result from transformation (Park et al. 2012). For this reason, according to Revi et al. (2014), the IPCC suggests that transformational adaptation may be only achieved by cities with high adaptive capacity (IPCC 2014), but as Sherman et al. (2016) propose, adaptation may not be possible without transformative changes to the system or structure in many developing countries with low adaptive capacity. Additionally, there are interactions between incremental and transformational adaptation. For example, the accumulation of incremental changes may trigger transformations in a process called "transitional adaptation". Pelling et al. (2015:117) define

this process as “changes that individually do not exceed systems thresholds, but in aggregate and over time can transform systems”. They add that incremental changes may have potentially the contrary effect and delay transformation or even block it. Other authors suggest that interactions between incremental and transformational adaptation can be kept positive, as they propose that both scales may be necessary to accomplish effective adaptation in the short and the long-term by adequately alternating between them (Park et al. 2012; Pelling et al. 2015; Sherman et al. 2016).

This research adopts the classification of adaptation scales from Pelling et al. (2015) as a basis for the conceptual framework of this thesis. This classification of adaptation scales is adopted since it is more comprehensive than other frameworks as it includes a lower scale of adaptation called “resistance”. Pelling et al.’s three scales of adaptation are presented in Table 2. The columns for the definitions of the scales and their advantages and disadvantages towards managing climate risks and change are directly adopted from Pelling et al. (2015). As can be observed, each scale of adaptation involves different objectives, outcomes and planning horizons. Each scale requires different types of resources, information and incentives to actors for its design and implementation. The final column of Table 2 has been added to show where various adaptation actions in the context of road infrastructure fit in this classification of adaptation scales (see Section 2.4.3 for examples of adaptation actions). The examples were selected to fit into each category according to the definition of each scale. It is important to note that the list of examples is not comprehensive but captures many key considerations that help to differentiate each scale with some tangible actions.

Table 2. Scales of adaptation based on Pelling et al. (2015) and examples of adaptation actions in the context of road infrastructure for each scale.

Scale of adaptation	Definition	Advantages	Disadvantages	Examples
Resistance	• Increased and concentrated investment in existing development pathways, infrastructure, institutions and practices	• Allows for 'business-as-usual': established stakeholders and institutional regimes are already in place and are supported by capital throughput. Investments are externally visible examples of risk management that produce political advantage.	• This 'all-or-nothing' strategy can narrow down worldview and technical capacity restricting management options and reducing flexibility over time so generating hidden vulnerability within system structures.	• Standard road maintenance practices to cope with weather events (e.g., regular cleaning of drainage structures, dealing with cracks and potholes). • Securing more budget for maintenance operations. • Use of standard insurance options for all assets at risk.
Incremental adaptation	• Marginal changes in infrastructure, institutions and practices that foster flexibility and fulfil capacity while not directly threatening systems' integrity.	• Enables re-organisation without causing major systemic disruption. Diversity in development vision and path, human resource and supporting systems can be built gradually over time rendering transactions cost more politically palatable. • Allows for system flexibility, diversity, supports redundancy and incrementally can open scope for experiments in decision-making enhancing broader governance objectives.	• Committed to functional persistence, it does not allow for challenges to the underlying values and assumptions that give rise to systemic vulnerability.	• Novel materials and novel construction and maintenance techniques. • Use of SUDS and 'green' infrastructure in combination with urban roads. • Review of land use planning legislation and of road construction standards. • Development of new climate change policies and strategies in the road sector. • New financing or insurance options to prepare for future climate disturbances. • Better climate data management and future-focused planning in the road sector.
Transformative adaptation	• Fundamental change to the functioning of systems.	• Opens new areas of policy response by going beyond existing systemic forms. Allows deep-rooted causes of risk and vulnerability to be addressed as part of a reorientation of development pathway towards social justice and sustainable development.	• Can cause significant and unexpected secondary costs as systems reach a new equilibrium. • Risks undermining the stability of economies, ecosystems or societies. • The poorest may be the most exposed to the transaction costs of transformation in the short term.	• The reorganisation of the road sector's institutional arrangements in a city. • Significant change in the use of roads in a city (e.g., the transformation of vehicle roads to pedestrian roads with "green" infrastructure). • The shift in prioritisation methods beyond economic appraisal to more sustainable decision-making methods.

3.1.1. The Adaptation Action Cycles (AAC) framework

The previous section presented the change management component of adaptation planning and the notion of scales of adaptation. This section describes briefly the concept of "Adaptation Action Cycles" (AAC) developed by Park et al. (2012) and its main assumptions. This concept is discussed here as this will allow the reader to understand better in the next section how the conceptual framework developed for this thesis expands the AAC concept.

The AAC framework developed by Park et al. (2012) is presented as a conceptual framework that helps to understand the information needs and policy support requirements of decision-makers, at the individual and enterprise scale, when acting in response to climate change. The authors suggest that their framework facilitates the understanding of adaptation and change processes occurring within typical decision-making timeframes of enterprises and human systems (typically less than ten years).

The AAC framework builds upon previous concepts of adaptation planning and transition management. This framework conceptualizes adaptation planning as an iterative action-learning cycle. In each iteration of the planning cycle, decision-makers implement adaptation actions based on their best current knowledge while at the same time (through evaluation and monitoring) they learn how to better adapt their systems in the next iteration. The framework considers only two scales of adaptation (incremental and transformation adaptation). These scales are depicted as two concentric action-learning cycles that operate as mutually exclusive and distinct processes (Figure 10). These concentric cycles explicitly represent the relative difference between incremental and transformation adaptation processes. As explained in the previous section, these processes differ in the resources needed, the scale of the agenda, the scale of the actions developed and implemented, and their effect over the socioecological systems being adapted. Furthermore, the authors hypothesize that the information and policy-support required by decision-makers depend on the scale of adaptation being pursued, although the drivers for both scales may be similar in some cases.

Adaptation is conceptualised here as a continuous cycle of incremental and transformative processes, and both processes cycle through the same four planning stages: 1) Problem structuring and establishing of the adaptation arena; 2) Developing the adaptation agenda, vision and pathway; 3) Implementing adaptation actions; and, 4) Evaluating, monitoring and learning. The authors state that "there is no pre-conceived outcome from the development and implementation of incremental or transformative adaptation actions, with capacity for infinite combinations of iterations at either scale of the concentric action-learning cycles" (Park et al. 2012:118). In other words, Park et al. suggest that there will always be uncertainty about the outcomes of adaptation actions and that the adaptation planning process is an iterative process. Because of this iterative nature, adaptation, in the long-term, occurs in different combinations of iterations of the adaptation planning cycle at either scale. For instance, a transformational cycle may be followed by several incremental cycles before another transformational

cycle happens again. The latter may be followed by another transformational cycle or by an incremental one and so on.

Park et al. (2012) suggest that there are different ways in which the incremental and transformational processes interact. First, the transition between the incremental and transformation cycles is a possible outcome of the knowledge or skills gained through evaluating, monitoring and learning activities (see arrow (a) in Figure 10), but the authors make no assumption that transformation is possible in all cases. Second, Park et al. suggest that once the outcome from a transformation strategy has been perceived as successful, the function of a system is re-established, possibly in another form, and the planning processes return to the scale of incremental adaptation until the conditions in the system require a further transformational change (See arrow (b) in Figure 10). Third, they suggest that there are dependencies between interacting spatial scales which allow incremental or transformative change to occur at a given scale (i.e. transformative change at a local system may allow for incremental change to continue being effective at a regional or national scale). And fourth, the authors suggest that both incremental and transformation processes can occur simultaneously at different sites within a complex system and that both may be required in the ongoing management of climate change as both short (tactical) and long-term (strategical) strategies are needed.

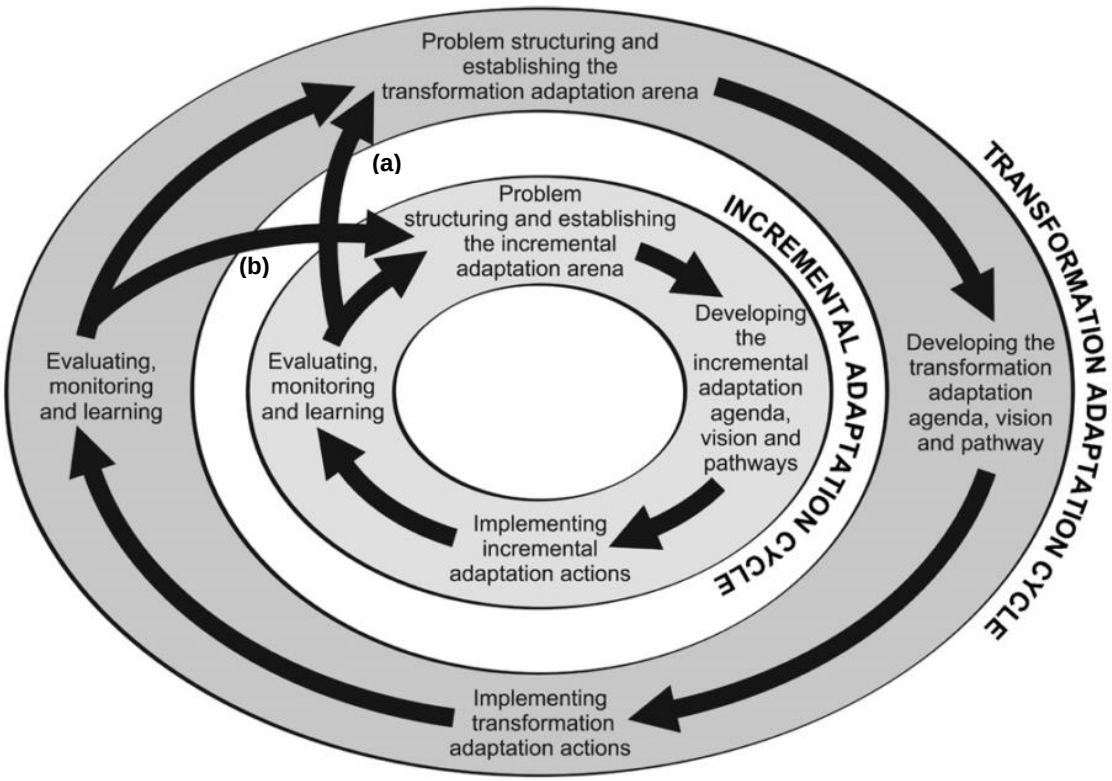

Figure 10. Schematic representation of the Adaptation Action Cycles, depicting two concentric, but linked, action learning cycles operating at different scales. Sourced from Park et al. (2012).

Park et al. (2012) also include the following assumptions about incremental and transformative adaptation in their conceptual framework:

- Both incremental and transformational responses are two sub-sets of a broader portfolio of possible adaptation strategies, which may include the active decision of not adapting. Nevertheless, Park et al. have decided to leave other scales of adaptation out of their framework.
- Transformation adaptation strategies, by their definition, involve purposeful decision-making.
- Both negative and beneficial outcomes may result from transformation.
- Transformation is a completely reversible process.
- Transformation can occur at any spatial scale or level of organisation.
- There is the potential for the desired outcomes that drive transformation, to not necessarily be present in the spatial scale that is required to transform.

In order to employ the framework as a diagnostic tool to understand the information and policy support required for adaptation planning, Park et al. (2012) propose using a series of key questions shown in Table 3. Park et al. formulate these questions expanding on a series of five key questions previously proposed by Wheaton and Maciver (1999) to understand the adaptation cycle. Park et al.'s questions offer the possibility of performing a systematic assessment of the decision-making processes in adaptation planning so decision-makers can develop more informed considerations of adaptation options and their implementation. Table 3 presents these questions and the stage of the adaptation cycle in which they should be used for this systematic assessment. The authors have demonstrated the utility of their conceptual framework by analysing a case study of the wine industry of Australia, but they suggest there is potential to use it in other sectors.

Table 3. Stage of the adaptation cycle and questions used to operationalise it. Sourced from Park et al. (2012).

Stage of adaptation planning cycle	Questions used for the assessment
1. Problem structuring and establishing of the adaptation arena	• What is the nature of vulnerability and the perceived risk? • Who or what adapts? • What do they adapt and why?
2. Developing the adaptation agenda, vision and pathway	• How do they adapt (processes)? • What are the opportunities for adaptation? • Costs and/or benefits of decisions?
3. Implementing adaptation options	• What implementation methods and resources are used? • What constrains or incentivizes implementation? • What impacts the results?
4. Evaluating, monitoring and learning	• How well do they adapt? • How does the system change? • What are the plans for the future?

This research acknowledges the potential of the AAC concept as a useful analytical tool to understand adaptation planning, but also recognises some of its shortfalls. For instance, the framework does not include all possible adaptation strategies (e.g., the resistance scale of Pelling et al.'s classification), immediately suggesting that it is incomplete. Consequently, this research expands on the AAC concept and presents a revised conceptual framework to capture more comprehensively all scales of adaptation. This revised conceptual framework goes further than other available frameworks as it links together the concept of the adaptation cycle, all scales of adaptation and the identification of barriers and opportunities; these are aspects that typically have been separately addressed in the literature. This research demonstrates the utility of this expanded framework for the urban transport sector in the final chapters of this thesis.

3.1.2. The Expanded Adaptation Action Cycles (EAAC) framework

This research proposes a modified version of Park et al.'s (2012) "Adaptation Action Cycles" (AAC) framework which includes the different scales of adaptation in a more comprehensive way and the possibility of identifying barriers to and opportunities for effective adaptation planning. This framework is named the "Expanded Adaptation Action Cycles" (EAAC) framework, acknowledging the foundation provided by Park et al.'s concept. Similar to the AAC, this revised framework aims to support insight into the decision-making processes and the associated resource requirements (i.e. information availability, policy support, financial resources, technology) of adaptation planning. The purpose of the EAAC framework is to provide more complete coverage of the key considerations of adaptation planning than existing frameworks. This means that in application it has the potential to help decision-makers and policymakers reach more informed considerations of the different adaptation pathways available to them and the implementation of actions related to these pathways. Ultimately, this will allow the different elements of sociotechnical systems managed by these decision-makers and policymakers to cope better with future and present climate risks and the required levels of change. The EAAC framework adopts many of the aspects of the AAC framework, such as focusing on the typical decision-making timeframes of enterprises and human systems (typically less than ten years).

While the AAC framework includes only the scales of incremental and transformation adaptation, the EAAC framework expands on it by including two more scales of adaptation: "resistance" and "no adaptation". Although Park et al. (2012) admit that there are more available adaptation pathways than incremental or transformational adaptation, they chose to omit them in their framework. These additional scales are included in the EAAC framework to capture more comprehensively all the available adaptation pathways. The scale of "no adaptation" is included since it should not be ignored that, in practice, it is clearly plausible that many stakeholders might take the active decision of not adapting (i.e., continue with business-as-usual practices), which could be justified in some cases. In

promoting adaptation, this has been ignored as well by other existing frameworks which have not acknowledged the possibility that a "no adaptation" pathway may be actively pursued.

In this framework, adaptation planning is conceptualized as an iterative action-learning cycle. In each iteration, decision-makers implement adaptation actions based on the best currently available knowledge while at the same time (through evaluation and monitoring) learn how to improve the adaptation of their systems in the next iteration. Figure 11 shows a schematic representation of the EAAC framework in which the scales of resistance, incremental adaptation and transformation adaptation are depicted as three concentric action-learning cycles that operate as mutually exclusive and distinct processes. At the centre of this representation is the option of "no adaptation", depicted as a point, as it constitutes a decision and not a process. The three concentric cycles shown in Figure 11 represent the differences in the extent of resources needed in each adaptation process (i.e. human, political, financial, technological, environmental, etc.), and the level of change pursued in the sociotechnical system on each scale of adaptation. The extent of resources needed and the level of change increase moving outwards from the central point (i.e., in the "no adaptation" option, no change is pursued, and no resources are used, while on the transformation adaptation scale, profound change in the system functioning is pursued which typically places a higher demand on resources).

The scale of adaptation required would depend on the level of risks faced. For example, the decision to not adapt is only rational when there is high confidence that the current and anticipated risks are moderate or low (Füssel 2007), while at the other extreme, transformation is required when the risks are so high that they could severely impair the functioning of the system (in this case, the urban road transport network) (Kates et al. 2012).

It is proposed that there is also a "gravitational pull" towards the centre of Figure 11, as there is a tendency to move towards lower scales of adaptation after effectively completing the processes on higher scales. For instance, after effectively adapting (i.e. the adaptive capacity of the system is increased), changes needed to maintain the function of the technical elements of a sociotechnical system would be less and societies would perceive a lesser need to invest resources in adaptation. As a consequence, adaptation efforts would remain usually between the resistance and incremental adaptation scales. This is congruent with the hypothesis proven by Park et al. (2012) that after transformation is successfully achieved, systems tend to go back to the realms of incremental adaptation.

An assumption from Park et al. which this research challenges, is that of considering transformation to be a completely reversible process. It is considered by this author, that it is highly unlikely, that, once deep changes are incorporated into a complex dynamic system, these changes could be completely reversed in order to return to a previous state, at least without any unforeseen, far-reaching consequences. For instance, transformations of the natural or built environment through the provision

of infrastructure are known to be difficult to reverse. This is what makes decision-making processes for infrastructure development or for urban planning so complex. For example, several government decisions made in Bogotá during the 1950s and 1960s sought to modernize urban planning in the city, which led to the construction of the main road network of the city. These decisions have proven to be difficult to change or reverse and are still affecting today the provision of transport infrastructure, land use patterns and the organisation of the territory in the city (Guzman, Oviedo, and Bocarejo 2017; Solano 2010). This phenomenon is not exclusive to Bogotá as "infrastructure lock-in" is prevalent around the world.

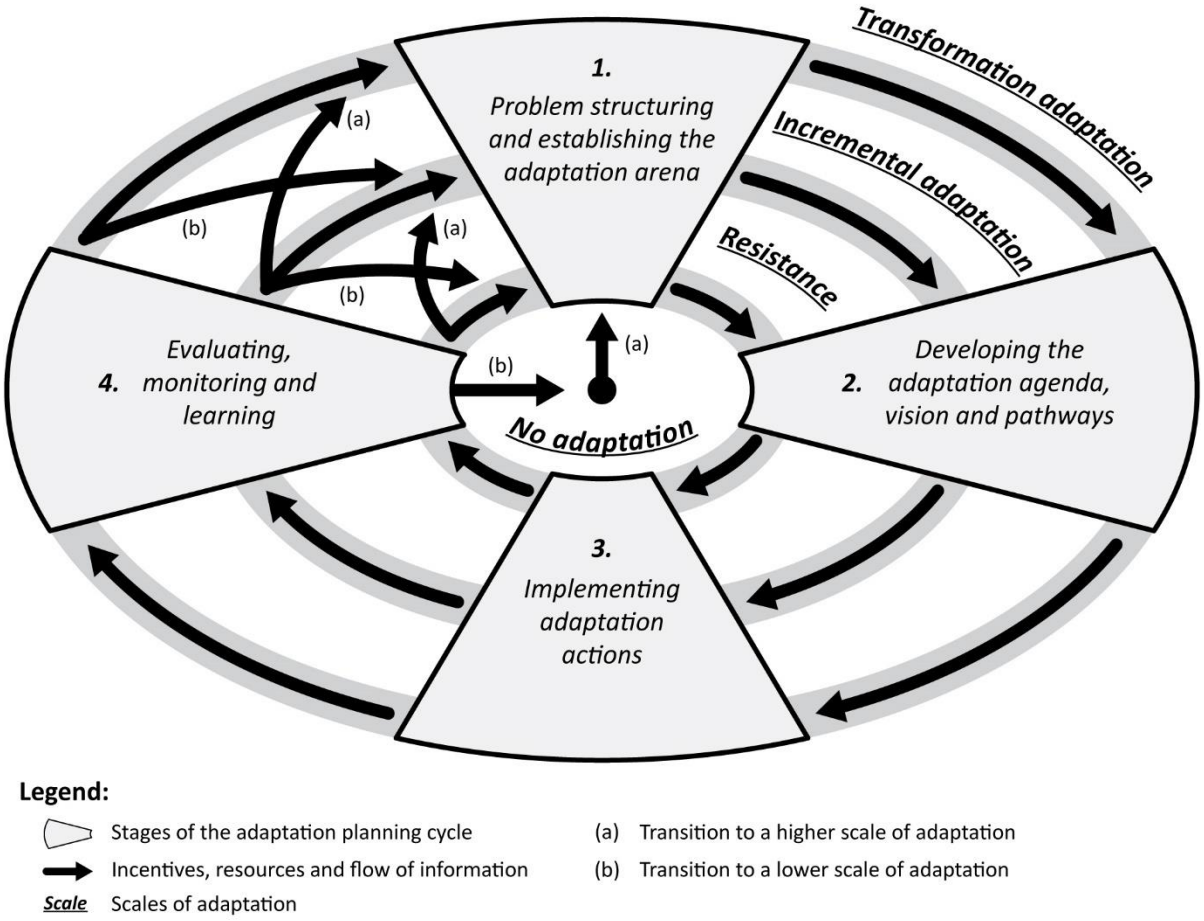

Figure 11. Schematic representation of the Expanded Adaptation Action Cycles.

As shown in Figure 11, in the EAAC framework each of the resistance, incremental adaptation and transformation adaptation processes cycle through the same four planning stages presented by Park et al. (2012). Similar to the AAC framework, it is assumed here that transition between scales can be an outcome of the knowledge or skills gained through accomplishing the evaluating, monitoring and learning activities, but that this transition is not a guaranteed process. The process can work in either direction, transitioning to a higher or lower scale of adaptation as shown by the (a) and (b) arrows in Figure 11. For example, after gaining more accurate knowledge about the possible climate change

impacts over a sociotechnical system, risks could be found to be higher or lower than expected, meaning that different actions could be needed in each scenario, leading to the implementation of a higher or lower scale of adaptation.

The framework incorporates the concept that decisions taken in each stage and before the transitions between stages and scales are dependent on three variables: information quality and availability; resources available; and incentives on which decision-makers have to act (Lehmann et al. 2015). Furthermore, problems can arise such as negative outcomes from the adaptation process, or different barriers that can hinder the effective implementation of actions in each planning stage or block the transitions between stages or scales of adaptation (see Section 2.4.4 for a review of literature about adaptation barriers). Therefore, continuous evaluation and monitoring are necessary to identify and overcome these barriers to be able to achieve effective adaptation.

The EAAC framework can be used as the basis to perform a systematic assessment of the decision-making processes in adaptation planning and of the information and policy support required by these processes by using two main analytical tools. The first analytical tool used by the EAAC framework is the series of key questions proposed by Park et al. (2012). These questions offer the possibility to develop more informed considerations of adaptation options and their implementation. Decision-makers have the possibility to invite other stakeholders (e.g., the community) to participate in the process of answering these questions to make sure that their perceptions and needs are also considered. Table 4 presents again these questions and the stage of the adaptation planning cycle in which they should be used for this systematic assessment. These analytical questions are used later in this thesis to guide the analysis presented in Chapter 6.

Table 4. Stage of the adaptation cycle and questions used to operationalise it. Sourced from Park et al. (2012).

Stage of adaptation planning cycle	Questions used for the assessment
1. Problem structuring and establishing of the adaptation arena	• What is the nature of vulnerability and the perceived risk? • Who or what adapts? • What do they adapt and why?
2. Developing the adaptation agenda, vision and pathway	• How do they adapt (processes)? • What are the opportunities for adaptation? • Costs and/or benefits of decisions?
3. Implementing adaptation options	• What implementation methods and resources are used? • What constrains or incentivizes implementation? • What impacts the results?
4. Evaluating, monitoring and learning	• How well do they adapt? • How does the system change? • What are the plans for the future?

The EAAC framework goes further than the ACC and other available frameworks and incorporates a method to identify barriers to and opportunities for effective adaptation planning. Although one of the analytical questions in the "implementing adaptation options" stage presented in Table 4 already touches upon barriers to and opportunities for implementation, the EAAC framework acknowledges that there are constraints and incentives that could be considered at each stage of the adaptation planning cycle and that these need to be identified. Consequently, the EAAC framework incorporates an analytical framework developed by Lehmann et al. (2015) as its second main analytical tool. This framework is presented in more detail in Chapter 7. It is presented there so the reader finds it easier to follow the methodology in Chapter 7 used to identify barriers to and opportunities for effective adaptation planning in the case study presented in this thesis.

3.2. Chapter summary

To conclude, this chapter has presented a conceptual framework called "Expanded Adaptation Action Cycles" which aims to help decision-makers and policymakers understand the decision-making processes and resource requirements associated with adaptation planning. The EAAC framework is a potentially valuable diagnostic tool as it offers a means to conceptually navigate the complex sociotechnical process of adaptation planning. This is because this framework can, first, provide the ability to understand the relative position of a city's approach to adaptation planning within a wider spectrum of possibilities, and second, it can provide insight into future possible planning interventions, their possible impact on, barriers to and opportunities for effective adaptation planning, and the necessary steps to follow in the planning process. It is proposed that the EAAC framework could be used to understand the decision-making processes of adaptation planning of any of society's sectors, but this research project will prove the practical value of this framework by using it to analyse a case study of adaptation of urban road infrastructure as presented in the rest of this thesis.

Chapter 4

4. Methodology

This chapter presents the methodology followed by this PhD project to answer the main research question of this thesis:

How can adaptation be incorporated into the planning and design of road infrastructure in cities?

And its two supporting sub-questions:

1) What is effective adaptation in the context of road infrastructure?
2) How is the adaptation planning process affected by the local social, political, economic, geographical and environmental context?

The chapter also presents the methodology followed to answer the questions associated with the case study, described in Section 1.3. The chapter discusses the guiding philosophy, the research design, the research methods used and their limitations.

4.1. Guiding philosophy

As described in the literature review, decision-making in the context of climate change has been predominantly tackled in the literature from separate disciplinary perspectives. These perspectives are that of engineering and that of the social sciences and humanities, each with different foci and objectives. This has produced limited results from both perspectives as different disciplines tend not to look at the problem in a holistic manner. In examining the decision-making processes for the adaptation of urban road infrastructure, this research seeks to integrate both perspectives by covering elements of resilience engineering (e.g., refer to resilience of engineering systems in Section 2.3); transport infrastructure planning (e.g., refer to the adaptation frameworks and strategies developed by road authorities presented in Sections 2.4.1 and 2.4.2); urban planning (e.g., refer to Lehmann et al.'s analytical framework in Section 7.1); development studies (e.g., refer to the discussion of the relationship between adaptation and development in Section 2.4); risk management (e.g., refer to the discussion of the risk management element of adaptation presented in Chapter 2); and change management (e.g., refer to the discussion about scales of adaptation in Section 3.1). This is with the intention to have a more holistic approach to answering the core research questions posed in this thesis. In other words, this research follows **a multidisciplinary approach** in its design which can be described as **sociotechnical**. The research is grounded in an engineering perspective of the problem based on

resilience engineering and transport infrastructure planning. This is complemented and enhanced by relevant elements from the social sciences and humanities disciplines, which can help give insights into the problem of adapting urban road infrastructure to climate change. This approach is driven by the underlying view that, in order to integrate both perspectives and to expand the benefits of resilient transport systems, transport infrastructure planning should move from a largely technical approach to a sociotechnical approach.

This investigation was performed on the basis of a **pragmatic paradigm**. This thesis will not explore the philosophy of pragmatism at length but given the cross-disciplinary nature of the research, the fundamental principles that have influenced the research process will be highlighted here. According to Cherryholmes (1992), Yardley and Bishop (2008) and Creswell and Creswell (2018) pragmatists follow the following principles:

- Pragmatists focus on understanding applications, consequences and solutions to problems. Therefore, instead of focusing on methods, pragmatist researchers emphasize the research problem and questions and use all approaches available to understand the problem.
- Pragmatists do not see the world as an absolute unity. Pragmatists believe that "truth" is what works at the time. In other words, pragmatists deny foundationalism, the view that grounded meaning and truth can be determined once and for all.
- Pragmatists do not believe that reality exists exclusively independent of the mind or exclusively within the mind. Therefore, "truth" cannot be completely objective or completely subjective. They believe that all human inquiry involves imagination and interpretation, intentions and values, but must also be grounded in empirical, embodied experiences.
- Pragmatists are not committed to any system of philosophy or interpretation of reality. They draw liberally from both quantitative and qualitative approaches to research. For pragmatists, the aim of research is to achieve a better, richer experience, whether through scientific analysis, artistic exploration, social negotiation, or any productive combination of these approaches.
- For pragmatists, individual researchers have freedom of choice. They are free to select the methods, techniques, and procedures that best meet their needs and purposes.
- Pragmatists agree that scientific research always occurs in social, historical, political, and other contexts.

These principles informed the methodological framework presented in this chapter. This paradigm gives the researcher freedom of choice to select the most appropriate methods and focuses on finding practical solutions. This is what makes this approach particularly suitable for sociotechnical research. For instance, this freedom of choice allows for the use of qualitative research methods in engineering research. Additionally, the pragmatic paradigm allows engineers to continue focusing on research that provides practical solutions to real-world problems. The data collection and analysis methods were

selected for this research on the basis that truth can come from both objective and subjective sources and is dependent on the socioecological context. It is acknowledged that the findings presented in this thesis cannot determine absolute truth, but there is reasonable confidence that the findings provide useful insights into the phenomena studied.

4.2. Research design

This research adopted a qualitative research approach in order to gain insight into the decision-making processes of a city regarding the development and maintenance of its road infrastructure and the inclusion of climate change adaptation considerations in those processes. This approach was selected as social inquiry is required to understand in depth the nature of the motivations and sociotechnical processes behind the decisions made by different stakeholders in a city regarding transport infrastructure planning and adaptation planning. The researcher decided to follow a single in-depth case study design and used different qualitative research methods to answer the research questions. The overall research process is shown in Figure 12.

As shown in Figure 12, this research was informed by the previous work done during the MRes year (**Year 0**) (see Section 1.2). **Year 1** was dedicated to a deeper understanding of the research problem. For this, an initial literature review and exploratory interviews were conducted. The first literature review helped prepare the exploratory interviews that were conducted in Bogotá, Colombia (detailed shortly in Section 4.4.1). The preliminary findings of these exploratory interviews and the initial literature review were reported for the purpose of internal examination in a report at the end of the first year.

Year 2 was dedicated to the main data collection activities in the form of expert interviews and the collection of policy, planning and technical documentation associated with the case study (Section 4.4.3) and to the updating of the literature review (Chapter 2). Each of these processes informed each other as can be expected in qualitative research projects. For example, different topics discussed in the interviews were based on the information found in the literature review, or the interviewees helped identify relevant policy, planning and technical documents that were later analysed as part of the case study. Based on the concepts and theories found in the literature review, a novel conceptual framework was developed (Chapter 3) to analyse the evidence gathered through the interviews and relevant document collection.

Year 3 was dedicated to completing the analysis of the case study evidence following the methodology described in Section 4.4.5. Interim findings of parts of the analysis have been reported separately in two conference papers. These interim findings are included in a revised and more holistic format in this thesis. The rest of this chapter explains in more detail the research methods used and their limitations.

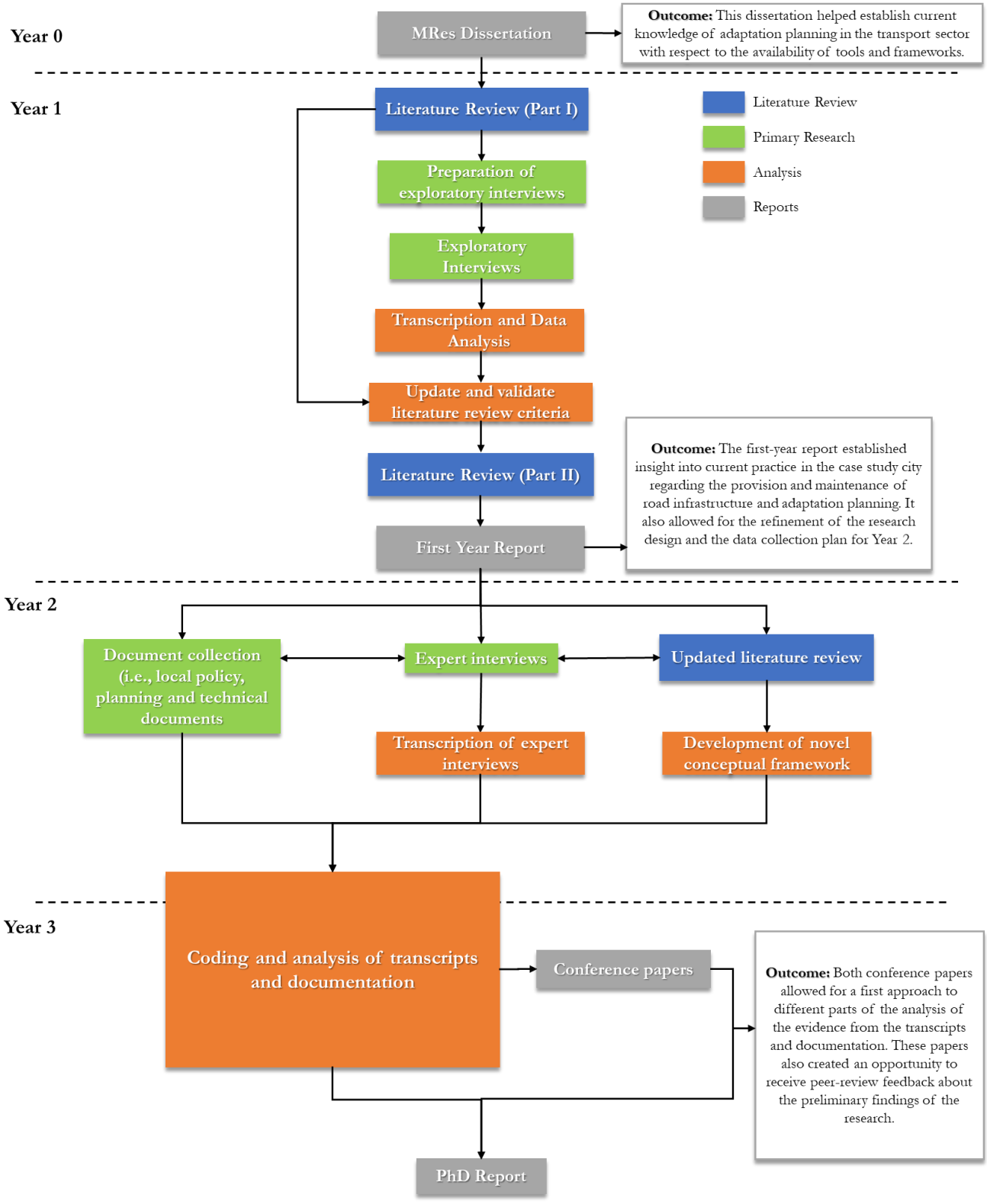

Figure 12. PhD research framework.

4.3. Case study

Yin (2003:1) describes case studies "as the preferred strategy when 'how' or 'why' questions are being posed, when the investigator has little control over events and when the focus is on a contemporary phenomenon within some real-life context". The principal aim of this PhD project is to answer the research question: "How can adaptation be incorporated into the planning and design of road infrastructure in cities?". This involves understanding the decision-making processes of any particular city for the development and maintenance of its road network which are, certainly, events out of the control of the researcher. The research focuses on a contemporary phenomenon in the form of the response of a contemporary city to climate change risk. Additionally, as shown in the literature review, case studies have already been used as a research strategy in papers that have investigated the effectiveness and costs of adaptation measures and strategies. Therefore, the case study was considered as a suitable research strategy for this PhD project.

There are two basic types of case study designs: single-case studies and multi-case studies (Yin 2003). This research follows a single-case study design. Single case studies are selected when the research aims for an in-depth understanding of the case and its context (Farquhar 2012). This type of research design has been used successfully before for understanding decision-making processes associated with infrastructure development. For example, Flyvbjerg (1998, 2006) conducted an in-depth single case study of urban politics, administration and planning in the town of Aalborg, Denmark. Only through the detailed view of the case, was Flyvbjerg able to demonstrate that the decision-making process in the city was highly undemocratic and that decisions were actually made by a semi-institutionalized secret council and not the democratically elected city council. MacAskill and Guthrie (2018) present another example in which a single longitudinal case study design was used to provide insights into how funding mechanisms shaped the decision-making processes associated with the reconstruction of infrastructure networks following the major earthquakes in Christchurch, New Zealand in 2010-2011.

This PhD conducted an in-depth single-case study of the current decision-making processes for the development and maintenance of road infrastructure in Bogotá, Colombia and the level of consideration of climate change adaptation in these processes. This city was selected as the focus because it represents an extreme case study. Other extreme case studies were not considered because the funding for this research was provided by the Mayor of Bogotá and a condition of the funding was to focus the research on the city. According to Flyvbjerg (2011), extreme cases are unusual cases that have especially good characteristics and are particularly well suited for theory development. Bogotá represents an extreme case study regarding the adaptation of road infrastructure to climate change due to the following characteristics:

- Bogotá has been praised by various authors and by the international community as perhaps the best example in the Latin America and the Caribbean region in terms of climate change adaptation and disaster risk management policies. Despite this, adaptation measures seem to have not yet been yet implemented in the city (Arroyo Narváez 2017; Krellenberg et al. 2014; Lombo 2014; Zeiderman 2016b).

- The Colombian government perceives its transport infrastructure as the most strategic infrastructure system that needs to be protected against the risks of climate change compared to other infrastructure systems. Additionally, transport infrastructure has an important character in Bogotá as it has had in recent years a crucial role in the urban transformation and planning of the city. Regardless of this, there is still not a specific response from the city's road sector to climate change (this will be explored in more detail in Chapter 5 and Chapter 6).

- Bogotá is at an interesting point for research as the city is currently facing important political debates concerning its urban structure. A new urban master plan has been in development by the city administration of mayor Enrique Peñalosa [2016-2020]. The contents of this new urban master plan will probably define the response of the city to climate change in the following decade. The nature of the response is still uncertain, as to date mayor Peñalosa has not been clear about his agenda regarding climate change adaptation. This is outlined in more detail in Chapter 5.

Case studies can obtain evidence based on a mix of quantitative and qualitative evidence (Flyvbjerg 2006; May 2011; Yin 2003). This research collected evidence for the case study through semi-structured interviews, complemented by an analysis of relevant local policy documents and technical reports. The next sections describe how the data was collected for this PhD project and how it was analysed.

4.4. Data collection and analysis

4.4.1. Expert interviews

Forty semi-structured interviews were conducted in total with forty-eight local professionals in transport planning, urban planning, climate change, risk management and politics. Semi-structured interviews were chosen as the appropriate method of interviewing for this research as they permit the conversation between the interviewer and the participant to cover a wide range of topics in a flexible framework. This type of interview allows for further elaboration of the topics when deemed necessary since the interviewer can formulate additional questions based on what is presented during the interview or the interviewer can tailor questions to the individual participants based on their expertise and their organisations (Létourneau 2015; May 2011; Yin 2003). The number of interviews conducted was deemed appropriate as data saturation was achieved in most topics covered, giving enough confidence

about the quality of the information obtained. For example, many of the aspects of the realities of the decision-making processes for the development and maintenance of road infrastructure in Bogotá, such as the disproportionate influence of the city's mayor, were confirmed by several participants (see Section 5.4). Other examples of the saturation achieved in the data collection are indicated in the analysis presented in later chapters of this thesis. Additionally, due to the nature of this qualitative research method, the goal was to reach people that have special access to the phenomenon studied (i.e., experts), rather than achieving an arbitrary minimum number of interviews. This is because it can be argued that their unique experience is highly valuable as they have influence or direct contact with the phenomenon studied, providing exclusive access to key aspects of it. This research involved interviews with key national and city actors involved in policy and transport planning and design, gaining broad coverage of the decision-making processes in the city for the development and maintenance of road infrastructure and the incorporation of climate change considerations in these processes.

The expert interviews were conducted in Bogotá, Colombia during two fieldwork campaigns, one between December 2016 and January 2017 and the other between December 2017 and January 2018. Interviews during the first fieldwork (INT1 to INT9) were of exploratory nature. These were conducted with different actors both at the local and national level. A preliminary analysis of these exploratory interviews informed a review of the research questions addressed by this PhD research and allowed the formation of an initial understanding of the key decision-making processes associated with the road sector in Bogotá and the role of stakeholders within those processes. All the exploratory interviews had questions on four main topics: climate change and roads, decision-making processes in the road sector, sustainable development and roads, and decision-support tools (Figure 13). The selection of these topics was informed by prior literature review work (discussed in Section 1.2).

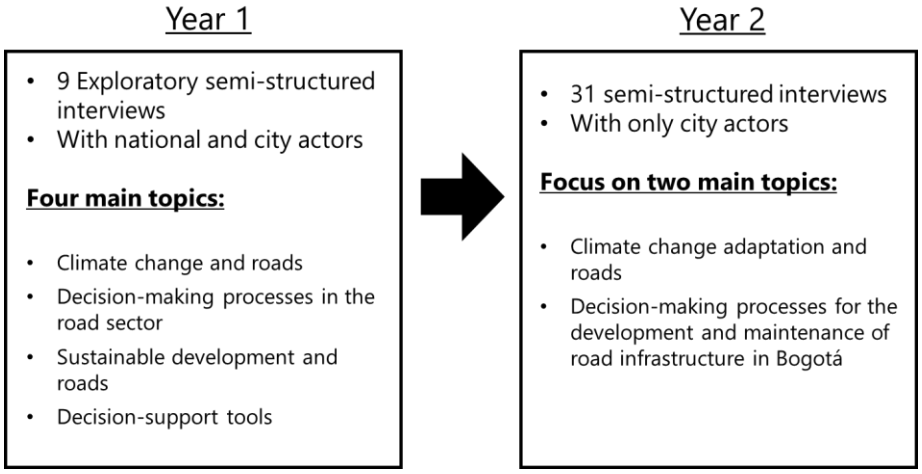

Figure 13. Differences between interviews in the two fieldwork campaigns.

Expert interviews during the second fieldwork campaign were conducted only with city actors and focused on two main topics: climate change adaptation and roads, and decision-making processes for

the development and maintenance of road infrastructure in Bogotá (Figure 13). Examples of common questions asked to the participants can be found in Appendix 5 – Guiding topics and common questions. Some of the expert interviews had a focus on specific elements of the processes of the city since the participants interviewed expressed that they had only expertise in some of these elements. An example of this is the interview conducted with the professional from the District Treasury Secretary who stated that he could only discuss how budgets are allocated to the different sectors of the city administration as he had no knowledge of the internal decision-making processes of the road sector.

The interviews conducted were typically between 30 and 70 minutes. The pie chart in Figure 14 shows in more detail the distribution of the length of the interviews conducted. As the figure shows, around 7% of the interviews lasted less than 30 minutes. This was because these participants either had very tight agendas and could not spare more time, or because they felt they could only talk about a very specific issue which did not require more time. On the other extreme, as the figure shows, around 8% of the interviews lasted more than 70 minutes. These participants were the keenest to talk and their interviews were that long because they were stopped only when it felt natural to do so.

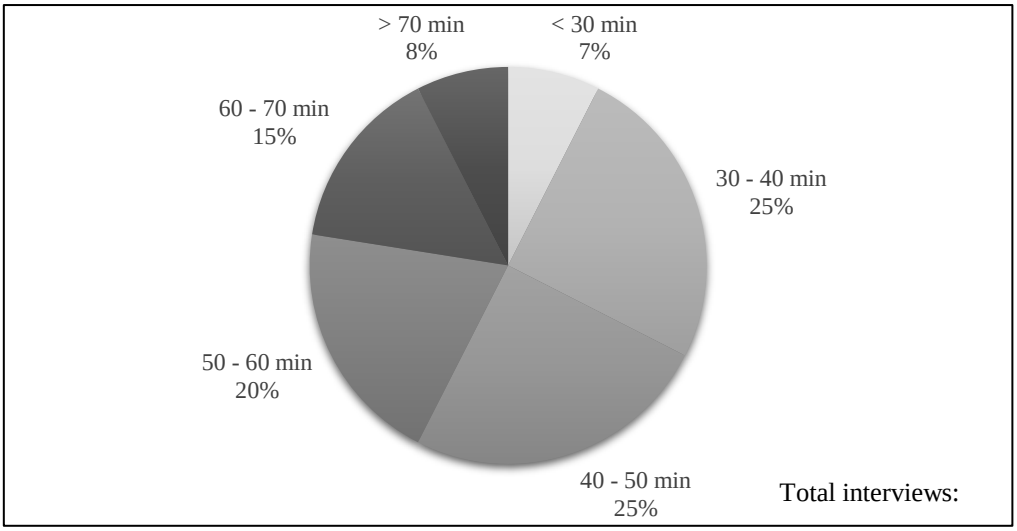

Figure 14. Length of the interviews conducted.

Participants were directly approached based on their roles in key public and private organisations of the transport, environmental and disaster risk management sectors of Bogotá (i.e., non-random sampling). The most relevant public and private organisations of these sectors were identified by the researcher through policy documents and publicly available documents. For instance, public organisations were selected based on their official missions and their roles in developing or implementing the policies of the city. Relevant private organisations involved in road infrastructure projects were identified by looking at public contracts' information found in the IDU web page. Other relevant organisations like United Nations Development Programme for Colombia (PNUD) or Steer Davies Gleave were selected due to their role as consultants for the city in the development of transport and climate change policies.

Potential participants were identified based on the relevance of their job positions in the selected organisations. This involved roles in risk management, climate change or asset management. Some participants were selected as a result of snowball sampling, that is, they were recommended by other participants. This process reached those who have extensive experience in the decision-making processes for the development and maintenance of transport infrastructure in Bogotá and obtained good coverage of those in key decision-making roles. The list of participants can be seen in Table 5. Participants are identified using codes in the form of "INT#" to keep their anonymity. Additionally, some participants codes have also a letter at the end (a, b or c). This was used to identify participants when more than one interviewee was involved in an interview. Participants are grouped in Table 5 by types of interviewee corresponding to general types of job positions relevant for this research. Detailed job descriptions are not given to protect the anonymity of participants. These codes are later used in this thesis to indicate reference to participants' comments in Chapters 6 and 7.

Table 5. Semi-structured interview participants.

Type of interviewee	Organisations	Interviewee codes
Public transport sector professional	Urban Development Institute (IDU), National Infrastructure Agency (ANI), Transport Ministry, National Road Institute (INVIAS), Special Attention Rehabilitation and Road Maintenance Unit (UMV), District Mobility Secretary	INT1, INT2, INT6, INT7, INT9, INT11a, INT11b, INT15a, INT15b, INT16, INT20, INT23, INT24a, INT24b, INT24c, INT28, INT39a, INT39b
Public environmental sector professional	District Institute for Risk Management and Climate Change (IDIGER), Water Company, District Environmental Secretary	INT5, INT8, INT12a, INT12b, INT12c, INT14, INT17a, INT17b, INT5-2, INT21, INT22, INT25, INT33
Urban planning professional	District Planning Secretary, District Treasury Secretary	INT13, INT19, INT32, INT34
Politician	Local mayoralty of Suba, Bogotá's Council	INT30, INT31, INT35
Private sector professional	HAP INGENIERIA SAS, OCEISA, Ingetec, Grodco, Independent Law Firm, Steer Davies Gleave	INT3, INT4, INT27, INT29, INT36, INT37
Academic	University College London (UCL)*, National University of Colombia (UNAL), Universidad de los Andes	INT10, INT18, INT38
NGO professional	United Nations Development Programme for Colombia (PNUD)	INT26

* This interview was the only one performed outside Bogotá. The participant is a Colombian academic who at the time was a research associate at UCL in London. The academic has led relevant research about Bogotá's public transport and was selected for this reason.

It is important to note that members of the community were not included as participants in this study. The exploratory interviews of Year 1 revealed that no effective participatory mechanisms exist in Bogotá associated with the decision-making processes for the provision and maintenance of road infrastructure. Therefore, for the purpose of this case study, it was deemed not necessary to interview

members of the community as they would not have been able to provide useful insights about the decision-making processes of the city as they have no significant participation in them.

The interviews were carried out at a time of convenience for the participant at their office and pre-arranged via email. Only one interview had to be carried out through Skype later in 2018. The email sent explained the purpose of the interview and why the approach had been made. Additional information about the research project and the interview, and the participation consent form were attached to the email. A sample of the email, the information sheets, and the participation consent form can be found from Appendix 2 - Email formats sent to participants to Appendix 4 - Consent form sample. All interviews were recorded with a digital voice recorder and later transcribed.

4.4.2. Limitations of the interview method

Semi-structured interviews allow for a flexible framework to discuss a wide range of topics between the interviewer and the interviewee, but this flexibility means that not every participant was asked exactly the same questions. This makes it potentially more difficult to identify common themes in the conversations, to compare the answers of participants and to guarantee a consistent research process. Additionally, the researcher had an evident role in guiding the conversation by formulating questions as the interviews progressed (as expected in the semi-structured approach). To manage these limitations, the researcher conducted all interviews following a general guide of themes and questions (see Appendix 5 – Guiding topics and common questions). Through the coding and analysis of transcripts, it was possible to identify the dominant themes in the conversations.

While the researcher had a good response rate during the selection of possible participants, a further limitation of the interview method is that the selection of interviewees is always dependent on their willingness to participate. For example, the head of the District Mobility Secretary and mayor Enrique Peñalosa were contacted but did not respond back. Their contributions would have provided a more personal perspective of their roles in the city, complementing the evidence described in this thesis.

Furthermore, the analysis shown in this thesis is inevitably a result of the researcher's interpretation of the information gathered in the interviews. There is the risk of misinterpreting the opinions recorded in the conversations or missing an important point through the choices made by the researcher in his analysis. To help mitigate this, the researcher triangulated information with other sources of evidence as recommended by Yin (2003) (see next section).

As an additional measure to mitigate the misinterpretation of the evidence, the researcher shared part of the interim analysis of the study in a small workshop with four participants to give them an opportunity to review the EAAC framework and some preliminary conclusions. This workshop took place in the offices of the District Mobility Secretary of Bogotá in December 2018. Three of the

participants were part of the internal group in charge of adaptation in the District Mobility Secretary and the other participant was an advisor from IDIGER. One of the participants from the District Mobility Secretary also previously participated in the interviews. The workshop started with a 20-minute presentation about the EAAC framework and preliminary findings of this research, followed by an interactive Question and Answer session with the four participants. Participants were also asked to fill in a feedback form asking them about the ability of the EAAC framework to describe adaptation planning processes and on the utility of the framework for their work. All participants of this workshop gave positive feedback regarding the EAAC framework. On a scale from one to five, where one means "badly" and five means "well", all participants gave the EAAC framework a score of five in terms of how well it explains the processes of adaptation planning. Participants also gave general positive feedback regarding the preliminary analysis presented. Participants were asked to rate on a scale from one to five, where one means "not accurately" and five means "very accurately", how well did the preliminary analysis presented to them described the reality of transport planning and adaptation planning in Bogotá. One participant gave the preliminary analysis a score of 3, two participants gave it a 4 and the other participant gave it a score of 5. The participant which gave the lower score to the preliminary analysis argued that for her "there [was] still no [complete] conceptualisation [of the information], and [no] global and particular analysis of the information gathered from the interviews". In contrast, the other participants understood that there was still pending work, but that the preliminary analysis was going in the right direction, and that they were interested in seeing the final product of the analysis. This represents the kind of feedback expected since the analysis presented was provisional. The three participants from the District Mobility Secretary expressed that the EAAC framework could be a useful tool for their work in adaptation.

It is important to acknowledge that this workshop had limitations. For instance, the researcher hoped to have more participants, but it was difficult to secure more time in the diaries of professionals from other agencies (some cancelling their participation at the last minute). Nonetheless, the process was helpful for refining some of the observations of the case study and to receive recommendations on some additional documents to consider for the document analysis.

4.4.3. Further data collection and triangulation

According to Yin (2003), multiple sources of evidence are necessary to attain construct validity for the case study design. For this, a complementary review of relevant documents was used to triangulate the information ascertained through the interviews. Relevant publicly available local policy documents about transport infrastructure planning, urban planning, climate change action and risk management were used for the analysis. Additional documents provided by some interviewees (for example, technical reports not publicly available) were also analysed. A list of the documents used in the analysis can be seen in Table 6. The documents are assigned a code for use in the case study analysis alongside

interview data. These codes are later adopted in Chapter 6 and 7 to reference these documents. This method of referencing is followed to differentiate references from the literature review from those used as evidence in the case study.

Table 6. Local policy, planning and technical documents analysed.

Code	Document
Report RVV	Report Updating of Vital Road Network of Bogotá (RVV) (Unión Temporal MOBIGA 2018)
Annex RVV	Technical Annex Updating of Vital Road Network of Bogotá (RVV) (Secretaría Distrital de Movilidad 2017)
Agreement 257	Agreement 257 of 2006 (Bogotá) (Concejo de Bogotá 2006)
Eco-urbanism	Public Policy on Eco-urbanism and Sustainable Construction + Annexes + Action Plan (Alcaldía Mayor de Bogotá 2014b; Secretaría Distrital de Planeación 2015a)
POT 2004	Decree 190 of 2004 (Bogotá) – Urban Master Plan (Alcaldía Mayor de Bogotá D.C. 2004)
Strategy IDU	IDU's Environmental and Climate Change Strategy (IDU n.d.)
Urban CC Guide	Climate Change Guide for Urban Mobility (Ministerio de Transporte 2016)
Report Quinto Centenario	Quinto Centenario Project Report (Buis, Guzmán, and González 2017)
UMV Model	UMV Prioritisation Model (UMV n.d.)
Development Plan	Development Plan 2016-2020 (Alcaldía Mayor de Bogotá D.C. 2016)
PDGR-CC	District Risk Management and Climate Change Plan – Bogotá 2015-2050 (Secretaría Distrital de Ambiente and IDIGER 2015)
Mobility Master Plan	Mobility Master Plan (Bogotá) (Alcaldía Mayor de Bogotá 2006)
PRICC	Adaptation Options – Integral Regional Plan for Climate Change (PRICC) (IDEAM et al. 2014a)
Diagnosis POT	Summary of General Diagnosis of the Urban Master Plan 2004 (Alcaldía Mayor de Bogotá and Secretaría Distrital de Planeación 2017)

4.4.4. Ethical considerations

The inclusion of human participants in any research project raises ethical issues about the possible risks that the investigation may cause. All human research must be conducted following the ethical principles of respect, beneficence, and justice. This means that the benefits of research should always outweigh the risks, and, that harm or burden to those involved in or affected by research must be always minimised. Because of this, the researcher must assess the potential risks to participants which are not limited to the physical harm but can also be economic, psychological, legal, and social (Heggen and Guillemin 2014).

After a self-assessment guided by the Department of Engineering research ethics guidelines, it was judged that the potential risk to the participants was minimal. To get the required approval by the Department of Engineering's Ethics Committee, a "light-touch review" was considered appropriate for both fieldwork campaigns, and approval was obtained this way (see Appendix 6 - Ethical Approval of Research Project).

To ensure that the research was conducted ethically, the following actions were taken:

- Participants were provided with information about the research project and the interview, and they provided consent to participate. Samples of the "information sheet" and the "participation consent form" can be found in Appendix 3 – Information sheet sample and Appendix 4 - Consent form sample.
- Participants gave permission to record and transcribe the interviews. They had the right to retract at any moment any commentary that they gave during the interview, edit their transcript or to leave the study without any repercussions.
- All data is anonymous, without any means of identifying the individuals involved. The recordings of the interviews are identified with codes. A list of the names associated with the codes has been kept safely in another location different from the one of the coded recordings. The recordings will not be shared with others and they are kept secured in a computer following the appropriate security measures. The researcher will keep the recordings after transcription until after the final examinations of the research project.
- Participants were not subject to discomfort or inconvenience. The interviews were conducted at a time and place of convenience for the participant and previously arranged with them via email. Anyone considered vulnerable was not interviewed. The latter was not a particular issue in this case given that participants were interviewed in their professional capacity and their anonymity has been maintained.

4.4.5. Data analysis

Both the interview transcripts and the case study documents were coded using the computer-assisted qualitative data analysis software NVIVO 11. Coding is described by Thornerg and Charmaz (2014) as "naming segments of data with a label that simultaneously categorizes, summarizes, and accounts for each piece of data". This is a process that is nonlinear and iterative, meaning that the researcher needs to come back and forth to the different stages of coding and analysis of the data. Coding involved several iterations to ensure that the interpretation of the information was as comprehensive as possible.

The codes developed were related to the concepts of adaptation, adaptation planning, climate change or transport planning. Additional codes were produced in relation to different stakeholders in the city and flagship infrastructure projects. Some codes were created before the coding process based on the conceptual framework of this research (e.g., "planning cycle" and its sub-codes) and others were created during the coding process based on trends found in the interviews and documents (e.g., "confusion with other concepts"). The most frequently used codes and their descriptions are shown in Table 8 and a complete list of all codes used in the analysis of the interview transcripts and case study documents can be found in Appendix 7.

The analysis of the evidence collected in the case study is presented in Chapters 6 and 7. Figure 15 at the end of this chapter summarises how the research questions have been answered in this PhD thesis in these and other chapters. The evidence has been used for an analysis of the adaptation planning of the transport sector of Bogotá through the lens of the EAAC framework. Chapter 6 shows how the relative position of the city in the adaptation planning process can be determined. This diagnosis is guided by a series of key questions that work as the first main analytical tool of the EAAC framework. They are presented here again in Table 7.

Table 7. Stage of the adaptation cycle and questions used to operationalise it. Sourced from Park et al. (2012).

Stage of adaptation planning cycle	Questions used for the assessment
1. Problem structuring and establishing of the adaptation arena	• What is the nature of vulnerability and the perceived risk? • Who or what adapts? • What do they adapt and why?
2. Developing the adaptation agenda, vision and pathway	• How do they adapt (processes)? • What are the opportunities for adaptation? • Costs and/or benefits of decisions?
3. Implementing adaptation options	• What implementation methods and resources are used? • What constrains or incentivizes implementation? • What impacts the results?
4. Evaluating, monitoring and learning	• How well do they adapt? • How does the system change? • What are the plans for the future?

It is important to note that these questions were not used as the guiding questions of the interviews for two reasons. First, the interviews were not conducted to exclusively discuss adaptation planning in Bogotá, but also, they were conducted to reveal several aspects and characteristics of the decision-making processes for the development and maintenance of road infrastructure in the city. Therefore, other types of questions were required to reveal these aspects. Second, some early evidence suggested that the city had not implemented yet any adaptation measures. This means that asking all of the questions in Table 7 to the interviewees, especially those questions from the later stages, would have made no sense since they would not have any valuable answer to them.

Chapter 7 presents how the barriers to and opportunities for the effective adaptation of road infrastructure in Bogotá can be identified. This is done by using the second main analytical tool of the EAAC framework, an analytical framework developed by Lehmann et al. (2015). This analytical tool offers the possibility to not only identify what barriers exist but also to explain how and why they emerge. This analytical tool is limited as it cannot capture all interactions and dependencies between

barriers and their underlying factors. Nevertheless, the objective of this analysis has been to identify the most critical barriers and opportunities and the data collected in this research through interviews and document analysis has certainly revealed these as demonstrated by Chapter 7. If a more detailed analysis of the barriers (and opportunities) to effective adaptation planning of a city is required, data collection could be complemented by ethnographic research methods, i.e., a researcher observes directly how decision-makers perform their jobs. Due to the scope of this PhD project, this was not deemed necessary given the research question posed in this thesis.

All coded statements were used as evidence for the analysis presented in Chapter 6 and 7. The evidence coded with the codes presented in Table 8 and Appendix 7 was useful to provide answers in different parts of the analysis. As an example, this is how statements coded under the following codes were used for answering some of the analytical questions of the EAAC framework (as presented in Chapter 6):

- **Question 1 – "What is the nature of vulnerability and the perceived risk?":** Statements coded under the codes "climate change effects" and "climate change perceptions" provided evidence to answer this question.
- **Question 2 – "Who or what adapts?":** Statements coded under codes such as "adaptation institutional arrangements" or "transport institutional arrangements" provided evidence to understand who or what adapts in the city.
- **Question 4 – "How do they adapt?":** Statements coded under codes such as "ecosystem-based adaptation" and "adaptation actions" provided evidence on how Bogotá's transport sector is planning to address adaptation.

For the analysis presented in Chapter 7, the principal evidence was provided by all statements coded using the code "barriers to adaptation" and three sub-codes associated with the categories of Lehmann et al.'s (2015) framework (i.e., 'information', 'resources' and 'incentives'). Other codes like "confusion with other concepts", "climate change perceptions" or "adaptation institutional arrangements" provided complementary evidence for the analysis of barriers to and opportunities for effective adaptation planning in Bogotá.

Finally, in some parts of the analysis shown in both chapters, interviewees are directly quoted to express crucial points, opinions or perceptions. Further quotes supporting the analysis are presented in Appendix 8. Interviewees' quotes are originally in Spanish but are shown in this thesis in English. These quotes have been translated into English by the researcher with an intent to remain as true as possible to the original Spanish version.

According to Corden and Sainsbury (2006), verbatim quotes have been used in qualitative research studies with one of the following purposes: as the matter of enquiry; as evidence; as explanation; as illustration; to deepen understanding; to give participants a voice, and to enhance readability. Verbatim

quotes are used in this thesis as evidence and for explanation. The quotes are presented as evidence to provide transparency on the development of the analysis and to allow readers to make their own judgements about the fairness and accuracy of this analysis. Due to constraints related to the available space in this thesis, not all quotations could be presented, and only representative quotes are shown in the main text and Appendix 8. Corden and Sainsbury argue that some researchers do not agree that direct quotes could be presented as evidence and that "the real evidence […] lay in the conceptualisation and thematic analysis of all the data, the linkages made and interpretations in relation to other factors. This might or might not require presentation of direct quotations" (Corden and Sainsbury 2006:12). This way of providing evidence has also been satisfied in Chapter 6 and 7. Additionally, verbatim quotes can also be used with the purpose of explaining complex phenomena through the words of participants. This makes it easier for the readers to understand how some of the participants positioned themselves within societal processes, and some of their underlying assumptions and perceptions. Some of the quotes presented in this thesis serve this purpose as well.

Table 8. Frequently used codes used in the analysis of the interview transcripts and case study documents.

Code	Definition
1. Adaptation	All mentions of the definition and understanding of adaptation as a concept by the interviewees, and the theories they mention about adaptation.
1.a. Confusion with other concepts	All instances in which adaptation is confused or associated incorrectly with other concepts such as mitigation or standard environmental management.
1.b. Adaptation vs. development	Evidence of the perception of conflict between adaptation and development needs by the interviewees.
1.c. Ecosystems-based adaptation	All references to ecosystems-based adaptation.
1.d. Adaptation by stealth	All instances in which adaptation is conceptually being hidden behind other concepts in practice.
2. Adaptation planning	All mentions of adaptation planning in Bogotá.
2.a. Adaptation actions	All references to the different adaptation actions found or planned in the city of Bogotá according to the typology by Biagini et al. (2014).
2.b. Adaptation institutional arrangements	All mentions of the different adaptation planning institutional arrangements in Bogotá made by the interviewees or found in the analysed documents.
3. Barriers to adaptation	All mentions of barriers or opportunities for the effective adaptation planning of road infrastructure in Bogotá based on the categories presented by Lehmann et al. (2015).
3.a. Information	This code collects all references to barriers or opportunities related to information quality and availability in Bogotá.
3.b. Resources	This code collects all references to barriers or opportunities related to resources availability in Bogotá.
3.c. Incentives	This code collects all references to barriers or opportunities related to incentives in which decision-makers have to act in Bogotá.
4. Climate change	All mentions of climate change.
4.a. Climate change effects	All references to climate change effects in Bogotá and impacts on the transport infrastructure of the city made by the interviewees or found in the analysed documents.
4.b. Climate change perceptions	Evidence of the perceptions and thoughts that the interviewees have regarding climate change and its effects.
5. Planning cycle	All references to the adaptation planning cycle and its different phases according to the EAAC framework in Bogotá.

5.a. Problem structuring	All references to the "Problem structuring and establishing of the arena" phase of the planning cycle according to the EAAC framework.
5.b. Agenda formulation	All references to the "Developing the adaptation agenda, vision and pathway" phase of the planning cycle according to the EAAC framework.
5.c. Implementation	All references to the "Implementing adaptation options" phase of the planning cycle according to the EAAC framework.
5.d. Evaluation and monitoring	All references to the "Evaluating, monitoring and learning" phase of the planning cycle according to the EAAC framework.
6. Transport planning	All mentions of the processes, documents and philosophies of Bogotá's transport planning.
6.a. Transport planning documents	All references to transport planning documents of Bogotá.
6.b. Construction	All mentions of the construction of new transport infrastructure in Bogotá.
6.c. Maintenance	All mentions of the maintenance of transport infrastructure in Bogotá.
6.d. Planning principles and prioritisation	The planning principles and prioritisation methods used in the transportation planning processes of Bogotá.
6.e. Transport institutional arrangements	All references to the different institutional arrangements that guide transport planning in Bogotá.
7. Stakeholders	This code collects all references to the stakeholders of the transport sector of Bogotá and its adaptation planning.
7.a. Academia	All mentions of academia.
7.b. Acueducto	All references to "Empresa de Acueducto y Alcantarillado de Bogotá" (Water Company of Bogotá).
7.c. Alcalde Mayor	All references to the city's mayor.
7.d. Alcaldías Locales	All references to the local mayoralties.
7.e. Community	All references to the community.
7.f. Concejo Bogotá	All references to the City Council.
7.g. Construction materials providers	All references to construction materials providers.
7.h. IDIGER	All references to IDIGER (District Risk Management and Climate Change Institute).
7.i. IDU	All references to the IDU (Urban Development Institute).
7.j. Jardin Botánico	All references to the city's Botanical Garden.
7.k. NGOs and International agencies	All references to NGOs and international agencies.
7.l. Private engineering companies	All references to private engineering companies.
7.m. Secretaría Ambiente	All references to the District Environmental Secretary.
7.n. Secretaría Hacienda	All references to the District Treasury Secretary.
7.o. Secretaría Movilidad	All references to the District Mobility Secretary.
7.p. Secretaría Planeación	All references to the District Planning Secretary.
7.q. Transmilenio	All references to Transmilenio.
7.r. UMV	All references to UMV (Special Administrative Unit for Road Maintenance and Rehabilitation).
7.s. Utility companies	All references to utility companies (not including the Water Company).

4.5. Chapter summary

This chapter has elaborated on the adopted research methodology. This research follows a multidisciplinary approach in its design, which can be defined as sociotechnical, based on the pragmatic paradigm. This PhD project has followed a single in-depth case study design and used a variety of qualitative research methods (i.e., semi-structured interviews, document collection and coding) to gather evidence from the case study. Following the methodology described in this chapter, Figure 15 presents graphically how the research questions of this PhD project are answered in this thesis.

The next chapter presents a brief description of the case study of Colombia and Bogotá that serves as context for the analysis presented later in this thesis of the adaptation planning processes of the transport sector of the city.

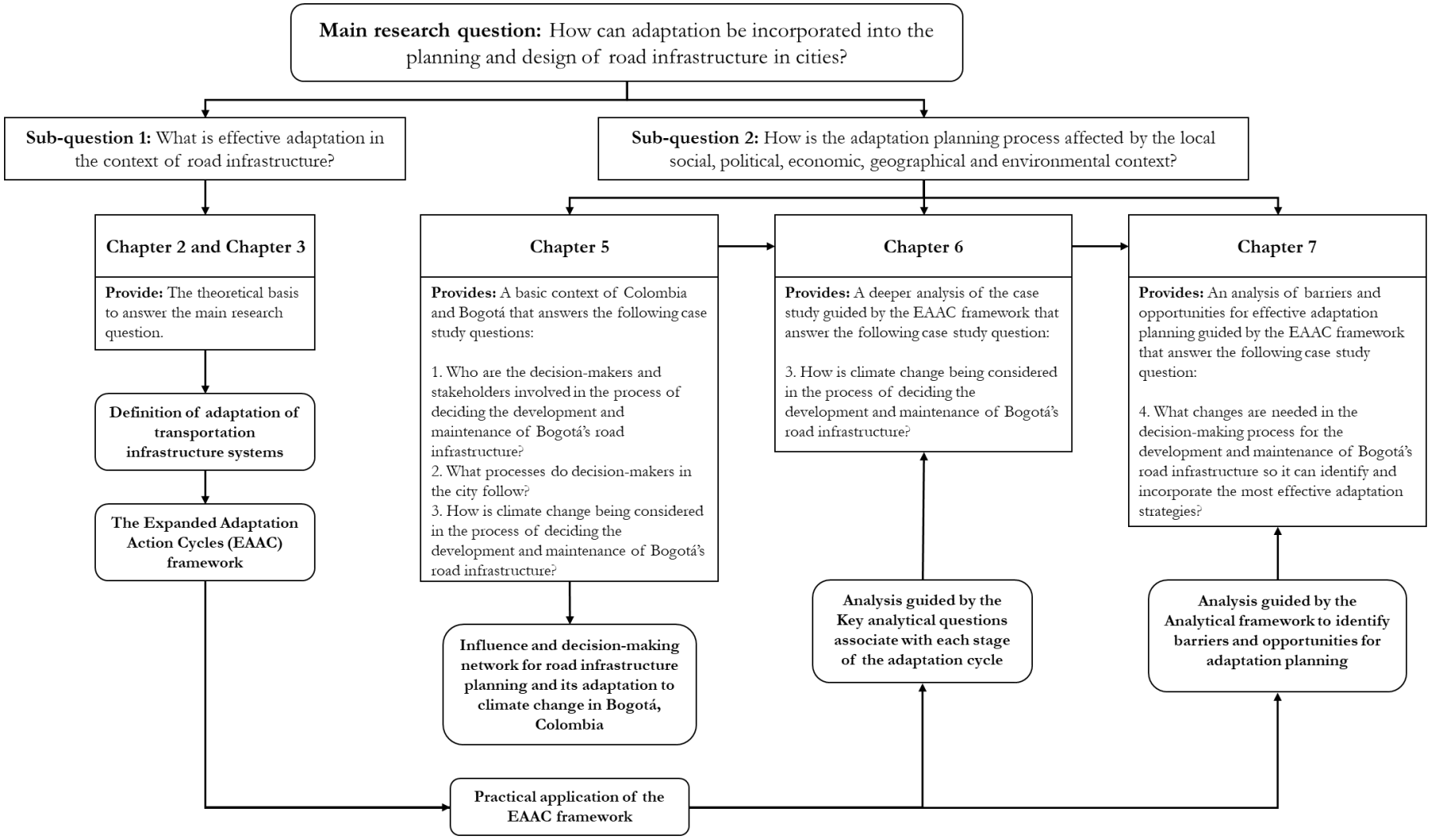

Figure 15. Research questions and how they are answered in this PhD thesis.

Note: The main products of this research project are shown in bold letters inside the boxes with rounded edges.

Chapter 5

5. Case study context

This chapter presents a brief review of the geographical context of Colombia and background to the governance and management of climate risk and transport infrastructure in Bogotá. The first section presents a short overview of the geography, climate, economy, and politics of Bogotá and Colombia. The second section explains the current national and local response to climate change. The third section describes the transport sector of Bogotá and its organisational arrangements. The chapter ends with an analysis of the decision-making processes for road infrastructure planning in the city and its adaptation to climate change. This analysis has been able to determine what organisations in the city have a direct role in the adaptation efforts and how the organisations of the city influence each other. The context presented in this chapter will be useful later to understand in more detail the analysis presented in the next two chapters.

5.1. Characterisation of Bogotá and Colombia

5.1.1. Geography

Colombia is a country located in the North-West of South America. Its coastlines border the Caribbean Sea in the North and the Pacific Ocean in the West. The country is divided by the Andes mountain range and includes part of the Amazon River basin in the south. It shares borders with Panama, Venezuela, Peru, Ecuador and Brazil (Figure 16). It spans over a territory of 2,070,408 km^2, where 928,660 are its maritime sovereignty and 1,141,748 its continental area (DANE 2012). As of 2017, the country had a population of around 49 million people (DANE 2017).

Bogotá, the capital of Colombia, is situated in the centre of the country on a high plateau in the Andes. Its urban area has developed historically between a range of hills to the east of the city and the Bogotá river to the west (see Figure 17). It is located at an average altitude of 2,650 metres above sea level and occupies a territory of 163,660 hectares (Secretaría Distrital de Ambiente and IDIGER 2015). Bogotá is the largest city in the country with a population of around 8 million people recorded in 2016 (DANE 2017).

Figure 16. Colombia's geographical context. Sourced from Wikimedia Commons (2020).

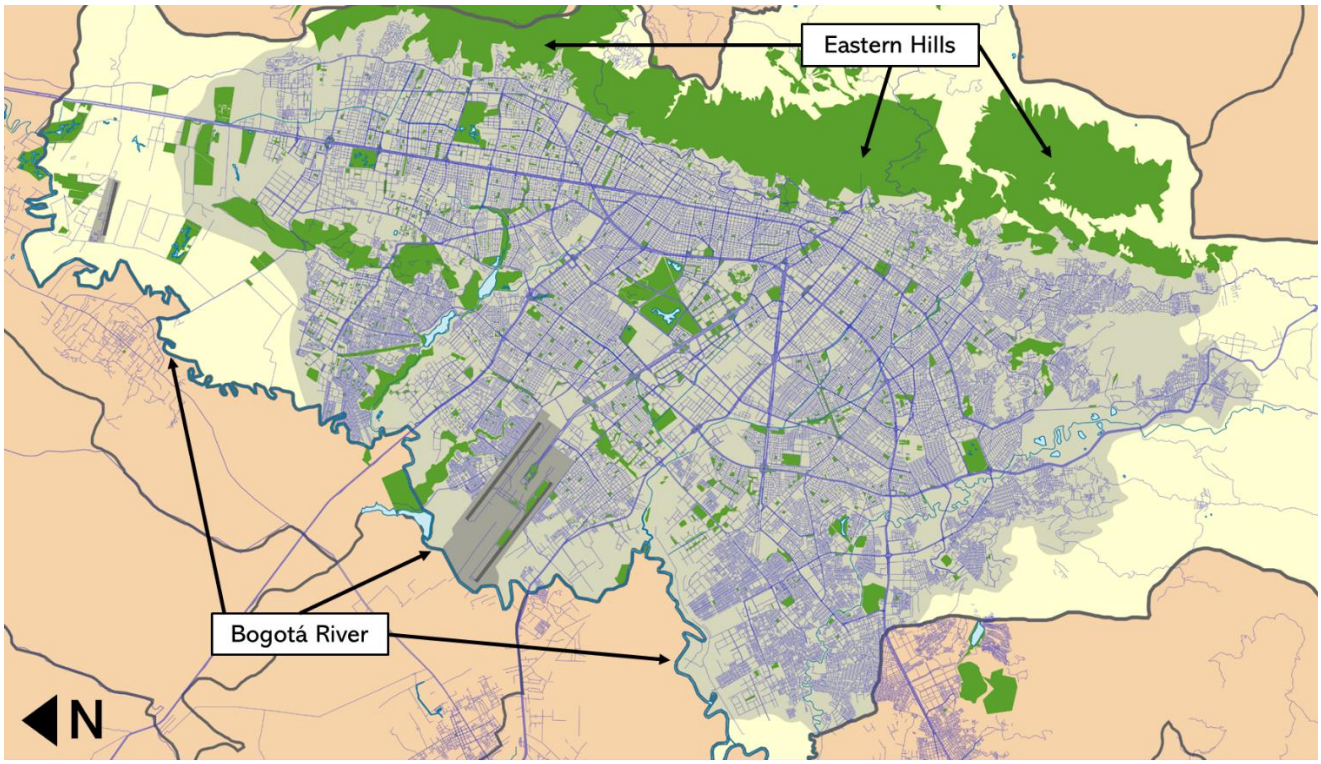

Figure 17. Bogotá's urban area and its road network. Adapted from Wikimedia Commons (2019).

5.1.2. Climate

The climate in the country is generally tropical and isothermal due to its proximity to the Equator and is influenced by the El Niño Southern Oscillation (ENSO), the Andes mountain range, the Intertropical Convergence Zone, and the particular and heterogeneous diversity of ecosystems in the country. Because of the presence of the Andes mountain range, there is a diversity of microclimates in the country found at different altitudes. The climate is characterised by being highly variable, alternating between periods of rain and periods of drought throughout the year (Kline et al. 2017; MinTransporte et al. 2014).

The climate in Bogotá is mainly influenced by the Intertropical Convergence Zone which produces two precipitation maximums in the city in April and October, and two minimums in January and July (IDEAM et al. 2017). The average temperature in Bogotá during the year is 14.5°C, and at a daily level, the temperature oscillation can be significant as it can reach values of a 10°C difference between the minimum and maximum daily temperatures (Secretaría Distrital de Ambiente and IDIGER 2015).

Colombia has a long history of weather-related disasters and the most recent event with national consequences was the occurrence of the La Niña Phenomenon between 2010 and 2011 (IDEAM et al. 2017). This phase of the ENSO generates an increase in the amount of precipitation in Colombia which causes floods and landslides all over the country. The floods of 2010/2011 caused widespread damage to infrastructure (Figure 18) and people's livelihoods which had profound social and economic consequences.[5] Only in Bogotá, for example, more than 32,300 families were affected by flooding produced by the increase in the rainfall product of the phenomenon (Secretaría Distrital de Ambiente and IDIGER 2015). Additionally, it was reported that costs due to damage in infrastructure reached COP$2.495.000.000 (about GBP£860.400) in 2012 (CEPAL 2012). The vulnerability of the country to weather-related events was evident and this event became a turning point for the attention to disaster risk reduction and adaptation to climate change policies in Colombia (Arroyo Narváez 2017; Krellenberg et al. 2014).

[5] A detailed review done by the Economic Commission for Latin America and the Caribbean of the United Nations of the damages caused by La Niña Phenomenon 2010/2011 can be found in (CEPAL 2012).

Photo of a road damaged in Colombia due to the effects of La Niña phenomenon removed for copyright reasons. Copyright holder is CEPAL.

(a)

Photo of road damaged by floods in Colombia associated with La Niña Phenomenon removed for copyright reasons. Copyright holder is El Heraldo.

(b)

Figure 18. Effects of La Niña phenomenon in Colombia. Sources: a) (CEPAL 2012), b) (El Heraldo 2010).

5.1.3. Economy

Colombia is catalogued by the World Bank as an upper-middle-income country (The World Bank 2019). The country's economy depends highly on energy, mining and agricultural exports. Colombia is the world's fourth-largest coal exporter, the world's third-largest coffee exporter, the world's second cut flowers exporter, and Latin America's fourth-largest oil producer (CIA 2019). This makes the country's economy vulnerable to a drop in commodity prices.

Bogotá's economic structure is dominated by the services and commerce sectors (around 61% of the city's economy in 2016), and it generates around 25% of the total National GDP of Colombia (Alcaldía Mayor de Bogotá and Secretaría Distrital de Planeación 2017). Despite the economic prosperity of the city, the income distribution of the population shows that there is great inequality. Additionally, the urban structure of the city reflects great socio-spatial segregation. The north and northeast of the city have predominantly high-income neighbourhoods with good infrastructure provision, while the south and west of the city hold low-income neighbourhoods with medium to poor access to infrastructure services (Guzman et al. 2017; Secretaría Distrital de Ambiente and IDIGER 2015).

5.1.4. Politics

Colombia, according to its last Constitution promulgated in 1991, is a presidential republic and its territory is administratively decentralised into 32 departments and a Capital District (Bogotá D.C.) (CIA 2019; DANE 2012). Colombia suffered a very violent twentieth century, but is currently experiencing a post-conflict process as it recently ended an internal conflict with a Marxist guerrilla that lasted for more than half a century (Murillo et al. 2017).

Bogotá is administratively a Capital District and it is divided into 20 localities. There is a district government of the city led by the city's mayor, and each locality has its own administration led by a local mayor (Secretaría Distrital de Ambiente and IDIGER 2015). Enrique Peñalosa is at the time of writing the current mayor of Bogotá and was elected in 2016 due to his opposition to Gustavo Petro, the previous mayor. His election meant a complete shift in the politics of the city. Mr Peñalosa brought back a city model based on infrastructure development, urban expansion and low attention to environmental and social issues. This model contrasts with that proposed by Mr Petro's administration [2012-2016] of an inclusive and compact city prepared for climate change (Arroyo Narváez 2017; Guzman et al. 2017; Zeiderman 2016b). This change has implications for how the city approaches climate change adaptation and this is discussed later in more detail in Chapters 6 and 7.

The city's district government is divided into 15 sectors. Each sector is led by one of the district secretaries and has ascribed and linked organisations (Concejo de Bogotá 2006; Secretaría General de la Alcaldía Mayor de Bogotá D.C. 2012). Although different sectors might have influence over the transport infrastructure of the city, the two most relevant sectors for this research project are the Transport sector and the Environmental sector. The Transport Sector is led by the District Mobility Secretary and includes the Urban Development Institute (IDU), the Special Attention Rehabilitation and Road Maintenance Unit (UMV), and the 20 localities. The District Mobility Secretary oversees the development of the sector's policies and the maintenance of adequate transit conditions in the city, while the responsibility for the development and maintenance of the transport infrastructure of the city is divided among the other organisations of the sector. The Environmental sector of the city is composed of the District Institute for Risk Management and Climate Change (IDIGER), the Botanical Garden, the District Institute for Animal Protection (IDPYBA) and the District Environmental Secretary, the head of the sector. The next sections in this chapter present a more detailed perspective of the institutional arrangements and decision-making processes around the city's response to climate change (Section 5.2) and transport planning in the city (Section 5.3). The final section describes the arrangements and decision-making processes for both transport planning and adaptation in the city based on what the participants reported to be the real practice in the city in the semi-structured interviews. These institutional arrangements are summarized in Figure 22 as a visual summary.

5.2. Bogotá's response to climate change

Colombia has a long tradition of engaging in international forums about climate change and has been actively involved in the international efforts to cope with it by, for example, being part of the United Nations Framework Convention on Climate Change (UNFCCC), being one of the first countries to ratify the Kyoto Protocol, and signing and adopting at a national level the Paris Agreement (Arroyo Narváez 2017; Krellenberg et al. 2014). In a study on the potential impacts of climate change over the country published in 2017, Colombia's Institute of Hydrology, Meteorology and Environmental Studies

(IDEAM) found that Colombia is highly vulnerable to climate change (IDEAM et al. 2017). Because of this and focused on avoiding a repetition of the country's experience during the occurrence of La Niña Phenomenon in 2010/2011, the national government has developed since 2012 a range of national climate change policies. These policies have been praised by some authors as one of the best examples in the region (Wilkinson and Brenes 2014; Zeiderman 2016b).

The most recent national climate change policy was published in 2017 (Murillo et al. 2017). Colombia emits only about 0.44% of the global emissions of GHG, so the policy focuses mainly on adaptation measures and proposes complementary mitigation measures to avoid further emissions. It is stated that the most strategic infrastructure for the country is transport infrastructure, especially inter-regional infrastructure, and that municipalities and districts should formulate an integral plan for climate change. This policy is related to other complementary policies such as the National Road Adaptation to Climate Change Plan (MinTransporte et al. 2014) and the National Risk Management Plan (NGDR 2016). Finally, the policy establishes the National Climate Change System which is regulated by the Decree 298 of 2016 (Figure 19).

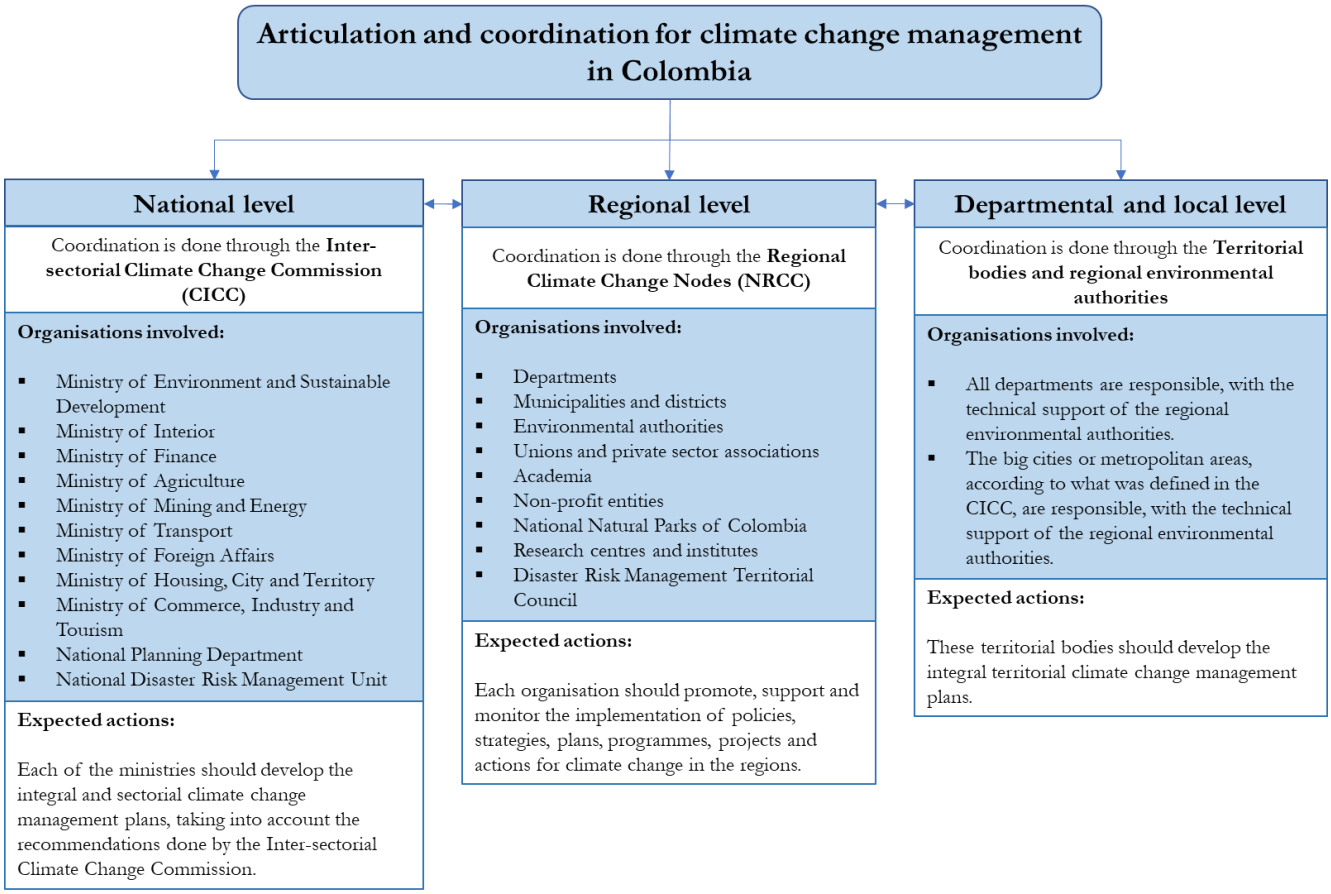

Figure 19. Articulation and coordination for climate change management in Colombia. Adapted from Murillo et al. (2017).

According to the most recent vulnerability assessment from IDEAM, Bogotá is one of the most vulnerable cities in the country (IDEAM et al. 2017). Due to the population and geographical location of Bogotá, the effects of climate change produce high risks mainly in relation to the food and water supply, and infrastructure of the city. Therefore, the city has developed its own climate change policies following the national government's example and requirements. An important shift towards including climate change in the political agenda of the district was achieved during the government of Gustavo Petro [2012-2016]. In May 2013, he announced the intention to revise the city's urban master plan so that it could consider climate change (Alcaldía Mayor de Bogotá 2013b), but this produced considerable opposition. The ensuing political debate over the urban master plan had a crucial effect on the implementation of adaptation measures in the city (Lombo 2014). In the end, the revision was not possible (Semana 2014; Zeiderman 2016a). Mr Petro's administration was only able to change the risk management system of the city by associating climate change to its mission. His administration created the District Institute for Risk Management and Climate Change (IDIGER), as an ascribed organisation to the Environmental Sector, to lead the new District Risk Management and Climate Change System (SDGR-CC) and its policies (Alcaldía Mayor de Bogotá 2013a, 2014a; IDIGER 2016). A schematic representation of the SDGR-CC is shown in Figure 20.

One of the first tasks of IDIGER was to develop the District Risk Management and Climate Change Plan for Bogotá D.C. 2015-2050, which is still in force, but previous reviews by Arroyo Narváez (2017) and Lombo (2014) suggest that its implementation has been limited. Additionally, some of the interviewees involved in this research suggested that the plan is being redeveloped at present, thereby further hindering its application. The plan proposes different programmes to deal with climate change risks in the city. In terms of infrastructure, sustainable urban drainage systems (SUDS) and the use of "green" infrastructure are proposed as the main adaptation measures for the city. However, there is no explicit mention of the adaptation of road infrastructure in this plan (the plan can be reviewed in Secretaría Distrital de Ambiente and IDIGER (2015)).

Due to the termination of the validity period of the previous urban master plan of the city, the current administration was assigned the task of developing the new urban master plan for Bogotá. In this plan, Mr Peñalosa's administration [2016-2020] is trying to promote a city model which is different from that promoted by Mr Petro's administration in 2013, as he promised his voters in 2016. As expected, this has produced a complex political debate over the future of the city. Until the new urban master plan is published, it will not be clear how the current government of Mr Peñalosa will include climate change considerations in the urban planning of the city, so the future of Bogota's adaptation agenda is still uncertain (Arroyo Narváez 2017; Zeiderman 2016a).

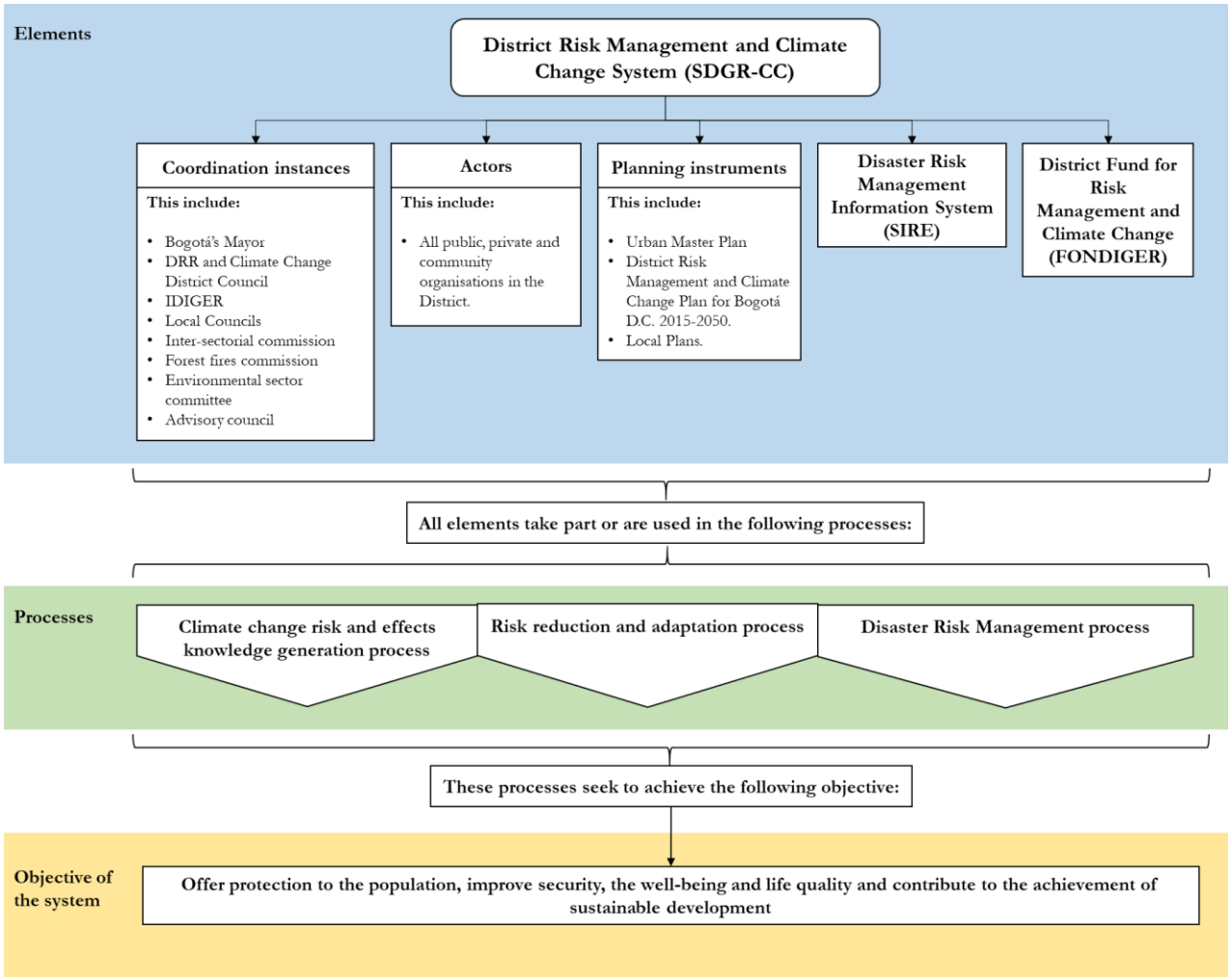

Figure 20. District Risk Management and Climate Change System (SDGR-CC). Adapted from IDIGER (2016).

5.3. The transport sector of Bogotá

Transport infrastructure is perhaps one of the most vital infrastructure systems in Colombia. It is catalogued as the most strategic infrastructure system for the country in the most recent national climate change policy (Murillo et al. 2017), and transport infrastructure has had a crucial role in the recent urban management and development of Bogotá, as exemplified by the urban renovation that Transmilenio, a Bus Rapid Transit (BRT) system, brought to the city in the early 21st century (Guzman et al. 2017).

The most important type of transport infrastructure found in Bogotá is urban roads. Urban roads have different classifications in the city depending on the level of traffic they support and their socio-economic importance (Secretaría Distrital de Planeación 2015b). Their classification is established by the District Planning Secretary through the Urban Master Plan. In this plan, the District Planning Secretary also defines the standard road profiles allowed for each of these categories and the most strategic infrastructure projects of the city. According to the most recent plan from 2004, urban roads

are classified in Bogotá as follows (Alcaldía Mayor de Bogotá D.C. 2004; Secretaría Distrital de Planeación 2019):

- **Principal arterial road network:** the road network highest in the hierarchy that acts as the main support for the urban and regional mobility and accessibility and for the connection of the city with the rest of the country.
- **Complementary arterial road network:** the road network that operationally links the subsystems of the principal arterial road network. It facilitates medium and long-distance mobility as an articulating element at the urban scale.
- **Intermediate road network:** constituted by a series of road segments that permeate the network composed by the principal and complementary arterial roads, functioning as a traffic alternative to them. It allows for access and traffic flow in the city at the zonal scale.
- **Local road network:** constituted by road segments whose principal function is to allow access to housing units.

Table 9 shows the condition of the road network in Bogotá in December 2018. The percentage of roads in good, regular or bad condition for each road classification and for the whole network are presented. The condition was established according to the Pavement Classification Index (PCI) calculated for each road segment following the technical standard ASTM D6433-2016.

Table 9. Diagnosis of the condition of Bogotá's road network in December 2018. Adapted from IDU (2018).

	Condition		
Road Classification	**Good**	**Regular**	**Bad**
Principal arterial	87%	12%	1%
Complementary arterial	65%	29%	6%
Intermediate	60%	32%	8%
Local	47%	30%	23%
Whole network	57%	29%	14%

The level of investment in the construction of new transport infrastructure and the maintenance of existing infrastructure in Bogotá for the last decade is shown in Figure 21. This figure shows an estimate of the percentage from the total budget of the city that is invested in transport infrastructure in Bogotá from 2007 to 2018. This has been estimated by using as a proxy the rate between the sum of the annual investment budgets of the Urban Development Institute (IDU) and the Special Attention Rehabilitation and Road Maintenance Unit (UMV), and the total annual budget of the city. The estimates shown here have been calculated using publicly available official data from the District Treasury Secretary

(Secretaría Distrital de Hacienda 2019). Figure 21 shows that the level of investment in the last decade has been between 5.8% and 10.5% of the city's total annual budget. In the figure, it can also be observed that the level of investment changes notably whenever there is a change of administration in the city. For instance, there is a noticeable difference between the level of investment during the government of Gustavo Petro [2012-2016] and during the government of Samuel Moreno [2008-2011]. Gustavo Petro's administration had, in general, more interest in investing in social programmes in the city and therefore the investment in infrastructure was reduced during his administration. The peak in 2014 corresponds to the budget assigned to start a cable car line project in the south of the city, which was the major infrastructure project financed by the city during Petro's administration. This shows the influence that the political agenda of the city's administration has over the investment in infrastructure.

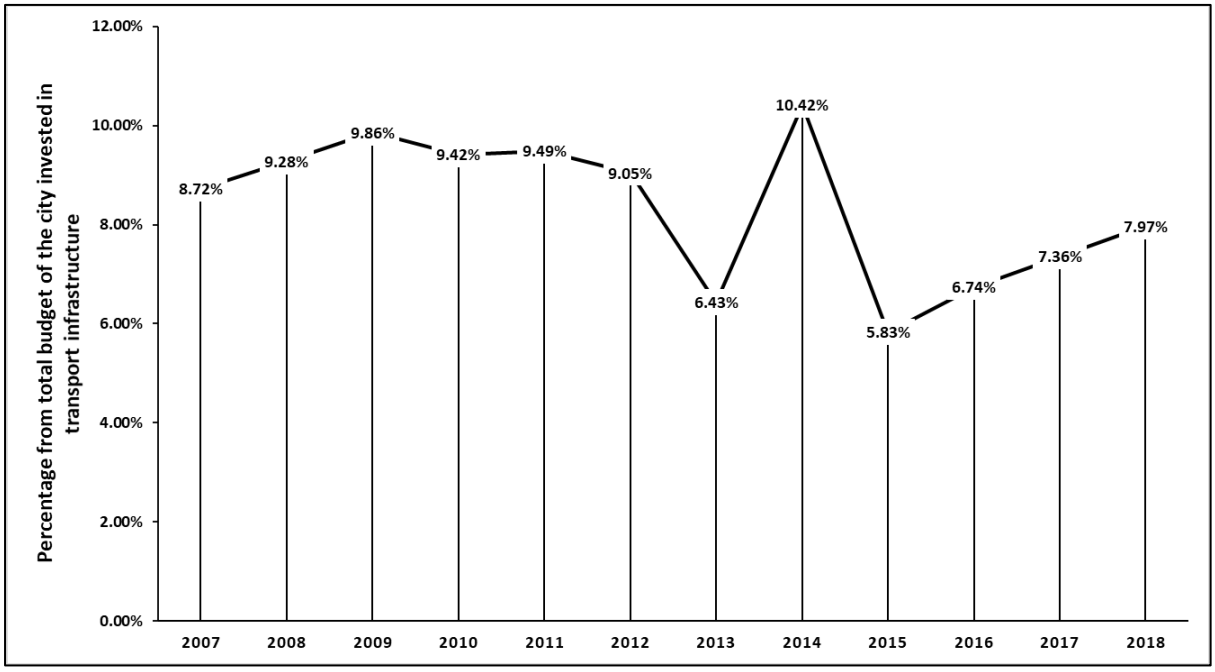

Figure 21. Level of investment in transport infrastructure in Bogotá from 2007 to 2018.

In addition, the city has a deficit in investment in infrastructure, especially in terms of maintenance investment. It has been estimated that in 2016, the city had a deficit in terms of maintenance of its road network of COP$11 trillion (about GBP£263 million) (Alcaldía Mayor de Bogotá D.C. 2016).

The transport sector in Bogotá is led by the District Mobility Secretary and the city's road infrastructure management is divided between the Urban Development Institute (IDU), the Special Attention Rehabilitation and Road Maintenance Unit (UMV) and the 20 local mayoralties of the city depending on the classification of the roads (Figure 22). For instance, the IDU is in charge of the construction and maintenance of the arterial and intermediate road network in the city that supports the public transportation system. The IDU is also in charge of all elements of public space in Bogotá (for example, sidewalks, squares or bikeways). Additionally, the IDU establishes the technical standards for the

construction of public projects in the city. These technical standards are limited to standardising the quality of construction materials and construction methods. The IDU provides some guidelines for the design of transport infrastructure, but the selection of appropriate design methods is left to the criteria of the designers in each project. The construction and maintenance of the intermediate roads that do not support the public transport system and the local road network is a responsibility of the local mayoralties. Both the IDU and the local mayoralties can construct or maintain their road networks themselves or can commission private companies for the job. According to some interviewees, during the current administration of Enrique Peñalosa [2016-2020], the standard has been to commission all projects to private engineering companies. The local mayors can also hire the UMV for maintenance works in their local network. This is the main type of work of the UMV in the city. The UMV also helps the IDU with higher hierarchy roads on special occasions if required (for example, in post-disaster reconstruction). As shown here, the District Mobility Secretary is not involved in the construction or maintenance of the road network of the city as their main mission is to act as the developer of the sector's policies and the transit authority of the city.

5.4. The decision-making processes for road infrastructure planning and its adaptation to climate change in Bogotá

This section describes how the decision-making processes in the city regarding transport planning and adaptation planning of road infrastructure function in reality. The analysis presented here is based on the formal institutional arrangements in Bogotá described in the previous two sections and the evidence collected through the case study interviews. The decision-making network is presented schematically in Figure 22 (this figure is also presented as a fold-out appendix at the end of this thesis for reference). The processes described in the figure show that in reality there are some instances in which decision-making does not follow what is expected by the established institutional arrangements outlined in the city and national policy. There are also instances in which there are responsibility gaps that can affect the effective outcome of planning in the city, especially with respect to the adaptation of urban roads.

The transport sector is located at the centre of Figure 22 showing the organisations described in the previous section. At the head is the city's mayor who is described by most of the interviewees as the most influential person in the city regarding all policies including transport planning and adaptation planning. The mayor exerts his influence over the district though a planning document called the Development Plan which is used as the government plan to guide the four-year administration term. The influence of the mayor in all aspects of policy in the city is represented in Figure 22 by the different influence arrows that are shown connecting the mayor with the different organisations and planning documents in the diagram. Here it is important to note two aspects in the decision-making processes of the city surrounding the city's mayor. First, as shown, the city's mayor does not act entirely

independently as he is also influenced by external organisations from the national government such as the country's president office or the ministries, and by international organisations like the United Nations Development Programme for Colombia (PNUD). For example, PNUD has been directly involved in the development of the city's climate change and risk management policies as an advisor (Secretaría Distrital de Ambiente and IDIGER 2015) and as a sponsor of several vulnerability analyses in the country (IDEAM et al. 2012, 2014b, 2017). Second, there exists weak influence between the Urban Master Plan and the Development Plan of the city's mayor. According to Colombian law, Colombian municipalities with a population of more than 100,000 should develop an Urban Master Plan with a validity of 10 to 12 years that rules over the use of land in the municipality and guides urban development. The District Planning Secretary has decided to develop an Urban Master Plan every 12 years, which encompasses three constitutional periods for mayors during the validity period of the document. The development of the document is a responsibility of the administration that oversees the end of the validity period of the existing Urban Master Plan. This has been the case for Enrique Peñalosa's current administration of the city making it the only administration within the current period with real influence over the development of the next 12-year plan. Additionally, according to the law, the Development Plans of the three mayors should align with the objectives of the Urban Master Plan, but unfortunately, Colombian law does not make mayors legally bound to do so. This consequently allows the Urban Master Plan to influence moderately or not at all the Development Plan of the mayor of the city. This has already occurred with the past Urban Master Plan as suggested by the diagnosis of its implementation completed by the District Planning Secretary (2017) (a point reinforced by some interviewees). It is because of this, that the arrow between the city's mayor and the Urban Master Plan is shown as a dashed line in Figure 22 to infer a weak connection.

Figure 22 also depicts the different organisations in Bogotá that are external to the transport sector but influence the decision-making processes within the sector. For example, as described before, the District Planning Secretary establishes the road categories, road profiles, land use and main infrastructure projects of the city through the Urban Master Plan. The District Treasury Secretary assigns the budgets for the organisations in the transport sector according to the Development Plan of the mayor after they are approved by the Bogotá's Council. Bogotá's Water Company has two main responsibilities. The Water Company, first, oversees the management of all water and sanitation infrastructure in the city, and second, it acts as an advisor to the transport sector in terms of how to manage water drainage in the city by providing guidelines and by approving all designs concerning water management in road projects. Because of its responsibilities, it is the organisation in charge of implementing SUDS in the city.

The environmental sector of the city is shown in the right-hand side of Figure 22. The District Environmental Secretary, as the leader of the sector, is the main environmental authority in the District. It is in charge of developing the sectorial policies of the city and exerts environmental control over the

organisations of the transport sector. It is jointly in charge of the management of "green" infrastructure with the Botanical Garden and another external organisation to both sectors called the District Institute of Recreation and Sport (IDRD). IDIGER, for its part, acts as the authority on risk management providing direct technical advisory services on risk management to the transport sector and through coordinating the District Risk Management and Climate Change System (SDGR-CC).

Additionally, Figure 22 presents (in green shading) all the organisations of the District that are actively in charge of an aspect of adaptation planning of the road infrastructure of Bogotá. The only organisation actively working on adaptation within the transport sector itself is the District Mobility Secretary, which according to some of the interviewees is currently in charge of developing the adaptation strategy for the sector. As described before, the city's Water Company is, according to the adaptation institutional arrangements in the city, responsible for overseeing the development of SUDS. Also, the District Environmental Secretary, the Botanical Garden and IDRD are in charge of "green" infrastructure, the other type of adaptation measure proposed by the city in its District Risk Management and Climate Change Plan for Bogotá D.C. 2015-2050. IDIGER provides the sector with all the necessary technical information regarding climate risks and coordinates the other organisations in the SDGR-CC that can aid the transport sector in their adaptation efforts.

Figure 22 shows that the three organisations in charge of road infrastructure in the city, the IDU, UMV and the local mayoralties, are not actually active in the adaptation efforts of the transport sector. This was not obvious at the beginning of the case study research, but the evidence (described later in detail in Chapter 6 and Chapter 7) demonstrated that this is the case. This reveals that there is a responsibility gap in the adaptation institutional arrangements of the city. This may prove to be a barrier in the planning for adaptation of road infrastructure as adaptation is not yet an internalised process of the road asset managers in the city. This and other possible barriers are analysed further later in Chapter 7.

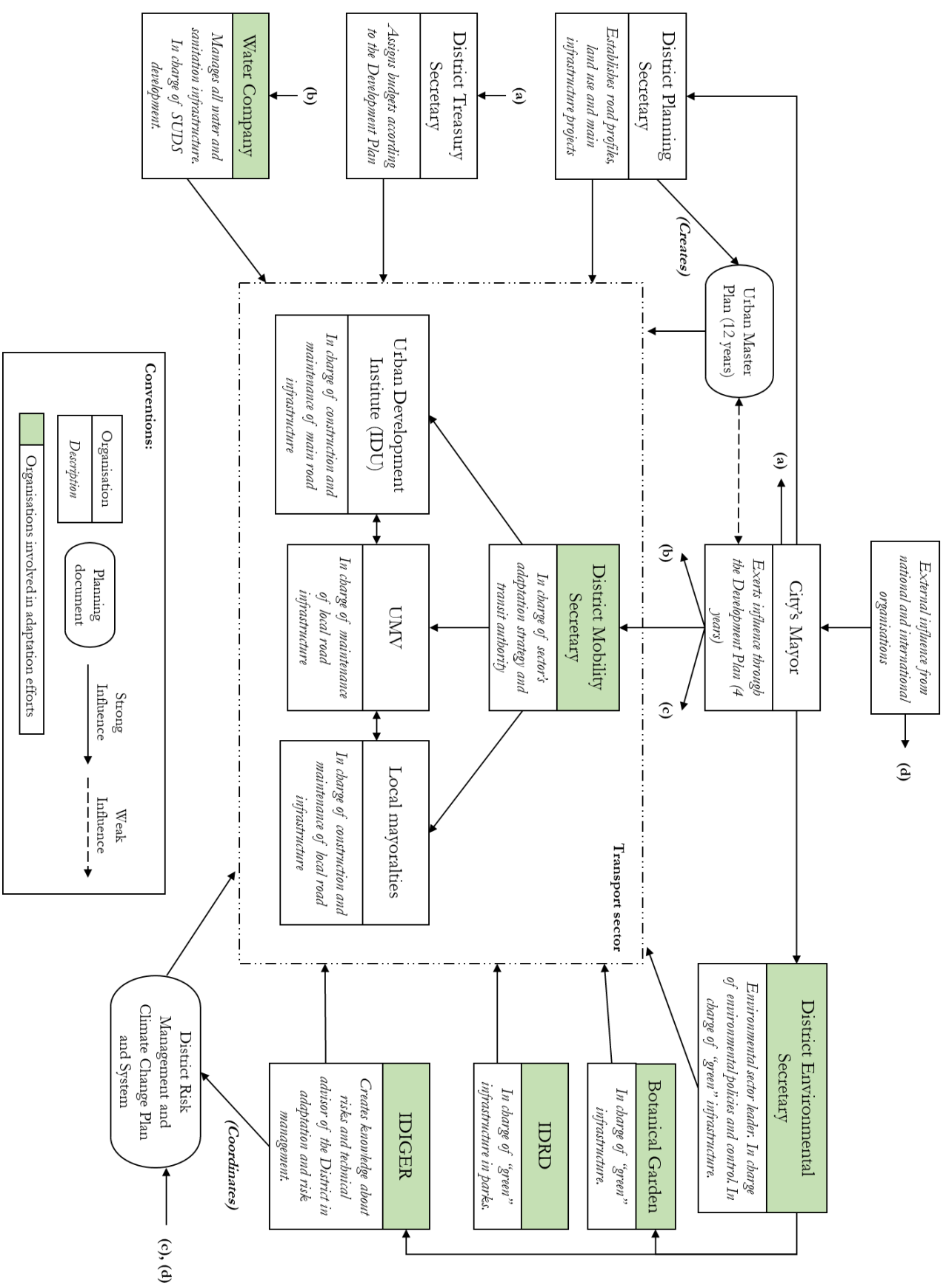

Figure 22. Influence and decision-making network for road infrastructure planning and its adaptation to climate change in Bogotá, Colombia.

5.5. Chapter summary

To conclude, this chapter has described briefly the characteristics of Bogotá, Colombia and presented the main institutional arrangements relevant to the adaptation of road infrastructure in Bogotá. Firstly, a short overview of the geography, climate, economy, and politics of Bogotá and Colombia has been presented. Secondly, this chapter has presented the city's official institutional arrangements for climate change action and transport planning, and the current state of the city's road network. Finally, it has described and analysed the decision-making processes for road infrastructure planning and its adaptation to climate change as reported by the participants of the interviews performed as part of the case study. This analysis has shown that there are some responsibility gaps in the institutional arrangements regarding the adaptation of urban road infrastructure in the city. This is because the organisations that are asset owners of road infrastructure in the city are not actually active in the adaptation efforts of the transport sector.

The context and the results of the analysis here presented contribute to answering the key questions associated with the case study as presented in Section 1.3 and the second sub-question to the main research question, how is the adaptation planning process affected by the local social, political, economic, geographical and environmental context?

The following two chapters of this thesis discuss further the planning processes for the adaptation of road infrastructure in Bogotá presented in Figure 22 by analysing it through the analytical questions of the EAAC framework in Chapter 6 and by showing how barriers to and opportunities for effective adaptation planning can be identified in the city in Chapter 7.

Chapter 6

6. Understanding adaptation planning of urban road infrastructure in Bogotá, Colombia

This chapter presents an analysis of the adaptation planning processes of the transport sector of Bogotá. It serves as an example of how the EAAC framework can be used as a diagnostic tool to understand the planning of adaptation of urban road networks. This diagnosis is completed by collecting evidence to form responses to the series of key questions associated with each stage of the adaptation planning cycle which work as the first main analytical tool of the EAAC framework. The analytical questions are presented here again in Table 10.

Table 10. Stage of the adaptation cycle and questions used to operationalise it. Sourced from Park et al. (2012).

Stage of adaptation planning cycle	Questions used for the assessment
1. Problem structuring and establishing of the adaptation arena	• What is the nature of vulnerability and the perceived risk? • Who or what adapts? • What do they adapt and why?
2. Developing the adaptation agenda, vision and pathway	• How do they adapt (processes)? • What are the opportunities for adaptation? • Costs and/or benefits of decisions?
3. Implementing adaptation options	• What implementation methods and resources are used? • What constrains or incentivizes implementation? • What impacts the results?
4. Evaluating, monitoring and learning	• How well do they adapt? • How does the system change? • What are the plans for the future?

This chapter is divided into sections that analyse the evidence providing answers to some of the key analytical questions presented in Table 10. Each section focuses on providing a response to one or two of these analytical questions. The questions are presented in the same order as they appear in Table 10. This is because the answers to the analytical questions of later stages depend on the results obtained in previous stages. The evidence collected in the case study can only be used to provide partial or complete answers to some of the questions associated with the first two stages of the adaptation cycle (as shown

in the analysis presented in Sections 6.1 to 6.4). Section 6.5 presents evidence on how Bogotá's transport sector is planning to approach the later stages in the adaptation planning process.

Examples and evidence supporting each of the findings are referenced in footnotes using the codes for interviewees and documents shown in Table 5 and Table 6 of Chapter 4. It is important to note that the number of times an issue was cited by interviewees or in the local documents should not be considered as a reflection of the significance of that issue for comparative purposes; the qualitative nature of this study does not allow for such conclusions to be drawn. However, this coding and reporting approach has been adopted to provide some transparency as to how the evidence has been collated and to show the rigour behind this process. Some examples of evidence associated with the footnotes can be found in the main text in the form of quotes, references to situations described by the interviewees or references to the documents analysed. Further examples of evidence associated with each footnote are provided in Appendix 8. These quotes are presented in an appendix to help maintain the flow of the main argument and development of the themes and insights in the main text. These additional examples are presented to provide further transparency on how the analysis presented has been developed and to allow readers to make their own judgements about the fairness and accuracy of this analysis. Due to constraints related to the available space in this thesis, not all quotations could be presented and only representative quotes are shown in the main text and Appendix 8. The chapter finishes with a discussion of the analysis presented and of the results of the diagnosis of the state of adaptation planning of road infrastructure in Bogotá. Possible future steps in the adaptation planning process of the transport sector of the city are also discussed.

6.1. Stage 1: What is the nature of vulnerability and the perceived risk?

The national and local environmental agencies have made various efforts in recent years to understand the nature of Bogotá's vulnerability to climate change following the technical guidelines of the IPCC. The most recent effort was made by Colombia's Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) in 2017 (IDEAM et al. 2017). In this effort, IDEAM performed a national vulnerability assessment of all departments and the capital district. IDEAM's assessment was multidimensional as it evaluated six dimensions of vulnerability: food security; water security; biodiversity and ecosystem services; human health; human habitat; and infrastructure. In their assessment of vulnerability to climate change, Bogotá is presented as one of the cities in the country with a higher risk to the effects of climate change. Their assessment presents infrastructure as the third biggest contributor to Bogotá's vulnerability and as an element with low adaptive capacity in the city (IDEAM et al. 2017). However, the infrastructure dimension is presented in IDEAM's analysis as an aggregated picture of roads, airports and electrical infrastructure. Because of this, the results of

IDEAM's assessment can be used only for creating a general understanding of the contribution of all infrastructure to the vulnerability of the city as the specific contribution of the city's road infrastructure is not presented. Similarly, Bogotá's District Institute for Risk Management and Climate Change (IDIGER), following the national example of IDEAM, generates local hazard maps using similar assessment methods that express the vulnerability of the city to different hazards in an aggregated manner.[6] An example of a hazard map for landslides produced by IDIGER is shown in Figure 23.

Figure showing a hazard map of climate change-induced landslides for the urban area of Bogotá removed for copyright reasons. Copyright holder is IDIGER.

Figure 23. Official hazard map of climate change-induced landslides for the urban area of Bogotá (Red = high, Yellow = medium, Green = low). Sourced from IDIGER (2019).

Due to this gap in knowledge about the specific contribution of different types of infrastructure to the overall vulnerability of the city, many interviewees expressed that there is an urgent need to better understand the nature of the expected local effects of climate change and the specific vulnerability of the city's road network. This understanding will serve as a necessary baseline for adaptation decision-making in the road sector.[7] Although there is not sufficient knowledge about the expected effects of climate change on specific road assets of the city, most interviewees expressed similar general perceptions of the common risks that the road network of the city is most likely to encounter. Most of them coincide in that the main risks expected are those associated with the increase in rainfall caused by the influence of climate change over common meteorological processes experienced in Bogotá and

[6] (INT5, INT5-2, INT8, INT17a, INT21, INT24a, INT24b, INT24c, INT39a, INT39b)
[7] (INT5-2, INT8, INT11a, INT11b, INT12a, INT12b, INT12c, INT13, INT14, INT20, INT21, INT24a, INT24b, INT24c, INT25, INT26, INT29, INT37, INT39a, INT39b, Report RVV, PDGR-CC).

other weather processes such as the El Niño/La Niña Phenomenon.[8] It is believed that this will generate increased flooding, ponding and landslides that have the potential of affecting the road infrastructure of the city. Additionally, some interviewees, mainly those with jobs related to the maintenance of the road network, suggested that the city's road infrastructure will have also problems during dry seasons related to subsidence-induced failures linked to the shrinking of plastic soils present in Bogotá (i.e. clays) and the presence of water-demanding plant species close to road infrastructure.[9]

Understanding the need for better knowledge about the vulnerability of Bogotá's road network, the District Mobility Secretary commissioned in 2017 a technical study to determine the Vital Road Network (RVV) of the city and how it will be impacted by the hazard scenarios created by IDIGER for 2017, 2020, 2038 and 2050. An official from the District Mobility Secretary explains the perceived challenges and importance of the task as follows:

"There is a huge effort there that [the consultants] will need to make and it is that they will need to determine how that Vital Road Network will help to reduce the risks associated with climate change in the city both in the mobility system and in the city if possible. Then, I believe that it will be an important input to create a baseline of risk in the city so other things can be done in the future" (INT24b).

The RVV study focuses on disaster risk management and emergencies management (Unión Temporal MOBIGA 2018). By following this focus, the baseline of risk created from the RVV will be limited as it will only provide information to the city on how to deal with one of the two types of risks associated with climate change, those related with extreme weather events. The city will still lack an understanding of the nature of the vulnerability of its road network against risks due to long-term changes in average climatic conditions until a similar study to the RVV is commissioned for this matter.

Bogotá has made some initial steps to understand the nature of the vulnerability of its road network, but still needs to fill in some gaps in the comprehension of how the two types of climate change risks will affect the city. Additionally, although most interviewees agree about the common types of risks that the city will most possibly face due to climate change, the evidence from the interviews and documents analysed show that there are different political interpretations of the nature of those risks. These interpretations ultimately affect the extent and type of adaptation actions selected by the city officials. This difference in political interpretations amongst actors in the city can become a barrier to the adaptation planning process as explored later in Chapter 7. In addition, the evidence from the interviews suggests that many city officials lack technical capacity regarding climate change and risk management, even officials dedicated to adaptation efforts. For example, an official dedicated to the development of

[8] (INT1, INT2, INT3, INT4, INT5, INT5-2, INT8, INT11a, INT11b, INT12a, INT12b, INT12c, INT14, INT17a, INT20, INT21, INT22, INT23, INT24a, INT24b, INT24c, INT27, INT28, INT29, INT31, INT32, INT33, INT38, INT39a, INT39b, Report RVV, Eco-urbanism, Diagnosis POT)
[9] (INT3, INT8, INT17a, INT20, INT22, INT23, INT31, INT32)

the adaptation strategy of the District Mobility Secretary observed that the concept of adaptation is still *"a bit abstract and ethereal"*[10] for his team and that there is a need to better understand this concept and its practical implications inside different organisations of the transport sector. Therefore, there is also a need to increase the technical capacity of the city professionals in these topics. This lack of technical capacity of city officials is explored further in Chapter 7. In summary, Bogotá's transport sector has made some initial efforts that help answer this first analytical question but still needs to understand more satisfactorily what the nature of vulnerability and the perceived risk is.

6.2. Stage 1: Who or what adapts? And, what do they adapt and why?

Complying with the national risk management law (Law 1523 of 2012 (Congreso de Colombia 2012)), Bogotá's administration created the District Risk Management and Climate Change System in 2014 (see Section 5.2). This system collects all the institutional arrangements for the management of disasters, climate change, emergencies and other risks in the city. IDIGER was created to lead the district system and the policies associated with risk management and climate change. However, this institute has limited power to execute projects,[11] as a coordinator of the District Risk Management and Climate Change System in IDIGER explains:

"IDIGER, as it is an institute, it is an organisation that should generate more knowledge, guidelines, policies. […] We are not, and we should not be, executors of those projects" (INT21).

The same interviewee then explains who should be adapting the road network of the city:

"But for that exists a transport sector and there is an Institute for Urban Development and the UMV. So, what do we do with them? We coordinate all actions. So, we are in that right now" (INT21).

In other words, according to the law and institutional arrangements, the transport sector must oversee the adaptation of its road network (use Figure 22 for reference or the fold-out appendix). As head of the sector, the District Mobility Secretary is in charge of coordinating, with the advice of IDIGER, the development of the adaptation strategy of the transport sector.[12] The responsibility over executing adaptation actions should be, according to what is established in Colombian law, divided amongst the different organisations in charge of road infrastructure in the city such as the IDU, UMV and the local mayoralties, but this is still not clear as there is no current adaptation strategy.[13] Furthermore, the city is proposing as principal adaptation actions the construction of sustainable urban drainage systems

[10] (INT24b)
[11] (INT5, IN5-2, INT8, INT12a, INT12b, INT12c, INT17a, INT21, INT22, INT24a, INT24b, INT24c, INT25, IN31, INT32, INT39a, INT39b)
[12] (INT21, INT24a, INT24b, INT24c, INT39a, INT39b, Report RVV)
[13] (INT1, INT5-2, INT11a, INT11b, INT21, INT24a, INT24b, INT24c, INT28, INT31, INT37, INT38, INT39a, INT39b)

(SUDS) and the use of "green" infrastructure and ecosystem services (Secretaría Distrital de Ambiente and IDIGER 2015), but according to the city's institutional arrangements these are the responsibility of organisations outside the transport sector, making the adaptation process even more complicated. For instance, SUDS are the responsibility of the city's water company and the "green" infrastructure of the city is a shared responsibility between the District Environmental Secretary, the Botanical Garden and the District Institute of Recreation and Sport.[14] Therefore, it seems that according to current institutional arrangements the IDU, UMV and the local mayoralties have in reality no active role in the adaptation of the road network.

The District Mobility Secretary is making a first attempt to assign more clearly the responsibilities of different organisations from inside and outside the transport sector over disaster risk management and adaptation actions for the city's road network through the RVV study. However, this will not be legally binding until the city creates a decree to adopt the RVV (Unión Temporal MOBIGA 2018). For now, it is only clear that the creation of an adaptation strategy for the road network of Bogotá is a responsibility of the transport sector led by the District Mobility Secretary and that the responsible organisations for the proposed adaptation actions are not part of the transport sector. In other words, there are no clear institutional arrangements that link adaptation planning to a coordinated set of actions implemented by those managing the road networks, thus creating a responsibility gap in the city.

The RVV study has been also used by the District Mobility Secretary as a first attempt to understand which roads need to be prioritised in their adaptation efforts and why.[15] This could provide answers to the question "what do they adapt and why?". The main objective of this project was to determine which is the most important, or vital, road network in the city. This will later help the transport sector to decide where to focus their main efforts to guarantee the increase of resilience of the city against disasters. This network has been established by the consultants leading the project by selecting the road assets that guarantee the best mobility in the city under all disaster scenarios modelled by IDIGER for 2017, 2020, 2038 and 2050. These disaster scenarios include flooding, landslides, forest fires and earthquakes (Unión Temporal MOBIGA 2018).

As the evidence shows, Bogotá's transport sector presents more progress in the judgement of which infrastructure assets will require more focus and in the establishment of responsibilities over adaptation efforts in comparison with the progress achieved to understand the nature of the underlying vulnerability of the city's road infrastructure and the perceived risk. This can be attributed to the fact that the city has well-established, but complicated, adaptation institutional arrangements at the district level and because the RVV project is helping the District Mobility Secretary to determine what needs to be adapted in its

[14] (INT2, INT5-2, INT8, INT12a, INT12b, INT14, INT15a, INT15b, INT20, INT21, INT22, INT23, INT24a, INT24b, INT24c, INT27, INT28, INT33)
[15] (INT24a, INT24b, INT24c, INT39a, INT39b, PDGR-CC, Annex RVV, Report RVV)

network. However, without having a comprehensive understanding of the nature of the vulnerability and a baseline, and without doing a revision of the adaptation institutional arrangements of the city, it will remain difficult to answer satisfactorily "who" adapts and "why" focus should be given to some roads and not others.

6.3. Stage 2: How do they adapt?

The District Management and Climate Change Plan for Bogotá D.C. 2015-2050 in its conceptual framework establishes that adaptation can be planned and implemented following different approaches that include ecosystem-based adaptation, community-based adaptation and infrastructure-based adaptation (Secretaría Distrital de Ambiente and IDIGER 2015) (see Box 1 of Appendix 1 - Approaches to adaptation planning for more detail on what these approaches mean). The city's mayor, the District Environmental Secretary and the District Planning Secretary have decided that the city should follow exclusively an ecosystem-based approach to adaptation.[16] This has resulted in a proposed urban planning approach in the city's policies focused on eco-urbanism and eco-efficiency in which "green" infrastructure (refer to Table 1 in Chapter 2) and SUDS are predominately presented as solutions to the city's socioecological problems (Alcaldía Mayor de Bogotá 2014b; Alcaldía Mayor de Bogotá D.C. 2016; Alcaldía Mayor de Bogotá and Secretaría Distrital de Planeación 2017; Secretaría Distrital de Ambiente and IDIGER 2015). Because of this and in accordance with the shared perception of the interviewees that the main risks to the city are those related with the increase of rainfall (as shown in Section 6.1), several interviewees mention SUDS and "green" infrastructure as the adaptation actions the city needs to implement in the foreseeable future to create resilience against the expected effects of climate change.[17] Some interviewees mention other types of actions such as the incorporation of new kinds of pavements[18] (many referred to draining pavements which can be part of SUDS systems) or different slope management techniques which include in some cases the use of plants to control soil movement and drainage.[19] Following the city's approach and policies, the RVV consultancy proposes also SUDS and "green" infrastructure as the main adaptation actions to implement in the RVV project (Unión Temporal MOBIGA 2018).

This ecosystem-based framing is problematic as it effectively generates tunnel vision of the concept of adaptation for professionals in the city. By conceptually limiting adaptation measures to the betterment of drainage systems, "green" infrastructure and the protection of crucial ecological systems that provide ecological services to the city, an exclusive ecosystem-based approach creates the illusion that other

[16] (INT5, INT5-2, INT12a, INT12b, INT12c, INT14, INT15a, INT15b, INT21, INT26, INT32, INT33, INT35, Diagnosis POT, Eco-urbanism, Development Plan)
[17] (INT1, INT5-2, INT8, INT12a, INT12b, INT12c, INT14, INT21, INT22, INT23, INT25, INT26, INT27, INT28, INT32, INT33, INT35, INT38, INT39a, INT39b)
[18] (INT11a, INT11b, INT21, INT22, INT23, INT27, INT29)
[19] (INT5-2, INT20, INT21, INT23, INT39a, INT39b)

elements of the city, for example, other structural elements of the road, do not need to be adapted. As shown by Biagini et al. (2014) (see Table 1 in Section 2.4.3), there are at least ten different categories of adaptation actions which the city could be implementing: capacity building; management and planning; practice and behaviour; policy; information; physical infrastructure; warning or observing systems; "green" infrastructure; financing; and technology. This critique is shared by some officials of IDIGER, as one explains:

"[Ecosystem-based adaptation] is a vision from the District Environmental Secretary, but us in IDIGER, as we are the coordinators of the system, we have discussed enough the necessity of [adaptation] not only being ecosystem-based adaptation, yes? But that we rather should incorporate a vision that is a bit more holistic" (INT21).

This suggests that some officials are already willing to explore alternative approaches to adaptation in the city to avoid the narrow perspective presented by an exclusive ecosystem-based approach.

Additionally, the selection of "green" infrastructure and SUDS is indicative of the scale of adaptation that the city and the transport sector are currently aiming to implement. The District Management and Climate Change Plan for Bogotá D.C. 2015-2050 and the RVV project propose implementing these measures in a way that only represents marginal changes to current infrastructure (Secretaría Distrital de Ambiente and IDIGER 2015; Unión Temporal MOBIGA 2018). This indicates that the city is aiming, at most, to achieve incremental adaptation according to the scales of adaptation of the EAAC framework (see Table 2 of Chapter 3).

The RVV study commissioned by the District Mobility Secretary also provides further answers to the question of "how do they adapt?". The RVV study is assigning responsibilities to different organisations from inside and outside the transport sector over disaster risk management and adaptation actions for the city's road network as explained in Section 6.2. In addition, the RVV study presents the recommendation of the consultant for developing a decree that legalizes the RVV project as the next step to follow in the project. Unfortunately, although the city has some clarity of how it proposes to adapt, the transport sector is still limited in its capacity to implement any type of actions on a large scale. This will be the case until binding institutional arrangements are in place in the city with the creation of, for example, an official adaptation strategy for the transport sector by the District Mobility Secretary, the RVV decree or more strict policies regarding eco-urbanism and green construction that provide clearer answers to the questions of who or what adapts, what do they adapt and how.

6.4. Stage 2: What are the opportunities for adaptation? And what are the costs and/or benefits of decisions?

Bogotá is currently at an interesting and decisive political moment as a new Urban Master Plan for the city has been in development since the beginning of Enrique Peñalosa's second period as mayor in 2016. This new Urban Master Plan will set the urban model and principal urban projects for Bogotá for the following 12 years, setting a route map for all major policies in the city including adaptation to climate change and risk management. Several interviewees see the development of this new Urban Master Plan as the main opportunity the city has for incorporating adaptation in the different planning processes of the city.[20] It is argued that the current administration is hoping to include elements of eco-urbanism, risk management and possibly adaptation into the structural elements of the new Urban Master Plan so they become legally binding for the next three administrations of the city as they will have to implement the planning document in the next 12 years.[21] This is not a new idea, as the administration of Gustavo Petro tried to make adaptation to climate change a priority for the urban planning of the city in 2013 with the expedition of Decree 364 of 2013 (Alcaldía Mayor de Bogotá 2013b) that modified exceptionally the Urban Master Plan of the city, but it was suspended by the National State Council as it considered it invalid for being outside the mayor's powers (Semana 2014). Although this time the modification of the Urban Master Plan is being done under valid legal processes (i.e., it is being done at the legal time for renewing the plan, which was not the case in 2013), it is still not clear what the extent of the incorporation of adaptation to climate change would be in the urban planning of the city until Enrique Peñalosa's administration makes the new Urban Master Plan public. This will determine whether the current modification of the city's Urban Master Plan ends up being a missed opportunity for including adaptation or not.

After a new Urban Master Plan is approved in the city, several organisations from the District need to develop another type of planning document called a Master Plan (for example, the transport sector needs to develop a Mobility Master Plan) which describes the strategies the different sectors of the city intend to follow in order to implement the projects found in the new Urban Master Plan and their goals. For some interviewees, this is another opportunity in which adaptation can be incorporated in the planning processes of the city.[22] INT33 (an engineer from Bogotá's Water Company) described that Bogotá's Water Company has already a draft of the new Master Plan for its water and sanitation networks in which a key component is adaptation to climate change through the implementation of SUDS, following the ecosystem-based adaptation approach of the city. INT37 argues that something similar could be done in the Mobility Master Plan but these documents are limited to following the proposals of the

[20] (INT5, INT8, INT12a, INT12b, INT12c, INT17a, INT17b, INT21, INT26, INT31, INT32, INT35, INT37)
[21] (INT17a, INT17b, INT21, INT26)
[22] (INT33, INT37)

Urban Master Plan, so it will depend on what ends up being promoted by Enrique Peñalosa's administration.

Another possible opportunity for adaptation is the use of another planning instrument in the city called Partial Plans. Partial Plans are urban planning documents similar to the general Urban Master Plan, but they are valid only for a new development in the city and include more details about the specific plans for the area. Some of the interviewees described a recent Partial Plan for a new development in the north of the city called "Lagos de Torca" (Alcaldía Mayor de Bogotá 2017) which is being promoted as a pilot project for eco-urbanism in Bogotá by the city authorities.[23] Although on paper it seems like a promising opportunity, INT14 suggests that in practice urban developers in "Lagos de Torca" are not showing signs of managing drainage in the area adequately, missing the opportunity for better-adapted infrastructure in the project. Additionally, the Partial Plan itself (Alcaldía Mayor de Bogotá 2017) presents no mention of adaptation or climate change, and "green" infrastructure and SUDS are presented as eco-urbanistic interventions rather than adaptation actions. This further confirms that this Partial Plan has been another missed opportunity. INT15 suggests that these instruments have had a history of being manipulated for different political objectives making them ineffective instruments for change in the city and probably for adaptation purposes (see Chapter 7). This type of planning instrument could provide interesting opportunities for adaptation planning in the future, but this will need to be demonstrated in practice.

Regarding the costs or benefits of the decisions, there is still uncertainty in this regard as the city has not proposed a definitive adaptation strategy for its road network. Nevertheless, the RVV study commissioned by the District Mobility Secretary seeks to give some initial answers to this question. The RVV study report presents, for instance, some calculations of the estimated costs of implementing the RVV project in Bogotá and the possible financial sources the city could use to develop the project. The report presents two estimations: one describing only the minimum costs of keeping the road surfaces of the RVV well maintained, and another one in which the costs of reinforcing structurally pedestrian and vehicular bridges in the RVV are added to the previous estimation (Unión Temporal MOBIGA 2018).

It is evident at this point of the analysis that the level of uncertainty in the answers provided by the evidence for the analytical questions of the EAAC framework is already high. This is because the answers to the analytical questions of later stages of the adaptation planning process depend on the results obtained in previous stages. This section has shown that although Bogotá's policy documents present several opportunities to incorporate adaptation in the planning processes of the city, there is uncertainty regarding their implementation, which relies on the publication of the new Urban Master

[23] (INT12a, INT12b, INT12c, INT14, INT15a, INT15b, INT33)

Plan for Bogotá by Enrique Peñalosa's administration. The costs and benefits of the decisions will not be known with greater certainty until Bogotá and its transport sector determines its strategy to cope with present and future climate risks. Some of the evidence collected shows that the city has already invested in preliminary work that could potentially provide some initial answers to the rest of the analytical questions of the EAAC framework as presented in the next section.

6.5. Stages 3 and 4: Implementation, evaluation, monitoring and learning

The next steps for the city are the development of an adaptation strategy for its transport sector and the implementation of the first adaptation measures to increase the resilience of the road system of the city. The evidence collected shows that both steps have not been yet performed. This would move the adaptation planning of the road sector to the third and fourth stages of the planning cycle of the EAAC framework. There is evidence that Bogotá's transport sector is already considering how to approach the later stages in the adaptation planning process.[24] For example, initial answers to some of the analytical questions of the EAAC framework, such as "what implementation methods and resources are used?" (Stage 3) or "how well do they adapt?" (Stage 4), can be obtained by viewing the results of the RVV study. The report developed by the consultancy presents, for instance, some calculations of the estimated costs of implementing the RVV project in Bogotá, the possible financial sources, a proposal of indicators for evaluating and monitoring the performance of the RVV, the organisations in charge of its elements, and a draft of the decree the city should approve so the RVV can be implemented. If implemented, the RVV has the potential to be an important initial benchmark for adaptation planning in the transport sector of Bogotá, but it must be considered that its scope is limited to only dealing with risks associated with extreme weather events.

Some of the interviewees also provided some insight that helps to approach the Stage 3 question "what constrains or incentivizes implementation?", despite the current absence of any major implementation efforts. Some of the main constraints identified by the interviewees were: the lack of a legal document for the implementation of the RVV;[25] the fact that Enrique Peñalosa's administration has been performing changes to the goals of the District Risk Management and Climate Change Plan – Bogotá 2015-2050;[26] the restriction presented to innovation by the current institutional arrangements of the city;[27] the fact that adaptation is not part of the legal competences of organisations;[28] and the

[24] (INT21, INT24a, INT24b, INT24c, INT26, INT39a, INT39b, PDGR-CC, Annex RVV, Report RVV)
[25] (INT39a, INT39b)
[26] (INT5, INT5-2, INT8, INT21, INT22)
[27] (INT22, INT27, INT29)
[28] (INT16, INT21, INT24a, INT24b, INT24c, INT26, INT39a, INT39b)

disproportionate influence of the Development Plan over the planning processes of the city.[29] These and other barriers and the factors that cause them are explored in more detail in Chapter 7.

Finally, in order to develop further its adaptation strategy, Bogotá's transport sector can use the lessons and products from the RVV as a baseline, as some interviewees indicated, and complement this initial knowledge with similar studies that are aimed to understand how to incorporate other elements of adaptation planning such as dealing with risks associated with the long-term change in average climatic conditions. The next section presents a discussion of the results of the analysis presented in this chapter and some recommendations on how the transport sector of Bogotá could continue its adaptation planning efforts.

6.6. Discussion

An example of the application of the EAAC framework has been presented in this chapter. This chapter has demonstrated the utility of the EAAC framework as a diagnostic tool, which should prove useful for decision-makers, stakeholders and policymakers that are involved in the management of sociotechnical systems, such as those associated with road infrastructure networks as it can provide more holistic insights of the current state of their system in the adaptation planning process. In particular, urban transport planners seeking to adapt road infrastructure systems to climate change in their cities could use the EAAC framework as a guide and replicate the example provided in this chapter in their contexts.

The EAAC framework helps to structure adaptation planning, which is becoming increasingly important, yet organisations find it challenging to meaningfully engage in action. The framework can, first, provide the ability to understand the relative position of a city's approach to adaptation planning within a wider spectrum of possibilities, and second, it can provide insight into future possible planning interventions, their possible impact and the necessary steps to follow in the planning process.

The practical usefulness of the framework has been demonstrated with the analysis of a case study of the transport sector of Bogotá, Colombia. This author argues that the analysis shows that Bogotá's transport sector is currently in between the "Problem structuring and establishing of the arena" and the "Developing the adaptation agenda, vision and pathway" stages of the adaptation planning cycle of the EAAC framework (Figure 24). This is demonstrated by the lack of complete answers provided by the evidence collected to most of the analytical questions of the EAAC framework as presented in this chapter. Also, by how the city is still trying to advance in understanding many of the aspects related to these analytical questions which could answer them more satisfactorily.

[29] (INT5, INT5-2, INT12a, INT12b, INT12c, INT15a, INT15b, INT20, INT23, INT30, INT34, INT38)

By looking at Bogotá's transport sector's progress in terms of adaptation and its associated policies, it is clear that the city does not yet have a clear picture of the vulnerability of its road network. This has consequences because, if Bogotá's transport sector does not understand more satisfactorily what the nature of vulnerability and the perceived risk is, it will be difficult for the city to advance effectively to further phases in the adaptation planning cycle. Nonetheless, this investigation into the city's transport sector and associated policies has helped to establish that some progress has been made to identify who and what needs to adapt and how. This is demonstrated mainly through the establishment of the city's Vital Road Network and the existing institutional arrangements. According to the current institutional arrangements in the city, the creation of an adaptation strategy for the road network of Bogotá is a responsibility of the transport sector led by the District Mobility Secretary. However, the existing institutional arrangements still exhibit some problems. For instance, the current arrangements present a gap in responsibilities since the organisations in charge of road infrastructure of the city (IDU, UMV and the local mayoralties) are not directly responsible for the implementation of the proposed adaptation actions in the city (i.e., SUDS and "green" infrastructure). This could prove problematic later if these arrangements are not revised since this level of decentralisation of responsibilities will prove to be challenging as problems with the coordination of activities could become a barrier to the effectiveness of the adaptation process (see Chapter 7 for further exploration of this point). Therefore, continuous effective leadership from the District Mobility Secretary and IDIGER will be required to determine adequate responsibilities in the adaptation process.

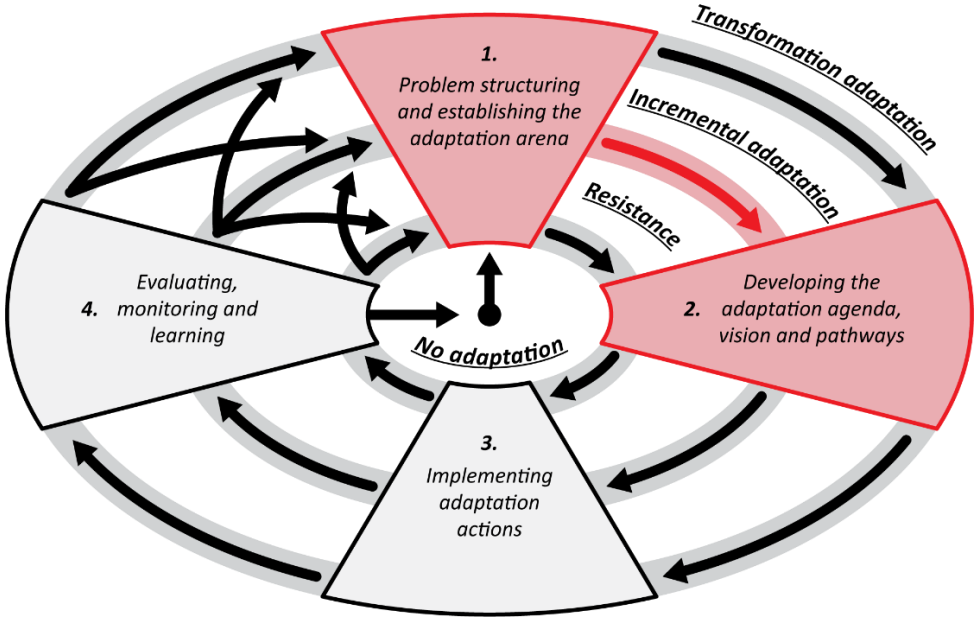

Figure 24. Bogotá's transport sector relative position in the adaptation planning process.

The analysis also provides some insight into other possible barriers to the adaptation process, such as the lack in technical capacity of some of the staff of the city's organisations regarding adaptation or the selection of ecosystem-based adaptation as the only approach followed by the city (a more detailed

analysis of adaptation barriers is presented in the next chapter). Regarding the latter, Bogotá's transport sector should reassess the appropriateness of an ecosystem-based approach for future planning. Transport planners could investigate the potential benefits of other approaches available in the district policies such as infrastructure-based adaptation (see Appendix 1 - Approaches to adaptation planning) which could be a better fit for the necessities of the sector and not limit artificially the possible adaptation measures to a handful of them. An infrastructure-based approach is focused on improving the adaptive capacity of infrastructure assets that play a determinant role in economic development, such as transport infrastructure. It considers other adaptation measures such as changes in design processes that include projections of the possible future climate, changes in maintenance operations, changes in road construction standards or changes in other elements of the physical infrastructure like pavement structures. The different approaches to adaptation are in principle not exclusive, so it could be possible to complement the infrastructure-based approach with some of the actions promoted by the ecosystem-based adaptation for better results in the adaptation process.

Is clear that the next steps for Bogotá's transport sector are to develop its adaptation strategy and implement the first adaptation measures. The city has already proposed "green" infrastructure and SUDS as the main adaptation measures to implement in the future suggesting that the city is aiming for a scale of incremental adaptation at the most (Figure 24). It should be recognised that Pelling et al.'s original framework (2015) would have reached the same conclusion with the same evidence, but the results presented in this chapter and the following chapter show how the EAAC framework is a stronger conceptual framework. The EAAC framework goes beyond and identifies not only the scale of adaptation, but also the stage in the adaptation planning process in which the transport sector of Bogotá currently is and the barriers to and opportunities for the effectiveness of these planning processes.

In order to continue the planning process into the next steps, Bogotá's transport sector could use the EAAC framework and the answers to the analytical questions presented in Table 10 as guidelines to develop further its adaptation planning processes and strategies. As shown by the findings presented in this chapter, the framework gives transport planners an opportunity to understand where they are at the present and where they should be moving next in the planning process. Additionally, trying to answer the analytical questions of the EAAC framework gives transport planners the chance to understand what the extent of their resource requirements is (i.e. information, policy support, financial resources, technology, etc.) to achieving effective adaptation planning of their road networks.

Finally, the analysis presented in this chapter could be used as an example by other urban transport agencies that may want to perform similar analyses with the EAAC framework of their own adaptation planning processes. Its capacity to support a diagnosis of both the current state of adaptation planning and to provide insight into future steps make it a valuable resource not only for urban transport planners but possibly for decision-makers in other sectors facing the challenge of climate change.

6.7. Chapter summary

This chapter has provided an example of the use of the first analytical tool of the EAAC framework, a set of key analytical questions, to perform a diagnosis of the current state of adaptation planning of road infrastructure in a city and to provide guidance on how to continue the process. The analysis of the evidence collected through the case study of Bogotá, Colombia shows that the city is currently in between the "Problem structuring and establishing of the arena" and the "Developing the adaptation agenda, vision and pathway" stages of the adaptation planning cycle. Additionally, there is evidence to suggest that the city is aiming to implement a scale of incremental adaptation at the most.

Chapter 7

7. Barriers to and opportunities for the adaptation planning of urban road infrastructure in Bogotá, Colombia

This chapter explores barriers to and opportunities for effective adaptation planning of road infrastructure in Bogotá, Colombia, taking a sociotechnical perspective. The chapter begins with the description of the second analytical tool of the EAAC framework in Section 7.1. This analytical tool is presented here in detail to enable the reader to follow the methodology used in this chapter to identify barriers to and opportunities for effective adaptation planning in Bogotá. The analysis of the evidence of the case study of Bogotá using the second analytical tool of the EAAC framework is presented in Section 7.2. The chapter concludes with a discussion of the barriers and opportunities identified in the analysis.

7.1. Analytical Framework

To identify barriers to and opportunities for effective adaptation planning, this chapter shows the application of the second main analytical tool of the EAAC framework, an analytical framework developed by Lehmann et al. (2015) (See Figure 25). Lehmann et al.'s framework was originally developed to understand what hinders or allows decision-makers in cities to take action regarding adaptation to climate change. As part of the EAAC framework, Lehmann et al.'s analytical framework is used in the specific context of adaptation planning of urban transport infrastructure.

This analytical framework was chosen for two reasons. First, unlike other frameworks which focus on identifying 'what' barriers and opportunities exist for effective adaptation planning (such as Eisenach and Stecker (2012) and Moser and Ekstrom (2010)), Lehmann et al. (2015) address the questions of 'how' and 'why' barriers and opportunities emerge. Other frameworks describe groups of barriers and opportunities one-dimensionally, while this framework describes them in a two-dimensional way. Lehmann et al. (2015) argue that the core message of their framework is that "it is not only that the adoption of adaptation strategies and action plans by local municipalities is contingent on certain variables which may turn out to be barriers or opportunities for action. These variables are themselves dependent on underlying factors" (Lehmann et al. 2015:79). This allows for a deeper analysis of adaptation planning processes and an understanding of how to possibly improve them. Second,

Lehmann et al.'s framework has applicability across different development contexts. Lehmann et al. (2015) demonstrated this by analysing the adaptation planning processes of two cities in Latin America (Lima, Peru and Santiago, Chile) and two cities in Germany (Berlin and Sangerhausen). Therefore, the categories of barriers (and opportunities) to adaptation of the framework are common across development contexts but differ in magnitude depending on each city. As a result, the framework is attractive since it can be employed by practitioners in any city regardless of its development status.

Figure representing the variables influencing decisions on adaptation planning in cities removed for copyright reasons. Copyright holder is Springer Science+Business Media Dordrecht.

Figure 25. Variables influencing decisions on adaptation planning in cities. Adapted from Lehmann et al. (2015).

Lehmann et al. (2015) present barriers to and opportunities for urban adaptation planning as associated with one of the following three categories (See Table 11):

a. Information quality and availability,

b. Resources available, and

c. Incentives on which decision-makers have to act.

Then, the framework introduces a series of three underlying factors that influence each of these categories. These factors are related to (See Table 12):

a. Actor-specific characteristics,

b. The institutional environment, and

c. The natural and socio-economic environment.

Table 11. Categories of barriers and opportunities and examples. Adapted from Lehmann et al. (2015).

Information	Resources	Incentives
• On climate stimulus	• Financial means	• Balance of costs and benefits of adaptation
• On impacts of climate change	• Personnel	• Co-costs/-benefits with other objectives of action
• On status of infrastructure assets	• Technologies	• Positive/negative externalities of action
• On available adaptation options	• Staff expertise	• Ease of management of the territory
• On the costs and benefits of adaptation options	• Materials	
• On the dynamics of the socioecological environment	• Time	

Table 12. Underlying factors and examples. Adapted from Lehmann et al. (2015).

Actor-specific characteristics	Institutional environment	Natural and socio-economic environment
• Perceptions	• Formal and informal rules that regulate the relationships and interactions of governing organisations, i.e., multi-level governance, mainstreaming of adaptation, participation and organisational routines	• Intensity, velocity, spatial and temporal scale of impacts of climate change
• Preferences		• Certainty regarding these patterns
• Experiences		• Number of actors affected
• Knowledge		• Level of economic development
• Leadership		• Demographic patterns
		• Urban territory characteristics

For example, it could be argued that the ease of management of the territory of a city (an incentive factor) could be attributed to one or more underlying factors: 1) actor-specific characteristics (for example, political differences and different interpretations of what is a priority among stakeholders in the city), 2) the institutional environment (for example, incomplete and/or rigid normative frameworks for territorial and infrastructure management), and/or 3) the natural and socio-economic environment (for example, the presence of consolidated inefficient urban structures).

Lehmann et al.'s analytical framework has its limitations as it cannot possibly reflect all of the interactions and dependencies between barriers and opportunities of adaptation planning and their underlying factors. But it can indeed highlight the most important interactions. Their work represents an important step towards understanding the wider sociotechnical system within which infrastructure is planned and delivered. Finally, their framework was designed to be descriptive and not normative, meaning that overcoming the barriers or exploiting the opportunities identified cannot be viewed as the only necessary steps to achieving effective adaptation planning in a city. As shown in the previous chapter, it is also necessary to answer other analytical questions in order to achieve effective adaptation planning.

7.2. Analysis

This section presents the results of analysing the case study interview and documentary evidence using Lehmann et al.'s framework as a guide. The section is divided according to the categories of barriers and opportunities presented in Table 11. Each subsection describes the main barriers and opportunities identified for the effective adaptation planning of the transport infrastructure of Bogotá in each category and their underlying causes. Examples and evidence supporting each of the findings are referenced in footnotes using the codes for interviewees and documents shown in Table 5 and Table 6 in Chapter 4. It is important to note again that the number of times an issue was cited by interviewees or in the local documents should not be considered as a reflection of the significance of that issue for comparative purposes; the qualitative nature of this study does not allow for such conclusions to be drawn. This approach to coding and reporting has been adopted to provide some transparency as to how the evidence has been collated and to show the rigour behind this process. Like in the previous chapter, some examples of evidence associated with the footnotes can be found in the main text in the form of quotes, references to situations described by the interviewees or references to the documents analysed. Further examples of evidence associated with each footnote are provided in Appendix 8.

7.2.1. Information quality and availability

Adaptation planning is a complex process in which decision-makers need a range of quality information to enable appropriate action to be taken. One of the requirements for availability is that information is shared appropriately amongst the different decision-makers and stakeholders. Unfortunately, some of the evidence collected suggests a lack of sharing of information between and inside the District agencies and with other stakeholders in Bogotá, thus creating a barrier for effective adaptation planning in the city. For example, the private consultancy that worked on updating the RVV explains in their report that some agencies like UMV or the District Planning Secretary did not share certain crucial information for their analysis.[30] Another example is given by the two councillors interviewed (INT31 and INT35) who stated that they had not received any valuable information regarding the development of the new urban master plan (as of the date of the interview) for them to be able to make an informed decision when voting later for the approval of the planning document. INT31 suggested that although he had officially requested reports on the development of the plan from the District Planning Secretary, he had been given only partial information and in some cases no information.

The lack of adequate sharing of information between decision-makers and stakeholders in the city could be explained by different underlying factors. Institutionally, there is (at the time of writing this thesis) not an adequate central information system in the city that collects all strategic data from all sectors and

[30] (Report RVV).

there are no protocols that standardize data management.[31] This complicates information sharing as agencies may be managing information in different formats creating more work when "translating" data sets from one format to another. Additionally, the lack of protocols and a central information system demonstrates a lack of channels for effective dialogue between District agencies, the private sector and academia.[32] Actor-specific characteristics also influence the lack of adequate sharing of information. Some actors feel antagonism towards actors of other agencies, due to political preferences, and therefore refrain from sharing information.[33] Other actors lack an open access culture and refrain from sharing information, something that could be associated with the presence of corruption in the city, leading to the instrumentalization of certain information for particular political and economic purposes.[34] INT5 provides an example of possible instrumentalization of information in the city. According to her, the current administration of Enrique Peñalosa has changed drastically the criteria for the development of flooding hazard maps around the Bogotá river produced by IDIGER. This is because, if this data is not changed, Enrique Peñalosa's administration will not be able to green-light new urban development around the river, which is one of the major projects that the mayor wants to include in the new Urban Master Plan.

Adaptation planning of transport infrastructure, in general, requires general system information about the natural environment, especially weather conditions, and about the current state of infrastructure assets. The evidence collected suggests that there are gaps in such information availability in Bogotá indicating the presence of other information barriers.[35] One such barrier is the lack of strategic up-to-date information from the transport infrastructure assets of the city. This could be attributed to factors from the natural and socio-economic environment. These include: the city's lack of financial resources, as a result of its development status; information is not regularly updated;[36] data collection campaigns are slow due to the complexity and size of the urban environment;[37] and the presence of corruption in the city, which is evidenced by the instrumentalization of some information and the lack of transparency in terms of how the information was obtained.[38] Institutional factors such as the degree of decentralisation of the administration of transport infrastructure in the city[39] and the lack of data management protocols and clear objectives for data collection are also influential.[40] With the presence of many decision-makers and stakeholders and the lack of useful data collection and management

[31] (Diagnosis POT, INT1, INT8).
[32] (Eco-urbanism, INT2, INT3, INT8, INT10, INT11a, INT11b, INT24a, INT24b, INT24c, INT26, INT27)
[33] (INT5-2)
[34] (INT5, INT5-2, INT8)
[35] (Report RVV, Development Plan, INT1, INT5, INT11a, INT11b, INT14, INT24a, INT24b, INT24c, INT37 INT39a, INT39b)
[36] (INT2, INT11a, INT11b)
[37] (INT2)
[38] (INT5-2)
[39] (INT10)
[40] (INT1, INT2, INT3, INT4, INT8, INT24a, INT24b, INT24c)

protocols, the different actors do not collect and manage information with the same rigour, thereby producing data of poor quality (i.e., duplicated information, inconsistent or incomplete data). Additional actor-specific factors such as the resistance of some actors to sharing information due to antagonism towards other actors, the lack of an open-access culture in the city, or the technical capacity of some actors in regard to data management all contribute to this information barrier.[41]

The evidence also suggests a lack of extended understanding of the natural environment in Bogotá and the possible local effects of climate change on the infrastructure of the city. For instance, some interviewees state that in Bogotá there is not adequate modelling of the climate and water systems at the local (urban) scale and that there is not enough research available about these systems in the city. [42] In an attempt to transform this barrier into an opportunity, the District Environmental Secretary recently opened the Centre for Environmental Information and Modelling.[43] Nevertheless, the data collected for climate change focuses only on mitigation metrics and not on improving adaptation planning in the city.

This information barrier regarding the natural environment and climate change has similar institutional underlying factors as the barrier associated with the lack of quality information about the transport infrastructure assets of the city, but there are some additional factors particular to this problem. These include factors like the current practice of road engineering in the city not incorporating climate projections in the design of new roads or the design of maintenance operations[44] and the fact that the weather observations system of the city has not had the required coverage in recent years.[45] The main natural and socio-economic factors that influence this barrier are the natural uncertainty of climate change and the presence of microclimates inside the city that add to the complexity of the system,[46] and the development status of the city which limits investment to improve climate data.[47] Actor-specific factors also have a strong influence on this barrier. For instance, it was observed that some actors are not well informed of which people or agencies are producing information about climate change;[48] some actors lack the technical capacity to understand the data; [49] and many actors lack a systemic understanding of the socio-environmental system of the city.[50] In addition, the perceptions of climate change risk are related to the political views of each individual, each organisation and each government, which results in different prioritisation and understanding of the risks.[51] The latter is evidenced by the disagreement that exists in the political interpretation of climate change risk between the previous and

[41] (INT2, INT5-2, INT8, INT24a, INT24b, INT24c)
[42] (INT4, INT14, INT21, INT24a, INT24b, INT24c)
[43] (INT25)
[44] (INT16, INT24a, INT24b, INT24c, INT37, INT39a, INT39b)
[45] (INT3, INT4)
[46] (INT21, INT24a, INT24b, INT24c)
[47] (INT11, INT26, INT28)
[48] (INT7, INT11a, INT11b, INT24a, INT24b, INT24c, INT26, INT30)
[49] (INT7, INT18, INT24a, INT24b, INT24c, INT26, INT30)
[50] (INT2, INT5-2, INT24a, INT24b, INT24c, INT31)
[51] (INT5, INT5-2, INT8, INT15a, INT15b, INT22, INT26)

current administration of the city. This is clear in the different perceptions that INT22 and INT17a have regarding the importance of climate change for the risk management of the city. Both interviewees are professionals of IDIGER who have worked for the director's office in the previous administration (INT22) and the current one (INT17a). INT22, for instance, stated that during his involvement in the previous administration climate change and adaptation were at the forefront of the political agenda. This is because there was a perceived need for them to be part of the institutional arrangements of the city if Bogotá wants to develop effectively in the future. In opposition, IN17a stated that for him and the current administration, climate change is not the most important risk in the urban development of the city, but that the attention should rather be focused on the city's seismic risk.

Effective adaptation planning of transport infrastructure requires not only strategic information about infrastructure assets and the possible effects of climate change but also a good understanding of the concept of adaptation. Understanding this concept means comprehending the required and available adaptation actions, how to measure their effectiveness, the costs of adaptation actions, and the benefits of climate change adaptation. There are problems in Bogotá in this regard which can be identified as another barrier to adaptation planning. For example, the group of professionals from the District Mobility Secretary in charge of the development of the adaptation strategy for the city's transport sector acknowledged that the task has been very challenging as they still perceive adaptation to climate change as a very ethereal or abstract concept and do not yet fully understand what it implies in practice.[52]

There are two main institutional underlying factors that explain this barrier. First, there is an issue with how adaptation has been framed conceptually in the city's policy documents. Due to the influence of national climate change policies, climate change action in Bogotá has been strongly associated with risk management and made a responsibility of the environmental sector. This has allowed for the concept of adaptation to be hidden behind other concepts in the city's policy documents such as risk management, eco-urbanism and environmental management, in what is called by some authors 'adaptation by stealth' (Di Giulio et al. 2017; Rasmussen, Kirchhoff, and Lemos 2017). This results in an unclear definition of what adaptation actually means in practice and creates confusion among the different stakeholders of the city which is evidenced in some interviews. After being asked what kind of adaptation actions their organisations have been performing or are planning to perform, interviewees mentioned actions regarding risk management, mitigation, environmental management or green construction as if they were adaptation actions.[53] Providing any example of environmental actions from this metaphorical 'environmental portfolio' to demonstrate that adaptation actions are being performed

[52] (INT24a, INT24b, INT24c, INT39a, INT39b)
[53] (Strategy IDU, Eco-urbanism, INT5, INT5-2, INT8, INT15a, INT15b, INT26, INT28, INT30, INT37, INT39a, INT39b)

seems to be perceived as logical by public servants in the city. This also has the potential to mask any non-performance of actions in their office.

The city has also decided to focus on ecosystem-based adaptation[54] which creates other issues with framing. This approach to adaptation effectively generates tunnel vision of the concept of adaptation for professionals in the city. Ecosystem-based adaptation considers only the betterment of drainage systems, "green" infrastructure and the protection of crucial ecological systems that provide ecological services to the city, as adaptation actions. This creates the illusion that other elements of the city, for example, road infrastructure, do not need to be adapted to climate change. As a result, INT21 mentions that some professionals in IDIGER are critical of this approach, as indicated in Chapter 6. Second, the legal mission of most District agencies does not openly include environmental management or adaptation planning.[55] This obstructs professionals in these organisations from focusing on adaptation planning as they are required by law to depend on the recommendations of authorities from the environmental sector such as the District Environmental Secretary and IDIGER. This results in the lack of technical capacity inside the organisations of the transport sector to deal with climate change issues and understand the concept of adaptation.

7.2.2. Resources available

Almost all participants interviewed agree that the most significant barrier is the lack of sufficient financial resources to manage all the city's needs. The maintenance of the transport infrastructure seems to be one of the least satisfied of all the needs.[56] This can be explained by several underlying factors. Regarding actor-specific characteristics, the evidence suggests that some decision-makers lack education in effective planning and resource use, which results in overinvestment or overrun costs in different investments of the city.[57] There is also no political will on the part of many decision-makers to prioritize certain investments, such as maintenance, as it is less attractive politically to restore old infrastructure than to open new infrastructure assets in the city.[58] As discussed by Hayat and Amaratunga (2014), this last point is a common issue around the world.

Regarding the institutional environment, first, the city has an unsustainable financial scheme for transport infrastructure maintenance that depends mainly on taxes on the fuel of motorized vehicles which do not produce enough funding to cover the city's needs for maintenance.[59] Second, the budget allocation in the city is inefficient and the prioritisation of investment is based on political rather than

[54] (INT12a, INT12b, INT12c, INT33)
[55] (INT16, INT21, INT30)
[56] (INT2, INT20, INT23, INT27, INT28, INT37)
[57] (INT2, INT14, INT15a, INT15b, INT28, INT29, INT30, INT31, INT35)
[58] (INT2, INT5, INT8, INT22, INT23, INT27, INT30, INT31, INT34, INT35, INT37, INT38)
[59] (INT2, INT15a, INT15b, INT23, INT34, INT35, INT37)

technical parameters.[60] Third, there are no adequate project management structures in the public sector of Bogotá which means that the understanding of the project life cycle has not been effectively institutionalized in the city.[61] Fourth, there are overinvestment and overrun costs due to the lack of quality information available to decision-makers in the city,[62] which relates to the information barrier regarding the lack of strategic up-to-date information from the transport infrastructure assets of the city described in the previous section of this chapter. INT2 provides an example of this. According to him, due to the slowness of the process of diagnosing the physical state of road infrastructure in the city, the information obtained is not useful for planning maintenance operations and this leads in many cases to unnecessary additional costs. Regarding the natural and socio-economic environment, the city has a complex urban structure, with consolidated old infrastructure in some parts of the city that is difficult to change in a low-cost manner, the wide presence of informal neighbourhoods that pressure the city's investment capacity in terms of development, and a continuous need to expand the provision of new infrastructure.[63] Also, incorporating new taxes to increase the finances of the city is not a politically popular measure, so politicians restrict themselves from using this measure.[64] Additionally, the presence of corruption in the city creates inefficient investment that benefits personal gains of certain stakeholders while the benefits for the community are secondary.[65] According to a report from the NGO Transparencia por Colombia (Transparency for Colombia), the city lost half a trillion Colombian pesos due to corruption between 2016 and 2018. The most affected sector by these monetary losses was infrastructure and transport (Periódico El Tiempo - Bogotá 2019).

As is the case in many cities, the availability of financial resources for adaptation to climate change in Bogotá is suboptimal. This has similar underlying factors to the overall lack of sufficient financial resources to manage the city's needs, but there are some particular factors relating to the problem of adaptation. From the perspective of the actors, the evidence collected suggests that many of the decision-makers of the city lack education about adaptation, which might explain why this topic has a low priority in their agendas.[66] A professional from the United Nations Development Programme for Colombia (PNUD) (INT26) explains further:

Bogotá has not been during the last 5 administration (which is an important period of time) the most proactive to develop important actions in relation to climate change adaptation and to mobility and transport. In an analysis we did [in PNUD] about what could be the reasons behind this, one of the

[60] (INT2, INT3, INT5, INT15a, INT15b, INT22, INT23, INT28, INT29, INT30, INT31, INT32, INT34, INT37, INT38)
[61] (INT2, INT15a, INT15b, INT35, INT37)
[62] (INT2)
[63] (Diagnosis POT, INT2, INT11a, INT11b, INT15a, INT15b, INT21, INT22, INT23, INT24a, INT24b, INT24c, INT30, INT37)
[64] (INT15a, INT15b, INT28)
[65] (Diagnosis POT, INT11a, INT11b, INT13, INT15a, INT15b, INT28, INT29, INT30, INT31)
[66] (INT26)

results, that seems paradoxical but that is real, […] is that the conceptual approach and the available knowledge about adaptation are being considered as if they were something very recent and very innovative, as if they were something that has just been developed in the last 4 years. [What happens is that] this topic and its importance have been generally ignored by the administrations [in Bogotá]. So, one of the elements that contributes to the lack of [adaptation] actions, is ignorance itself. And yes, everyone talks about climate change and adaptation, but try to make them act in relation to the topic and there is no way to bind them due to the lack of knowledge of the process that is a bit more technical and scientific (INT26).

This relates to the barrier described about the lack of understanding of the concept of adaptation. Also, the evidence suggests that adaptation actions are perceived by decision-makers as costly in all cases, creating the perception that adaptation and development needs are antagonistic.[67] This is related to the information barrier of not understanding truly the costs of adaptation actions, and decision-makers ultimately decide not to invest in adaptation due to potentially incorrect assumptions of the costs.

Regarding the institutional environment, there are two factors that affect investment in adaptation. First, the current District Risk Management and Climate Change Plan – Bogotá 2015-2050 has, according to some interviewees, overly ambitious goals with respect to adaptation in the city which cannot be sufficiently financed with the current state of available financial resources.[68] Second, the evidence collected reflects the lack of a long-term planning culture and the lack of emphasis on keeping the institutional memory in the city's administration which affects long-term projects and investment like that required by adaptation.[69]

7.2.3. Incentives on which decision-makers have to act

The two main barriers to effective adaptation planning associated with incentives are the lack of ease of managing and controlling the territory in Bogotá, which translates into the lack of ease of managing urban-environmental issues in the city. These barriers reflect the difficulty that most decision-makers and actors in the city face in order to produce transformations or even minor changes to the urban territory (which may tackle various problems like those associated with urban-environmental issues). The magnitude of the problem ends up being perceived as too big, too uncertain and too complex, and this ultimately results in disincentivizing decision-makers and actors in Bogotá who wish to transform the territory and tackle climate change.

For both barriers, the principal underlying factors are those in the institutional environment. For instance, the normative frameworks for territorial management, infrastructure management,

[67] (INT6, INT17a, INT17b, INT21, INT22, INT24a, INT24b, INT24c, INT31, INT37, INT38, INT39a, INT39b)
[68] (INT12a, INT12b, INT12c, INT21)
[69] (INT29, INT30, INT34, INT35)

environmental management and risk management are rigid, incomplete and complex in terms of responsibilities.[70] Examples of this include:

- The Development Plan of each mayor supersedes all other planning documents in the city, including the Urban Master Plan, allowing for many topics to depend on the political preferences of the current administration (e.g., climate change adaptation is not mentioned in a meaningful way in the current Development Plan, so it cannot be prioritized by any district agency);[71]
- The administration of the city is highly decentralized which creates problems regarding coordination and in some cases grey areas of responsibility (e.g., both the District Planning Secretary and the Urban Development Institute have the design and planning of new road infrastructure stated as part of their respective missions);[72]
- There are low levels of community participation in the development of the different planning documents of the city,[73] which results in the community being later disengaged in or even against any territorial management, infrastructure management, environmental management and risk management process;
- There is a lack of strong control institutions in the city that can keep track of the correct use of public resources and the correct implementation of technical standards;[74]
- IDIGER recommendations are only legally binding if they are included in planning documents by other agencies, but there is evidence of instrumentalization of the work of IDIGER;[75] and
- The legal mission of most agencies in the district does not include environmental management or adaptation planning which legally limits the professionals that wish to work in these areas in these agencies.[76]

Some actor-specific characteristics that influence these barriers are, for example, the expected attitude of public servants to limiting their work to what is normative and legally binding,[77] the lack of technical capacity of the public agency staff to understand the territorial or environmental issues of the city,[78] dependency on actors that are champions of climate change (e.g., a mayor that includes climate change as a priority in his development plan),[79] or the political interpretations between actors in the city over

[70] (Eco-urbanism, Diagnosis POT, INT5, INT5-2, INT13, INT15a, INT15b, INT16, INT21, INT22, INT26, INT28, INT30, INT31, INT32, INT35, INT37, INT38, INT39a, INT39b)
[71] (INT5, INT5-2, INT8, INT13, INT15a, INT15b, INT19, INT26, INT31, INT32, INT34, INT37)
[72] (INT5, INT10, INT13, INT22, INT28, INT30, INT32, INT37, INT38)
[73] (INT18, INT19, INT38)
[74] (INT5, INT5-2, INT31, INT36, INT37)
[75] (INT5, INT5-2, INT8)
[76] (INT16, INT21, INT30, INT31)
[77] (INT7, INT26, INT28, INT30, INT31)
[78] (INT30, INT31, INT38)
[79] (INT5, INT9, INT30, INT31)

what is a priority in the development of the city.[80] Some natural and socio-cultural factors that influence the lack of ease of managing the territory or its urban-environmental issues in Bogotá are, for example, the deficit in quality and quantity of effective public space (permanent green areas, parks, or plazas) in the city. The city provides 3.93 m^2 of effective public space per capita, when the minimum, according to the city's Public Space Master Plan, should be 10 m^2 (Alcaldía Mayor de Bogotá 2014b). In addition, the quantity deficit of effective public space is higher in the peripheries of the city (Alcaldía Mayor de Bogotá 2014b). Further examples of natural and socio-cultural factors are the wide presence of informal neighbourhoods,[81] the large population of the city,[82] the presence of corruption in the city,[83] and the complex and consolidated urban structure.[84]

Finally, the lack of ease in incorporating new technologies or methodologies for design, construction or maintenance in the transport sector of the city presents a further barrier to effective adaptation planning in Bogotá.[85] As with the other incentives barriers, the main underlying factors are those related to the institutional environment. The evidence from the interviews suggests that approving new technologies and methodologies is a very slow and bureaucratic process,[86] and that private companies are legally bound by contracts offered by the public sector to only use previously approved technologies.[87] These factors cause the incorporation of new technologies and methods to be complicated or even impossible, thereby discouraging innovators in both the public and the private sector. Other factors include opposition from certain actors to change,[88] and political lobbying from certain companies that try to avoid change so they can still benefit financially by selling their products.[89]

7.3. Discussion

This chapter applies the analytical framework developed by Lehmann et al. (2015) to identify barriers (and opportunities) to effective adaptation planning of transport infrastructure in a city, using Bogotá, Colombia as a case study. The framework offers the possibility to not only identify what barriers exist but also to explain how and why they emerge. This framework is helpful in highlighting the most important interactions, which is a crucial step in understanding how to improve adaptation planning

[80] (INT5, INT5-2, INT8, INT13, INT15a, INT15b, INT17a, INT17b, INT21, INT22, INT26, INT29, INT31, INT32, INT34, INT35, INT38)
[81] (INT14, INT21, INT22, INT30, INT31, INT36)
[82] (INT31)
[83] (INT5-2, INT16, INT22, INT30, INT31)
[84] (INT21, INT30, INT31, INT33, INT37)
[85] (INT22)
[86] (INT22, INT29)
[87] (INT4)
[88] (INT22, INT29)
[89] (INT22)

processes. There are also some limitations in the data collection for this study, however, the information gathered has been sufficient for providing substantial insight.

The application of the analytical framework identified barriers in all three categories (information, resources and incentives) for the effective adaptation of transport infrastructure in Bogotá. The most determining barriers that limit the ability of decision-makers and other actors in the city to act with regard to climate change adaptation are a lack of understanding of the concept of adaptation, the lack of sufficient financial resources for all needs in Bogotá, especially road maintenance needs, and the lack of ease in managing the territory and its urban-environmental problems. The evidence suggests that the most influential underlying factors in all categories are those associated with the institutional environment, such as: problems in the framing of the concept of adaptation in Colombia and Bogotá's policies, unsustainable financial schemes for the road network of Bogotá, the high degree of decentralisation of the administration of transport infrastructure in the city, and the rigid, complex and incomplete normative framework for the management of the territory, its infrastructure and its environmental issues. All the barriers identified can be transformed into opportunities through adequate and effective systemic solutions. The District Mobility Secretary seems to be trying to achieve this with the development of a Vital Road Network (RVV) for disaster risk management in the city which is expected to help overcome some of the barriers in all three categories of the sector.

Finally, the evidence also suggests that decision-makers and actors in Bogotá are aware of only some of the barriers identified in the analysis presented in this chapter. For example, most interviewees demonstrated awareness of the financial resource barrier that the city experiences, but many are not conscious of their limitations in the understanding of the concept of adaptation (many showed no reservations in mixing up all actions from the 'environmental portfolio' of their organisations when asked about adaptation actions). This shows the importance of applying the framework presented in this chapter (the second main analytical tool of the EAAC framework) to help transport planners and other actors in cities to not only identify the most evident barriers but also those of which they are not immediately aware, which is necessary for the achievement of effective adaptation planning in Bogotá and other cities.

7.4. Chapter summary

This chapter has described in detail the second main analytical tool of the EAAC framework and how it can be used to identify barriers to and opportunities for the effective adaptation of urban road infrastructure from a sociotechnical perspective. The chapter has shown an analysis of the evidence of the case study of Bogotá, Colombia to exemplify the use of this analytical tool. Barriers and opportunities were identified related to information, resources and incentives. This chapter demonstrates how the EAAC framework goes further than other available frameworks as it

complements the analysis presented in Chapter 6 of the current state of adaptation planning or road infrastructure in Bogotá. This is done by providing a wider picture of the state of adaptation planning by additionally identifying barriers and opportunities to this process.

Chapter 8

8. Conclusions and future work

This chapter presents the concluding remarks of this thesis. The chapter begins with a review of the purpose of the research. After this, the chapter summarises the responses to the core research questions. The chapter ends with some suggestions on possible directions for future work.

8.1. Review of purpose

This PhD project set out to answer the research question *"how can adaptation be incorporated into the planning and design of road infrastructure in cities?"*. This is in response to two main needs. First, there is a need to better understand the underlying principles behind adaptation planning. By improving the understanding of these principles, it will be possible to develop useful guidelines on how to initiate and sustain effective adaptation planning processes in different sectors, such as the road infrastructure sector. This will also allow decision-makers and practitioners to begin exploring the practical implications of implementing adaptation to climate change. The widespread recognition of the inevitability of climate change has made adaptation to climate change more relevant in the arena of climate action, hence making the need to understand adaptation planning more evident in recent years. Historically, in the field of climate action, considerably more attention has been given to actions aiming to address and stop the causes of climate change (i.e., mitigation) than to those actions that aim to deal with the risks associated with climate change (i.e., adaptation). This bias is also evident in the transport sector, where greater emphasis has been placed on the reduction of greenhouse gas emissions from vehicles than on increasing transport infrastructure's resilience to climate change. Consequently, this has created a knowledge gap related to the concept of adaptation and its practical implications for the transport sector. Because of this, this research also found it necessary to answer the research sub-question *"what is effective adaptation in the context of road infrastructure?"*.

The second main need is the necessity to introduce adaptation planning processes in cities as they will be crucial actors in the efforts against climate change. Cities are complex and dynamic socioecological systems in which different technical, social and ecological elements interact with each other. Transport infrastructure systems are one of the main technical systems in cities and are vital for their effective functioning. Because of this, there is a growing need to adapt these systems to climate change to ensure that cities become and remain safe, resilient, inclusive and sustainable. That is why this thesis has focused on finding how to incorporate adaptation planning into the development and maintenance of

urban road infrastructure. Additionally, the existence of complex interactions between technical, social and ecological elements in cities cannot be ignored and therefore any analysis of the development and maintenance of urban road infrastructure, or any other type of infrastructure, needs to include an understanding of those interactions. Because of this, this research also responds to the research sub-question *"how is the adaptation planning process affected by the local social, political, economic, geographical and environmental context?"*.

The rest of this chapter summarises the answers provided in this thesis to these research questions. It is acknowledged in the methodology chapter (see Chapter 4) that these answers have limitations, but there is reasonable confidence that the contributions of this thesis provide useful insights into the phenomena studied and a foundation for future research work.

8.2. Conclusions

Through a review of literature on resilience and adaptation to climate change, it was observed that in the context of climate change, decision-making has been approached from two independent perspectives, from the disciplines of engineering and from the social sciences and humanities. Engineering authors tend to approach decision-making by recommending the use of decision-support tools as a way of justifying decisions regarding specific interventions in the built environment. On the other hand, the social sciences and humanities research focuses on the analysis and design of climate change policies and climate risk governance. There is a need to integrate both perspectives to holistically approach decision-making in the context of climate change and there is potential to do this through adaptation planning, which is demonstrated in this thesis.

An early observation of this research during its MRes component was that several decision-support tools for adaptation planning of road infrastructure are available, but there is a lack of widespread use of these tools amongst transport planners and designers. This suggested that there is a wider systemic issue with respect to adopting adaptation principles into engineering practice, something that has been also observed in the case study performed during the PhD component of this research. This has shown that adaptation to climate change cannot be treated as a pure engineering problem, but neither as a pure policy problem, and that a multidisciplinary approach is necessary. This also suggested that proposing a new decision-support tool would not be a valuable contribution to current knowledge. Rather, a more valuable contribution is to investigate the characteristics of the decision-making processes associated with the adaptation planning of road infrastructure and investigating how the existing challenges for transport planners and designers could be identified. Because of this, this PhD project has followed a sociotechnical approach and has focused on understanding the key principles behind the adaptation planning process.

In exploring the key principles behind adaptation planning, this thesis reviewed the related concepts of decision-making, risk and resilience in the context of climate change, and the concept of adaptation. Adaptation is presented in this thesis as a precautionary approach to coping with the risks caused by climate change and as a process of resilience building of sociotechnical systems. Adaptation to climate change can be defined in simple terms as the simultaneous management of climate risks and the management of change. This thesis aimed to contextualize adaptation in the setting of road infrastructure and developed the following definition of adaptation for transport infrastructure systems:

> *Adaptation involves modifications to transportation infrastructure systems in response to actual and expected impacts of climate change which occur in the context of other socioecological changes interacting with them. This may involve the development, modification, maintenance and renewal of physical infrastructure, operations and policies. Adaptation strategies and actions can range from short-term coping to longer-term deeper transformations. Strategies and actions may aim to meet more than climate change goals alone and may or may not succeed in moderating harm or exploiting beneficial opportunities. This includes infrastructure changes to support mitigation efforts.*

In this definition, transportation infrastructure systems should be understood as being part of wider complex sociotechnical systems in which complex interactions exist between social infrastructure elements, technical infrastructure elements and the environment.

This definition and the review of the concept of adaptation and associated concepts such as risk and resilience provide an answer to the first research sub-question *"what is effective adaptation in the context of road infrastructure?"*. The review of existing literature found that there is consensus among various sources that the most effective and least costly adaptation measures are those implemented in an anticipatory and precautionary way. If adaptation to climate change is implemented effectively with road infrastructure systems, as with the technical components of other sociotechnical systems, it can provide important socio-economic and environmental benefits. This precautionary approach has the potential to be more beneficial in regions of the world where investment possibilities are limited and avoiding the costs of future damage to infrastructure is crucial.

Building upon the definition of adaptation presented above and a review of the risk management component and the change management component of adaptation, this research presented a novel conceptual framework called the "Expanded Adaptation Action Cycles" (EAAC) (shown in Figure 26). This framework provides a relatively simple, yet comprehensive conceptualisation of adaptation planning. The "Expanded Adaptation Action Cycles" framework receives its name acknowledging the foundation provided by Park et al.'s concept of "Adaptation Action Cycles" (Park et al. 2012). The EAAC framework goes further than Park et al.'s concept and other available frameworks that aim to conceptualise adaptation planning as it links together three aspects of adaptation that typically have

been separately addressed in the literature. The EAAC framework links together the concepts of: the adaptation planning cycle; scales of adaptation; and barriers to and opportunities for effective adaptation planning. For this, it adopts the conceptualisation of scales of adaptation from Pelling et al. (2015) to provide a more holistic assessment of the possible scales of implementation of adaptation. It also adopts an analytical framework developed by Lehmann et al. (2015) as one of its analytical tools.

The aim of developing the EAAC framework is to support insight into the decision-making processes and the associated resource requirements (i.e. information availability, policy support, financial resources, technology) of adaptation planning. In this framework, adaptation planning is conceptualised as an iterative action-learning cycle that cycles through the four stages shown in Figure 26. In each iteration, decision-makers implement adaptation actions based on the best currently available knowledge while at the same time (through evaluation and monitoring) learn how to improve the adaptation of their systems in the next iteration. Additionally, adaptation can be implemented at different scales that range from "no adaptation" to "transformational adaptation".

Invoking the pragmatic paradigm followed by this research, the EAAC framework has also a practical application as it can be used as the basis to perform a systematic assessment of the decision-making processes in adaptation planning and of the information and policy support required by these processes. For this, the EAAC framework incorporates two main analytical tools. It must be noted here that these tools should not be confused with decision-support tools. Decision-support tools have the purpose of assisting decision-makers in the selection of alternatives of action (for example, selecting which road project to prioritise in terms of construction or maintenance). Analytical tools, on the other hand, have the purpose to help their users to understand better a problem or a situation (for example, diagnosing where in the adaptation planning cycle a city is located). The first analytical tool of the EAAC framework is a series of key questions associated with each stage of the adaptation planning cycle. The second analytical tool is an analytical framework developed by Lehmann et al. (2015) that allows for the identification of barriers to and opportunities for effective adaptation planning from a sociotechnical perspective.

In its practical application, the EAAC framework can be compared to a map. A map has two functions: first, it can show one's relative position, and second, it can show the way to a desired destination. Firstly, using the EAAC framework as a diagnostic tool allows decision-makers, such as transport planners and designers, to understand their relative position in the adaptation planning process as demonstrated by this thesis. Secondly, the EAAC framework can also provide insights to different decision-makers of the possible future pathways a city can follow in order to adapt its sociotechnical systems, such as road infrastructure, as is discussed later in this chapter. This tackles the need described previously for guidelines for the incorporation of adaptation in the planning processes of cities.

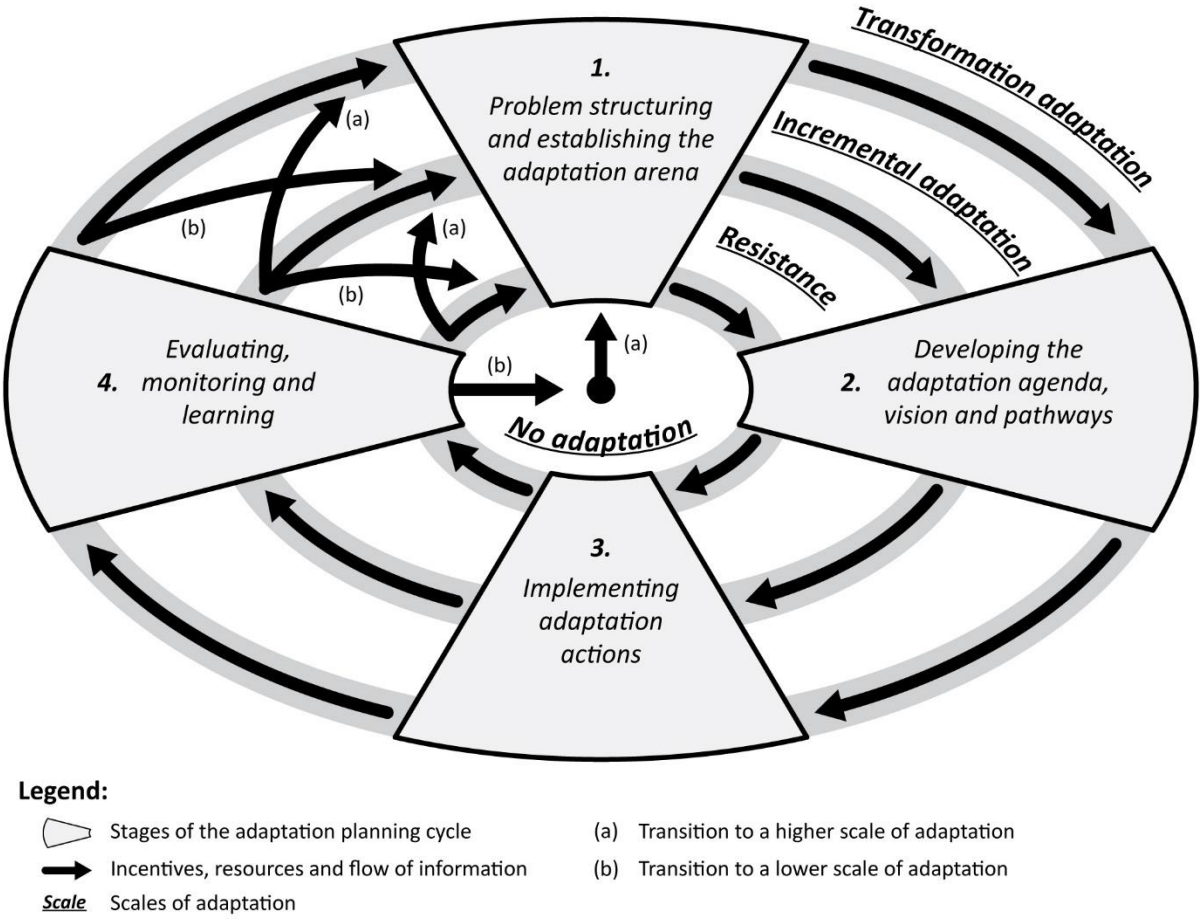

Figure 26. Schematic representation of the Expanded Adaptation Action Cycles.

The relatively simple, yet comprehensive conceptualisation of adaptation planning provided by the EAAC framework is one of the principal contributions of this PhD project to the theory and knowledge of adaptation planning. This conceptualisation of adaptation planning also contributes to resilience engineering, urban planning, risk management and change management literature. It provides a theoretical basis to understand how adaptation can be planned and incorporated into the planning and design processes of any sociotechnical system such as urban road infrastructure. Additionally, the framework offers the theoretical background to the answer to the second research sub-question. The conceptualisation of barriers to and opportunities for adaptation included in the EAAC framework proposes that factors related to actor specific characteristics, the institutional environment and the natural and socio-economic environment have influence over barriers to and opportunities for urban adaptation planning. These barriers and opportunities are associated with information availability and quality, resources available and incentives on which decision-makers have to act. This suggests, then, that factors in the local social, political, economic, geographical and environmental context can indeed hinder or allow decision-makers in cities to take action regarding adaptation to climate change. Based on this conceptualisation, the second analytical tool of the EAAC framework can provide insight into

how these factors affect adaptation planning. This was demonstrated with the analysis of the evidence of the case study as described in the next section.

This thesis has gone further than only answering its research questions in a theoretical manner and has aimed to provide a practical component to these answers by investigating the practical application of the EAAC framework in the context of urban road infrastructure. This has allowed the author to complement the answer to the main research question by looking at the specifics of incorporating adaptation to the planning and design of road infrastructure in cities. In order to demonstrate this practical application of the EAAC framework, this PhD project performed an in-depth case study of the decision-making processes for the development and maintenance of road infrastructure of Bogotá, Colombia and performed an analysis of the evidence collected using the two analytical tools of the EAAC framework. The findings of this analysis are discussed in more detail in the next section. The selected study research design involving a case study and the use of qualitative research methods allowed an in-depth look at the local context of Bogotá and an improved understanding of the nature of the motivations and sociotechnical processes behind the decisions made by different stakeholders in the city regarding transport planning and adaptation planning. This involved answering some specific questions related to the case study which helped answer the second sub-question of this research as shown by Figure 15 in the methodology chapter.

The influence and decision-making network for road infrastructure planning and its adaptation to climate change in Bogotá, Colombia was identified through the case study investigation. This influence and decision-making network is presented as a figure in the fold-out appendix at the end of this thesis. The figure also presents graphically one of the principal findings of the analysis which is that there are some responsibility gaps in the institutional arrangements regarding the adaptation of urban road infrastructure in the city. This is discussed in further detail in the next section. The results of the analysis (summarised in this figure) provided answers to the questions of who is involved in the decision-making processes for the development and maintenance of road infrastructure in the city, what processes they follow and some initial indications on how climate change is being considered by the transport sector of the city.

In order to explore further the nature of the influence of the context over the adaptation planning processes of the city, the evidence of the case study was analysed using the EAAC framework. The analysis performed using the first analytical tool of the EAAC framework provided a more complete answer to the question *"how is climate change being considered in the process of deciding the development and maintenance of Bogotá's road infrastructure?"*. This analysis showed that Bogotá is currently in between the first two stages of the adaptation cycle and is aiming for incremental adaptation at the most. This is described in more detail in the next section. The analysis performed using the second analytical tool of the EAAC framework gave some insights on what changes might be needed in order

to incorporate the most effective adaptation strategies in the road sector of Bogotá. The analysis of the barriers to and opportunities for effective adaptation planning in Bogotá particularly helped to answer the second sub-question of this thesis. It provided the practical component that complements the theoretical background already given by the EAAC framework as described earlier. Existing barriers and opportunities were shown to be influenced by all underlying factors related to actor-specific characteristics, the institutional environment, and the natural and socio-economic environment in Bogotá. The evidence of the case study showed that the most influential underlying factors were those associated with the institutional environment. This is consistent with what has been proposed by other authors (Dhar and Khirfan 2017; Di Giulio et al. 2017; Wise et al. 2014). This thesis cannot conclude that the underlying factors associated with the institutional environment are the most influential in all cities. However, future research could study other cities to investigate further which aspects of the context have a higher influence over adaptation planning processes and perhaps reach appropriate generalisations.

A more detailed description of the conclusions of the case study is shown in the next subsection.

8.3. Case study conclusions

This thesis has demonstrated the practical utility of the EAAC framework by performing an analysis of an in-depth single case study of the current decision-making processes for the development and maintenance of road infrastructure in Bogotá, Colombia and the level of consideration of climate change adaptation in these processes. This section discusses the conclusions reached from the analysis of the evidence collected using the analytical tools of the EAAC framework and presents some recommendations for the city.

The analysis performed using the first analytical tool shows that Bogotá's transport sector is currently in between the "Problem structuring and establishing of the arena" and the "Developing the adaptation agenda, vision and pathway" stages of the adaptation planning cycle of the EAAC framework (see Figure 27). This is demonstrated by the lack of complete answers provided by the evidence collected to most of the analytical questions of the EAAC framework and how the city is still trying to advance in understanding many of the aspects related to these questions which could answer them more satisfactorily. By looking at Bogotá's transport sector's progress in terms of adaptation and its associated policies, it is clear that the city does not yet have a clear picture of the vulnerability of its road network. This has consequences because, if Bogotá's transport sector does not understand more satisfactorily what the nature of vulnerability and the perceived risk is, it will be difficult for the city to advance effectively to further phases in the adaptation planning cycle. Nonetheless, this investigation into the city's transport sector and associated policies has helped to establish that some progress has

been made to identify who and what needs to adapt and how. This is demonstrated mainly through the establishment of the city's Vital Road Network and the existing institutional arrangements.

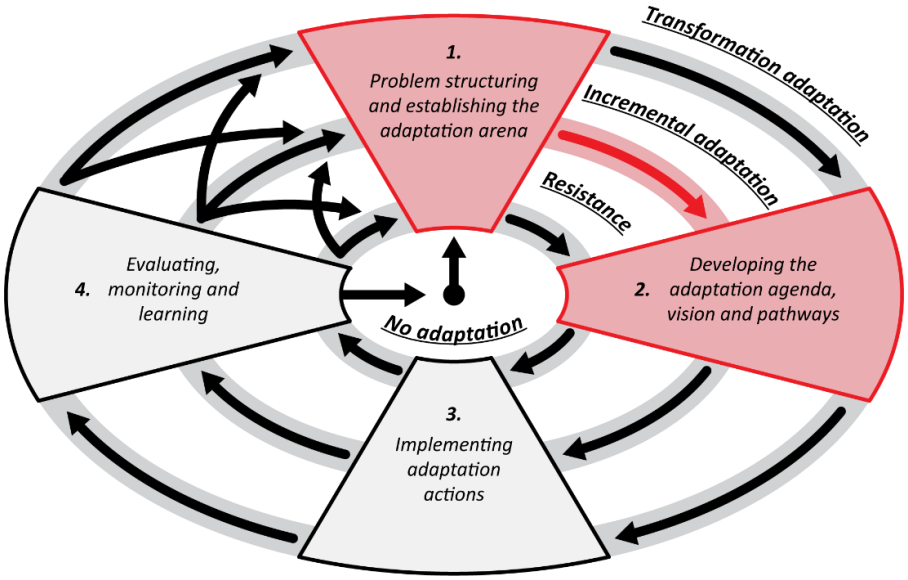

Figure 27. Bogotá's transport sector relative position in the adaptation planning process.

According to the current institutional arrangements in the city, the creation of an adaptation strategy for the road network of Bogotá is a responsibility of the transport sector led by the District Mobility Secretary. Additionally, the current arrangements present a gap in responsibilities that was not obvious at the beginning of the case study research, as described earlier in this chapter. The case study demonstrated that the three organisations in charge of road infrastructure in the city, the IDU, UMV and the local mayoralties, are not actually active in the adaptation efforts of the transport sector. This is shown graphically in the figure of the fold-out appendix at the end of this thesis. This gap in responsibilities could prove problematic later if these arrangements are not revised since this level of decentralisation of responsibilities will prove to be challenging as problems with the coordination of activities could become a barrier to the effectiveness of the adaptation process.

It is clear that the next steps for Bogotá's transport sector are to develop its adaptation strategy and implement the first adaptation measures. In other words, advancing to the next stages of adaptation planning cycle. The evidence shows that the transport sector of the city has not developed yet an adaptation strategy and without one the city will find it impossible to advance into the implementation stage of the adaptation planning cycle. The city has already proposed "green" infrastructure and SUDS as the main adaptation measures to implement in the future suggesting that the city is only aiming for incremental adaptation at the most (Figure 27). In order to continue the planning process into the next steps, Bogotá's transport sector could use the EAAC framework and the answers to the analytical questions of its first main analytical tool as guidelines to develop further its adaptation planning processes and strategies. Answering these questions can provide insights into what possible future

pathways the city can follow in order to adapt its road infrastructure. Additionally, trying to answer the analytical questions of the EAAC framework could give transport planners in the city the chance to understand the extent of possible resource requirements to achieve effective adaptation planning of their road networks.

The application of the second main analytical tool of the EAAC framework identified barriers in all three categories (information, resources and incentives) for the effective adaptation of transport infrastructure in Bogotá. The most determining barriers that limit the ability of decision-makers and other actors in the city to act with regard to climate change adaptation are a lack of understanding of the concept of adaptation, the lack of sufficient financial resources for all needs in Bogotá, especially road maintenance needs, and the lack of ease in managing the territory and its urban-environmental problems.

The evidence suggests that one of the most important barriers in the city is the lack of understanding of the concept of adaptation. The main cause behind this information barrier is how adaptation has been framed conceptually in the city's policy documents and institutional arrangements. Due to the influence of Colombia's national climate change policies, climate change action in Bogotá is conceptually associated with risk management and is institutionally a responsibility of the environmental sector. This has allowed for the concept of adaptation to be hidden behind other concepts in the city's policy documents in what is called by some authors "adaptation by stealth". This results in an unclear definition of what adaptation actually means in practice and creates confusion among the different stakeholders of the city. Additionally, the city has decided to focus on ecosystem-based adaptation which creates other issues with framing. For example, this approach to adaptation effectively generates tunnel vision of the concept of adaptation for professionals in the city. Because of this, Bogotá's transport sector should reassess the appropriateness of an ecosystem-based approach for future planning. Transport planners could investigate the benefits of following the other approaches available in the district policies such as infrastructure-based adaptation which could be a better fit for the necessities of the sector and not limit artificially the possible adaptation measures to a handful of them.

Another major barrier in the city is the lack of sufficient financial resources for all needs in Bogotá, especially road maintenance needs. One of the causes behind this barrier is that there is no political will on the part of many decision-makers to prioritize certain investments, such as maintenance, as it is less attractive politically to restore old infrastructure than to open new infrastructure assets in the city. As discussed by Hayat and Amaratunga (2014), this last point is a common issue around the world. Another main cause of this barrier is that the city has an unsustainable financial scheme for transport infrastructure maintenance that depends mainly on taxes on the fuel of motorized vehicles. This scheme seems to have no simple political solution as it will need the increase of taxes in the city which is a measure very few politicians are willing to promote.

A third major barrier in the city is the lack of ease in managing the territory and its urban-environmental problems. This barrier reflects the difficulty that most decision-makers and actors in the city face in order to produce transformations or even minor changes to the urban territory (which may tackle various problems like those associated with urban-environmental issues). The magnitude of the problem ends up being perceived as too big, too uncertain and too complex, and this ultimately results in disincentivizing decision-makers and actors in Bogotá who wish to transform the territory and tackle climate change. The main factor behind this barrier is institutional. For instance, the main cause for this barrier is that the normative frameworks for territorial management, infrastructure management, environmental management and risk management are rigid, incomplete and complex in terms of responsibilities.

Finally, the analysis of the evidence collected in the case study suggests that the most influential underlying factors in all categories of barriers and opportunities are those associated with the institutional environment, such as: problems in the framing of the concept of adaptation in Colombia and in Bogotá's policies, unsustainable financial schemes for the road network of Bogotá, the high degree of decentralisation of the administration of transport infrastructure in the city, and the rigid, complex and incomplete normative framework for the management of the territory, its infrastructure and its environmental issues. This suggests that there is an opportunity in Bogotá to review and change the current institutional arrangements so future arrangements allow the effective incorporation of adaptation considerations in the planning processes of the city. There are opportunities to perform the necessary changes in the development of several new planning documents in the city (for example, the new Urban Master Plan), but the evidence shows that past planning documents have missed the opportunity to make substantial changes and that the documents currently in development are not considering it either. This opens the possibility for new research endeavours that investigate which new institutional arrangements could work as better enablers of adaptation planning in Bogotá and other cities and how to implement them.

Section 8.5 discusses some other possible directions for future work.

8.4. Limitations of the study

The main limitations regarding the data collection and analysis have been discussed in the methodology chapter (see Chapter 4). These include, for example, limitations of the interview method related to the flexibility of the semi-structured-interviews format, the researcher's evident role in guiding and interpreting the conversations and the selection of interviewees being dependent on their willingness to participate. The potential issues with these limitations have been mitigated by following certain measures such as following a general guide of themes and questions during the interviews, triangulating information with other sources of evidence, and sharing interim results and analysis with experts in

Bogotá. Other limitations of the study include the potential loss of meaning in the translation of the verbatim quotes from Spanish to English or limitations of the second analytical tool of the EAAC framework to reflect all the interactions and dependencies between barriers to and opportunities for effective adaptation planning and their underlying factors. Nevertheless, the data gathered has been deemed sufficient and the analytical tools used in the study have been deemed appropriate to provide useful insights into the case study as shown in this thesis.

Further, this thesis has focused on understanding the internal processes related to adaptation planning of a socio-technical system, using as an example, the socio-technical system associated with the urban road infrastructure of Bogotá, Colombia. The interactions of the urban road network of the city with other interconnected socio-technical systems, such as the water management system, were explored to some extent in this thesis, but this research did not attempt to explain in detail how the adaptation planning processes of these interconnected socio-technical systems can be coordinated to increase their effectiveness. As it is stated in the next section, this could be potentially addressed by future research.

8.5. Future work

There are several ways in which the research presented in this thesis could be taken further or could inspire future works of research. The most obvious way of taking this research further is by using the EAAC framework as a diagnostic tool of the adaptation planning processes of the transport sector of other cities. This thesis has demonstrated the practical utility of the EAAC framework by analysing a case study of Bogotá, Colombia, and the methodology and analysis described could be used as a guiding example for similar studies and analysis in other cities. There is also the possibility of doing comparative studies using the EAAC framework in which the current adaptation planning status of several cities is compared. Additionally, it is argued by this author that there is the potential of using the EAAC framework to also analyse the adaptation planning processes related to regional and national road networks, and even, to analyse adaptation planning in any other sector that is facing the challenge of preparing how to deal with the risks associated with climate change. This potential exists because the EAAC framework was developed based on concepts with universal application such as the adaptation planning cycle or the scales of adaptation. This allows for the conceptual framework to be easily transferable and applicable to other sectors.

Another way in which this research could be taken further is by performing a longitudinal case study that allows the observation of how Bogotá's transport sector has acted throughout the whole adaptation planning cycle. Due to the time scope of this PhD project, this was not a possibility and the results presented in this thesis can only provide an analysis of the adaptation planning processes of the transport sector of Bogotá until 2018. By performing a longer case study, it might be possible to observe how the city performed in future stages of the adaptation planning cycle, and assuming that the city adopted the

EAAC framework as a guideline, it might be also possible to analyse whether the EAAC framework worked as an effective guideline for the city or not. This could be also the purpose of another study.

As with any research endeavour, when looking for answers to a research question it is always the case that additional research questions appear. Due to the time and scope of this research project, some of these additional questions were not tackled. These research questions could guide future investigations. Some of these questions are:

- What are the implications for cities in terms of increased access to international funds for adaptation if their current status in the adaptation planning process is diagnosed?
- What kind of underlying factors behind barriers to and opportunities for effective adaptation are the most influential in any city?
- What is the most effective adaptation approach a city could follow?
- How could the adaptation planning of interconnected infrastructures be coordinated in a city?

Finally, this author hopes that the work presented here inspires other engineers trying to tackle present and future problems of the built environment to think about approaching these problems from a multidisciplinary perspective, especially from a sociotechnical one. This thesis has demonstrated that it is necessary to understand the influence of the social and ecological context over our technical work and that of our colleagues. Before proposing more decision-support tools, as was the original intention of this author at the beginning of this research project, engineers should take a step back and first understand those decision-making processes they want to help become more effective. This author also hopes that his experience in this research project will inspire more engineers in the future to decide to tackle decision-making more actively in their research and professional lives. This research was also driven by an underlying view that it is a matter of professional ethics for engineers to not only understand decision-making processes for the management of the built environment but also to participate in them. It is good to remember that engineers and other built environment professionals have the capacity to comprehend the risks that future challenges like climate change will impose and therefore understand how to prepare for them. This capacity comes with the ethical responsibility of ensuring that our societies will be safe, especially those that are more vulnerable. Consequently, engineers need to ensure that their technical understanding of how to alleviate damage to infrastructure, and the human suffering caused by that, is incorporated into planning decisions if they truly want their work to have an ethical impact. Only then will we be able to come closer to having more inclusive, safe, resilient and sustainable cities.

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Appendix 1 - Approaches to adaptation planning

Box 1. Some approaches to adaptation planning. Source: (DNP 2012)	
Community-based adaptation	Community-based adaptation is an approach that seeks to improve the adaptive capacity of the most vulnerable communities to the impacts of climate change and climate variability. The most vulnerable communities are those that are more strongly affected by the impacts of weather due to their spatial location and their inherent inability to put forward preventive actions and to adapt and recover in the short term from the effects of climate variability and extreme events over their livelihoods and the conditions of their environment in order to preserve their lives. Community-based adaptation is about processes which are led by communities and are supported by the local priorities, necessities, knowledge and capacities, which aim to empower communities so they can face the impacts of climate change in the short and long term.
Ecosystem-based adaptation	Ecosystem-based adaptation seeks to integrate the use of biodiversity and ecosystem services in the development of an adaptation strategy that results cost-efficient and generates social, economic and cultural benefits, while it contributes to the conservation of biodiversity. Ecosystem-based adaptation seeks that the conservation of ecosystems and their traditional relationship with the local communities be the basis for an adequate management of natural resources and that this guarantees the provision of ecosystem services that are essential for the adaptation of humanity to climate change and climate variability, as well for other benefits that impact positively human well-being. Its purpose is to maintain and improve the adaptive capacity and to reduce the vulnerability of ecosystems and people.
Infrastructure-based adaptation	Infrastructure-based adaptation is an approach which seeks to improve the adaptive capacity of infrastructure assets that play a determinant role in economic development. Physical infrastructure has an impact over economic growth, the efficiency of the productive sector and social development, both for its effects in terms of connectivity and population access to services, as well for its determinant role in local and regional progress, and in national and international integration. Due to climate change and climate variability, infrastructure is currently operating under different climatic conditions as the ones it was designed for. This affects its integrity and stability and compromises its capacity to sustain the livelihoods of the population. Infrastructure-based adaptation consists on modifying the design processes of infrastructure by including longer return periods and risk scenarios that derive from these.

Box 2. Typology of adaptation approaches in the development context. Source: (Sherman et al. 2016)			
Adaptation approach	**Adaptation and its relationship with Development**	**Assumptions**	**Main critique**
Technocratic risk management	• Adaptation reduces the likelihood of negative climate change impacts. Adaptation can be added on to existing development, but adaptation itself is distinct from normal development. • Examples of adaptation might include increasing the level of robustness in infrastructure, screening development programs for climate risk, and creating emergency funds.	• Adaptation as a specific response to climate change, meant to offset the negative impacts of climate change. • Adaptation is additional to baseline development.	• Adaptation may be ineffective by failing to consider other underlying drivers of vulnerability. • Limited ability to advance broader vulnerability reduction.
Pro-poor vulnerability reduction	• Adaptation needs to be integrated into existing development in order to fully address underlying drivers of vulnerability. • Examples of adaptation might include projects that seek to generally reduce poverty and strengthen livelihoods, such as general education, improving access to healthcare, and increasing institutional accountability and transparency.	• Vulnerability to climate change depends on socioeconomic factors as well as climatic factors. Adaptation also has the potential to improve development outcomes. • Socioeconomic inequality and broader structural drivers of vulnerability need to be considered in both adaptation and development. • Adaptation can be successfully integrated into existing development to reduce both poverty and vulnerability. • An enabling environment is essential for both adaptation and development.	• Limited consideration of the consequences of development and adaptation on multiple spatial and temporal scales. • Limited consideration of power relations.
Sustainable adaptation	• Adaptation needs to be integrated into a type of development that is socially and environmentally sustainable in order to address underlying drivers of vulnerability and to avoid maladaptation. • Examples of adaptation might include projects that achieve adaptation, development, and mitigation outcomes (i.e., 'climate	• The current discourses surrounding adaptation and sustainable development are influenced by governance structures, power relations, and development agendas. • It is thus critical to consider how both adaptation and development are being framed in practice. In many ways,	• Difficult to operationalize. • Alternative development trajectory may not be sustainable and/or reduce vulnerability.

	compatible development', 'triple-wins'), such as solar-powered drip irrigation.	adaptation has become a new development paradigm. • Adaptation has the potential to promote or inhibit social equity and environmental integrity, depending on how it fits into sustainable development on the ground. • Adaptation provides an opportunity to address failures in the current development pathway. • Adaptation can also be leveraged to promote a particular socio-political agenda and further business-as-usual development practices. • There may be a need to rethink development to achieve sustainable adaptation. • It is thus important to consider the actual consequences of adaptation at multiple spatial and temporal scales.	

Appendix 2 - Email formats sent to participants

English version (Exploratory interviews)

Subject: Request for an interview for PhD research

Dear Mr./Mrs.,

I am approaching you today because I will like to interview you as part of my PhD research project in which I am trying to understand and improve the decision-making processes regarding the adaptation of road infrastructure to climate change. After reviewing your profile, I consider that your experience in the road sector is going to be an invaluable contribution to mi research. Through the interview, I expect to understand how decisions are taken regarding the road network of Bogotá and Colombia, and how the dimension of climate change is being included in the planning processes of the road sector.

My name is Juan Sebastián Cañavera Herrera and I am a PhD Student at the **University of Cambridge** in the United Kingdom where I am working with Professor Peter Guthrie and Dr Alice Moncaster. my PhD thanks to the Scholarship Beca Rodolfo Llinás awarded by the Alcaldía Mayor de Bogotá and Fundación Ceiba.

I will be in Bogotá between **December 7th of 2016 and January 12th of 2017**, and I will very grateful if you can offer me **30 to 60 minutes** of your time for an interview. I expect to call you soon to your office to arrange the details of the meeting.

I attach to this email a summary of my research project and an information sheet about the interview. According to the Research Ethics Protocols of the University of Cambridge, if you accept being interviewed you will have the right to withdraw any comments you do during the interview at any moment or withdraw completely from the study. If you have any further questions about my project or the interview, please do not hesitate to contact me.

Thank you for your time and kindness.

With the best regards,

Juan Sebastián Cañavera Herrera

Spanish version (Exploratory interviews)

Sujeto: Solicitud de entrevista para investigación de doctorado

Respetado Sr./Sra.,

Me dirijo a usted porque quisiera entrevistarlo como parte de un proyecto de investigación de doctorado que estoy realizando para entender y mejorar los procesos de toma de decisiones respecto a la adaptación de infraestructura vial al cambio climático. Luego de revisar su perfil considero que su experiencia en el sector vial va a ser una contribución invaluable a mi investigación. A través de la entrevista busco entender mejor como se toman decisiones respecto a la red vial de Bogotá y como la dimensión del cambio climático es incluida en los procesos de planeación del sector vial.

Mi nombre es Juan Sebastián Cañavera Herrera y soy estudiante de doctorado de la **Universidad de Cambridge** en el Reino Unido donde estoy trabajando con el Profesor Peter Guthrie y la Dra. Alice Moncaster. Estoy desarrollando mis estudios de doctorado gracias a la Beca Rodolfo Llinás otorgada por la Alcaldía Mayor de Bogotá y la Fundación Ceiba.

Estaré en Bogotá entre el **7 de diciembre de 2016 y el 12 de enero de 2017,** y estaría muy agradecido si me puede ofrecer **30 a 60 minutos** de su tiempo para una entrevista. Espero llamarlo pronto a su oficina para definir los detalles de nuestra reunión.

Adjunto a este correo, un resumen de mi tesis de investigación y un documento con información de la entrevista. De acuerdo a los protocolos de ética en la investigación de la Universidad de Cambridge, si acepta ser entrevistado tendrá el derecho de retractarse en cualquier momento de cualquier comentario o de retirarse del estudio. Si tiene alguna pregunta sobre mi proyecto o sobre la entrevista, por favor no dude en contactarme.

Muchas gracias por su tiempo y amabilidad.

Cordialmente y en espera de una pronta respuesta,

Juan Sebastián Cañavera Herrera

English version (Expert interviews)

Subject: Invitation to participate in an interview as part of a PhD research

Dear Mrs./ Mr.

My name is Juan Sebastián Cañavera Herrera and I am currently a PhD student at the **University of Cambridge** in the United Kingdom. I am working under the supervision of Dr Kristen MacAskill and Dr Alice Moncaster. I am developing my doctoral research thanks to the scholarship Beca Rodolfo Llinás awarded by Alcaldía Mayor de Bogotá and Fundación Ceiba.

I am writing to you today because I am interested in interviewing you as part of my doctoral research. In my research project, I am aiming to understand and improve the decision-making processes of Bogotá regarding the adaptation of its road infrastructure to climate change. After reviewing your profile, I consider that your experience in the city will be an invaluable input to my research. Through the interview, I wish to understand more about the decision-making processes behind the development and maintenance of the road network of Bogotá, and how climate change is being considered in the planning processes of the road sector.

I will be in Bogotá between **December 13, 2017, and January 29, 2018**, and I would be very pleased to know if you can give me between **30 and 60 minutes** of your time for the interview. I hope to call you soon to your office to define the details of our meeting.

I attach to this email a summary of my research project and an information sheet about the interview. According to the Research Ethics Protocols of the University of Cambridge, if you accept being interviewed you will have the right to withdraw any comments you make during the interview at any moment or withdraw completely from the study. If you have any further questions about my project or the interview, please do not hesitate to contact me or my main supervisor Dr Kristen MacAskill (kam71@cam.ac.uk).

Thank you for your time and kindness.

With the best regards,

Juan Sebastián Cañavera Herrera

Spanish version (Expert interviews)

Sujeto: Solicitud de entrevista para investigación de doctorado (Invitación a participar en entrevista para investigación de doctorado)

Respetado Sr./Sra.,

Mi nombre es Juan Sebastián Cañavera Herrera y soy estudiante de doctorado de la **Universidad de Cambridge** en el Reino Unido donde estoy trabajando bajo la supervisión de la Dra. Kristen MacAskill y la Dra. Alice Moncaster. Estoy desarrollando mis estudios de doctorado gracias a la Beca Rodolfo Llinás otorgada por la Alcaldía Mayor de Bogotá y la Fundación Ceiba.

Me dirijo a usted porque quisiera entrevistarlo(a) como parte de mi proyecto de investigación de doctorado. En mi proyecto busco entender y mejorar los procesos de toma de decisiones en Bogotá respecto a la adaptación de su infraestructura vial al cambio climático. Luego de revisar su perfil considero que su experiencia en la ciudad va a ser una contribución invaluable a mi investigación. A través de la entrevista busco entender mejor los procesos de toma de decisiones detrás del desarrollo y mantenimiento de la infraestructura vial de Bogotá, y cómo la dimensión del cambio climático está siendo considerada en los procesos de planeación del sector vial.

Estaré en Bogotá entre el **13 de diciembre de 2017 y el 29 de enero de 2018,** y estaría muy agradecido si me puede ofrecer **30 a 60 minutos** de su tiempo para una entrevista. Espero llamarlo(a) pronto a su oficina para definir los detalles de nuestra reunión.

Adjunto a este correo, un resumen de mi tesis de investigación y un documento con información de la entrevista. De acuerdo a los protocolos de ética en la investigación de la Universidad de Cambridge, si acepta ser entrevistado tendrá el derecho de retractarse en cualquier momento de cualquier comentario o de retirarse completamente del estudio. Si tiene alguna pregunta sobre mi proyecto o sobre la entrevista, por favor no dude en contactarme o a mi supervisora principal la Dra. Kristen MacAskill (kam71@cam.ac.uk).

Muchas gracias por su tiempo y amabilidad.

Cordialmente y en espera de una pronta respuesta,

Juan Sebastián Cañavera Herrera

Appendix 3 – Information sheet sample

English version

Information sheet for participants

Research Project: Roads to adaptation: Improving decision-making for the adaptation to climate change of the road infrastructure of Bogotá, Colombia

Researcher: Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061). Future Infrastructure and Built Environment Centre for Doctoral Training (FIBE-CDT). University of Cambridge.

Supervisor: Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817). Department of Engineering. University of Cambridge

Before you decide to take part in this study it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. The researcher can be contacted if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

I would like to invite you to take part in my research that is exploring adaptation of road infrastructure to climate change, with a focus on Bogotá. The purpose of my visit is to meet with people who are involved in the development and maintenance of the road network of Bogotá to gain insight into the decision-making processes in this sector and the extent to which climate change is being, or could be, considered.

I am a PhD student in the Engineering Department at the **University of Cambridge** in the United Kingdom and I previously completed my master's degree at the same institution and my degree in Civil Engineering at the National University of Colombia.

The main objective of my research is to understand how Bogotá, Colombia should develop effective adaptation strategies for its road network, where adaptation is understood as "the development, modification, maintenance, and renewal of transportation infrastructure, operations, and policy to moderate the impacts of climate change".[90]

How do I want you to participate?

I would like to arrange an interview with you to discuss your experience in Bogotá in any of the following areas: the development and maintenance of road infrastructure, urban planning policy making, urban development, disaster risk management and/or climate change adaptation. Please, note that you don't need to have experience in all the areas mentioned.

[90] Oswald, M. R. and S. McNeil. 2012. "Methodology for Integrating Adaptation to Climate Change Into the Transportation Planning Process." *Public Works Management & Policy* 18:145–66. Retrieved (http://pwm.sagepub.com/cgi/doi/10.1177/1087724X12469016).

The interview should take between **30 and 60 minutes**, it will take place in person, and an electronic audio recorder will be used to record your answers. The time, date and place of the interview will be arranged by email or by phone with you for it to take place in a place and time convenient for you.

Who is funding this study?

My PhD research is being funded principally by the Alcaldía Mayor de Bogotá and Fundación Ceiba with the Scholarship Beca Rodolfo Llinás.

Will your participation be confidential?

If you agree to be interviewed, your name will not be included in any research reports or papers and will not be circulated to others, unless permission is received to do so. It is possible that the title of your work position might be mentioned in any research reports or papers, only if it is necessary to understand or explain any results of the research. For this, you will be asked to provide the researcher with a specific title with which you would be happy to be cited as.

The recordings of the interviews will be identified with codes. A list of the names associated with the codes will be kept safely in another location different from the one of the coded recordings. The recordings will not be shared with others and they will be kept secured in a computer following the appropriate security measures. The researcher will keep the recordings after transcription until after the final examinations of the research project.

If you agree to be interviewed, you will have the right to unsay at any moment any commentary that you do during the interview or to leave the study.

Who else is taking part in the study?

I am contacting a range of stakeholders in the public and private sector involved in decision-making processes regarding road infrastructure and adaptation to climate change.

What will happen to the results of the research project?

Results will be presented at conferences and written up in journals and in the final thesis. Results are normally presented in terms of groups of individuals. If any individual data are presented, the data will be totally anonymous, without any means of identifying the individuals involved.

What are the advantages of taking part?

You will be updated regarding papers and reports that the researcher publishes, this will allow you to keep track of how the research is progressing. The end goal of the PhD is to find evidence that will allow stakeholders to work and improve their decision-making processes collectively. This could bring benefits to all the stakeholders in the long-term.

What else do you need to know?

The interview will be recorded using an electronic audio recorder and later it will be transcribed. Before the interview takes place, I will remind you of this and check with you verbally that it is ok. Transcripts will not be circulated. You may later, if you wish, have the opportunity to review the transcription to clarify or redact your comments.

If you want to discuss anything ‘off the record’ during an interview, recording will be stopped. If you would prefer not to be recorded, please inform me before the interview takes place.

Who is doing the Ethical review of the study?

The project has received ethical approval from the Engineering Research Ethics Committee of the University of Cambridge.

If you have any further questions about the research project or about the interview, please do not hesitate to contact me or Dr Kristen MacAskill

Spanish version

Información de la entrevista para el participante

Título del proyecto: Vías para la adaptación: Mejorando los procesos de toma de decisión para la adaptación de infraestructura vial al cambio climático de Bogotá, Colombia

Título original: Roads to adaptation: Improving decision-making for the adaptation to climate change of the road infrastructure of Bogotá, Colombia

Investigador: Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061). Future Infrastructure and Built Environment Centre for Doctoral Training (FIBE-CDT). University of Cambridge.

Supervisora: Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817). Department of Engineering. University of Cambridge

Antes de que decida participar en esta investigación, es importante para usted entender por qué ésta se está llevando a cabo y que involucra su participación. Por favor dedique unos minutos a leer cuidadosamente la siguiente información y discútala con otros si así lo desea. Puede contactar al investigador si encuentra que algo no es claro o si desea obtener más información. Tome el debido tiempo para decidir si desea participar o no en el estudio.

Quisiera invitarlo(a) a participar en mi investigación la cual está explorando la adaptación de infraestructura vial al cambio climático, con un enfoque en Bogotá. El propósito de mi visita es reunirme con diferentes personas que están involucradas en el desarrollo y mantenimiento de la red vial de Bogotá para entender mejor los procesos de toma de decisiones en el sector y el grado al cual el cambio climático está, o puede llegar a ser, considerado.

Soy un estudiante de doctorado en el Departamento de Ingeniería de la **Universidad de Cambridge** en el Reino Unido y completé previamente estudios de maestría en esta misma institución y de Ingeniería Civil en la Universidad Nacional de Colombia.

El principal objetivo de mi tesis es entender cómo Bogotá, Colombia debería desarrollar estrategias efectivas de adaptación para su red vial, donde adaptación se entiende como "el desarrollo, modificación, mantenimiento, y renovación de infraestructura de transporte, operaciones y políticas para moderar los impactos del cambio climático".[91]

[91] Oswald, M. R. and S. McNeil. 2012. "Methodology for Integrating Adaptation to Climate Change Into the Transportation Planning Process." *Public Works Management & Policy* 18:145–66. Retrieved (http://pwm.sagepub.com/cgi/doi/10.1177/1087724X12469016).

¿Cuál es su forma de participar en mi investigación?

Me gustaría concertar una entrevista con usted para discutir su experiencia en Bogotá en cualquiera de las siguientes áreas: el desarrollo y mantenimiento de infraestructura vial, generación de políticas de planificación urbana, desarrollo urbano, manejo del riesgo de desastres y/o adaptación al cambio climático. Por favor note que no necesita tener experiencia en todas las áreas aquí mencionadas.

La entrevista tiene una duración de entre **30 y 60 minutos,** va a ser en persona, y en ésta se utilizará una grabadora de audio electrónica para registrar sus respuestas. La hora, fecha y lugar de la entrevista serán concertadas por correo electrónico o por teléfono para que se desarrolle en un tiempo y lugar adecuado para usted.

¿Quién está financiando esta investigación?

Mi investigación de doctorado está siendo principalmente financiada por la Alcaldía Mayor de Bogotá y la Fundación Ceiba a través de la Beca Rodolfo Llinás.

¿Va a ser su participación confidencial?

Si acepta ser entrevistado, su nombre no se va a incluir en ningún reporte de investigación o artículo científico, y no se circulará a otros, a menos de que usted de permiso para ello. Es posible que el nombre de su posición laboral sea mencionado en algún reporte de investigación o artículo científico, sólo si es necesario para entender o explicar algún resultado de la investigación. Para ello se le pedirá que le provea al investigador un título específico con el cual usted estaría de acuerdo se utilice al ser citado.

Las grabaciones de las entrevistas van a ser identificadas con códigos. Una lista de los nombres asociados con los códigos se mantendrá guardada de manera segura en una locación diferente a la de las grabaciones. Las grabaciones no se serán compartidas con otros y se mantendrán guardadas de manera segura en un computador siguiendo las medidas apropiadas de seguridad. El investigador guardará las grabaciones luego de la transcripción hasta después de las últimas evaluaciones del proyecto de investigación.

Si acepta ser entrevistado tendrá el derecho de retractarse en cualquier momento de cualquier comentario que haga en la entrevista o de retirarse del estudio.

¿Quién más está participando en la investigación?

Estoy contactando a una serie de personas en entidades públicas y privadas que estén involucradas en los procesos de toma de decisión respecto a infraestructura vial y respecto a adaptación al cambio climático.

¿Qué pasará con los resultados de la investigación?

Los resultados se presentarán en conferencias, en revistas científicas y en la tesis final. Los resultados se presentan normalmente en términos de grupos de individuos. Si cualquier tipo de información individual es presentada, la información será totalmente anónima, sin ningún medio de identificar al individuo involucrado.

¿Cuáles son los beneficios de hacer parte de la investigación?

Será mantenido actualizado(a) respecto a artículos científicos o reportes que publique el investigador, lo que le permitirá mantener un registro del progreso de la investigación. El objetivo final de la tesis de doctorado es encontrar evidencia que le permita a las partes

interesadas trabajar y mejorar sus procesos de toma de decisiones colectivamente. Esto traerá beneficios a las partes en el largo plazo.

¿Qué más necesita saber?

La entrevista será grabada con una grabadora de audio electrónica y más adelante será transcrita. Antes de que empiece la entrevista, volveré a asegurarme verbalmente de que está de acuerdo con ser grabado(a). Las transcripciones no serán divulgadas. Tiene derecho, si así lo desea, de más adelante revisar la transcripción para clarificar o redactar sus comentarios.

Si quiere discutir algo “extra oficialmente” durante la entrevista, la grabación será detenida. Si prefiere no ser grabado, por favor infórmeme antes de que la entrevista ocurra.

¿Quién da el consentimiento ético a la investigación?

El proyecto ha recibido aprobación ética por parte del Comité de Ingeniería sobre Ética de la Investigación de la Universidad de Cambridge.

Si tiene alguna pregunta sobre mi proyecto o sobre la entrevista, por favor no dude en contactarme o a la Dra. Kristen MacAskill.

Appendix 4 - Consent form sample

English version

Participant Consent Form

Research Project: Roads to adaptation: Improving decision-making for the adaptation to climate change of the road infrastructure of Bogotá, Colombia

Researcher: Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061). Future Infrastructure and Built Environment Centre for Doctoral Training (FIBE-CDT). University of Cambridge.

Supervisor: Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817). Department of Engineering. University of Cambridge

1) I confirm I have read and understood the information sheet which explains the research project.

2) I understand that my participation is on a voluntary basis and I am free to withdraw at any time without giving reason and without there being any negative consequences. I am free to decline to answer any questions during the interview.

3) I understand that the interview will be recorded and transcribed by the researcher. If I am not happy to be recorded, I have informed the researcher of this.

4) I understand that my responses will be kept confidential (unless permission is obtained otherwise).

5) I am happy for the research to be used for papers published relating to the PhD project and for the PhD thesis.

6) I agree to take part in the above research project.

If you are happy with all of the above, please confirm your willingness to participate and acceptance by signing this form.

If you have any further questions after the interview you can contact the researcher Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061) or his supervisor Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817).

_____ _____

Signature Date

Print Name:

Role title for citation:

☐ Please tick this box if you would like to review the transcript of your interview in the future to clarify or redact your comments.

Spanish version

Formulario de consentimiento del participante

Título del proyecto: Vías para la adaptación: Mejorando los procesos de toma de decisión para la adaptación de infraestructura vial al cambio climático de Bogotá, Colombia

Título original: Roads to adaptation: Improving decision-making for the adaptation to climate change of the road infrastructure of Bogotá, Colombia

Investigador: Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061). Future Infrastructure and Built Environment Centre for Doctoral Training (FIBE-CDT). University of Cambridge.

Supervisora: Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817). Department of Engineering. University of Cambridge

1) Confirmo que he leído y entendido la hoja de información en donde se explica el proyecto de investigación.

2) Comprendo que mi participación es voluntaria y que soy libre de abandonar el estudio en cualquier momento sin dar ninguna razón para ello y sin que haya ningún tipo de consecuencias negativas. Entiendo que soy libre de negarme a responder cualquier pregunta durante la entrevista.

3) Comprendo que la entrevista va a ser grabada y transcrita por el investigador. Si no estoy de acuerdo con que me graben, le he informado al investigador sobre esto.

4) Comprendo que mis respuestas se archivaran de manera confidencial (a menos que se obtenga permiso para lo contrario).

5) Estoy de acuerdo con que la investigación sea publicada en artículos científicos relacionados con la investigación de doctorado y en la tesis de doctorado.

6) Estoy de acuerdo en participar en este proyecto de investigación.

Si está de acuerdo con todo lo anterior, por favor confirme su voluntad de participar y su aceptación de las condiciones firmando este formulario.

Si tiene cualquier pregunta adicional después de la entrevista usted puede contactar al investigador Juan Sebastián Cañavera Herrera (Email: jsc80@cam.ac.uk, Tel: +447985345061) o a su supervisora Dr Kristen MacAskill (Email: kam71@cam.ac.uk, Tel: +44 1223 3 32817).

_____ _____

Firma Fecha

Nombre:

Título del rol para ser citado:

☐ Por favor marque ésta casilla si le gustaría revisar la transcripción de su entrevista en el futuro para clarificar o redactar sus comentarios.

Appendix 5 – Guiding topics and common questions

Exploratory interviews

Topic: Climate change and roads

1. What do you think will be the impacts of climate change on the road infrastructure of Bogotá/Colombia? Is this a real concern for the community?
2. Is it discussed among the actors of the road sector to increase the resilience of the road infrastructure? Have you touched this topic in your work?

Topic: Decision-making processes

1. Could you tell me how are decisions made for the design, construction, administration and maintenance of the road network in the city/country?
2. Which actors are involved in these processes?
3. Which position do you consider has the real decision-making power?

Topic: Sustainable development and roads

1. What do you believe is sustainable development?
2. Do you consider that sustainable development is being used as a guiding philosophy for the decision-making processes in the road sector in Bogotá/Colombia? Is this an objective?

Topic: Decision-support tools

1. Do you use any type of decision-support tool for the planning and execution of your projects? Do you think they are useful?
2. What kind of results do you believe a good decision-support tool should generate for decision-making processes?

Expert interviews

Topic: Climate change adaptation and roads

1. What do you think are going to be the main effects of climate change in Bogotá?
2. How do you think the city's road infrastructure will be affected by climate change?
3. How do you think the city should be prepared to face climate change?
4. Is there a strategy of the road/transport sector of the city to face climate change?
5. Is climate change being considered in the planning of the development and maintenance of Bogotá's road infrastructure?

Topic: Decision-making processes for the development and maintenance of road infrastructure in Bogotá

1. How are decisions made regarding the development and maintenance of the road network in Bogotá?
2. What factors influence decision making?
3. Do you consider that you are part of the decision-making processes? Where do you participate in these processes?
4. How much influence do you feel you have in the decisions made?
5. Who do you think has the greatest influence on decisions?
6. What factors do you consider are the most influential in the decisions of the road sector?
7. Could you describe the last road infrastructure project in which you participated and how the decisions were made regarding your development?
8. What do you think should be the main focus for the future development and maintenance of road infrastructure in Bogotá? What should be the most important things to keep in mind?

Appendix 6 - Ethical Approval of Research Project

Exploratory interviews

UNIVERSITY OF CAMBRIDGE
Department of Engineering

Philip Guildford
Director of Research

Mr Juan Sebastian Canavera Herrera
Department of Engineering
University of Cambridge

2 December 2016

Dear Juan,

Ethical Approval for your Research Project: Roads to Adaptation: Understanding decision-making for adaptation of road infrastructure to climate change

Your application has now been considered under the Light Touch Process in line with recommended procedures concerning ethical approval of research.

I am able to inform you that, with respect to ethical considerations, approval has been given to your project. Please note that this approval is based on the documentation you provided. You must re-submit your application to the Committee should you subsequently make any substantive changes relating to matters reviewed by the Committee.

We are content for this letter to be forwarded to your grant sponsors or to any partner institutions you may be working with if appropriate.

Yours sincerely

Philip Guildford
Director of Research

Philip M. Guildford
Director of Research
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ
director-of-research@eng.cam.ac.uk

Expert interviews

UNIVERSITY OF CAMBRIDGE
Department of Engineering

Professor Daniel Wolpert
Chairman of the Ethics Review Committee

Juan Sebastian Canavera Herrera
Division D

7 December 2017

Dear Juan

Ethical Approval for your Research Project: Roads to adaptation: Improving decision-making for the adaptation to climate change of the road infrastructure of Bogotá, Colombia

The Department's Research Ethics Committee has considered the documentation you provided in support of your research project in line with recommended procedures concerning ethical approval of research.

I am able to inform you that, with respect to ethical considerations, approval has been given to your project. Please note that this approval is based on the documentation you provided. You must re-submit your application to the Committee should you subsequently make any substantive changes relating to matters reviewed by the Committee.

We are content for this letter to be forwarded to your grant sponsors or to any partner institutions you may be working with if appropriate.

Yours sincerely

Daniel Wolpert

Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ
research-ethics@eng.cam.ac.uk

Appendix 7 – List of codes used for the coding of transcripts and documents

The following is a complete list of all codes used during the coding of transcripts and documents done in this research as described in Chapter 4.

Code	Definition
1. Adaptation	All mentions of the definition and understanding of adaptation as a concept by the interviewees, and the theories they mention about adaptation.
1.a. Confusion with other concepts	All instances in which adaptation is confused or associated incorrectly with other concepts such as mitigation or standard environmental management.
1.b. Adaptation vs. development	Evidence of the perception of conflict between adaptation and development needs by the interviewees.
1.c. Ecosystems-based adaptation	All references to ecosystems-based adaptation.
1.d. Adaptation by stealth	All instances in which adaptation is conceptually being hidden behind other concepts in practice.
2. Adaptation planning	All mentions of adaptation planning in Bogotá.
2.a. Adaptation actions	All references to the different adaptation actions found or planned in the city of Bogotá according to the typology by Biagini et al (2014).
2.a.1 Capacity building	All references to adaptation actions that involve "developing human resources, institutions, and communities, equipping them with the capability to adapt to climate change" (Biagini et al. 2014)
2.a.2. Management and planning	All mentions of adaptation actions that involve "incorporating understanding of climate science, impacts, vulnerability and risk into government and institutional planning and management" (Biagini et al. 2014)
2.a.3. Practice and Behaviour	All mentions of adaptation actions that involve "revisions or expansion of practices and on the ground behaviour that are directly related to building resilience" (Biagini et al. 2014)
2.a.4. Adaptation policy	All mentions of adaptation actions that involve "the creation of new policies or revisions of policies or regulations to allow flexibility to adapt to changing climate" (Biagini et al. 2014)
2.a.5. Information	All references to adaptation actions that involve "systems for communicating climate information to help build resilience towards climate impacts (other than communication for early warning systems)" (Biagini et al. 2014)
2.a.6. Physical infrastructure	All references to adaptation actions that involve "any new or improved hard physical infrastructure aimed at providing direct or indirect protection from climate hazards" (Biagini et al. 2014)
2.a.6.a. Drainage management and SUDS	All mentions of adaptation actions that involve drainage management or SUDS.
2.a.7. Warning and observing systems	All references to adaptation actions that involve "implementation of new or enhanced tools and technologies for communicating weather and climate risks, and for monitoring changes in the climate system" (Biagini et al. 2014)
2.a.8. "Green" infrastructure	All references to adaptation actions that involve "any new or improved soft, natural infrastructure aimed at providing direct or indirect protection from climate hazards" (Biagini et al. 2014)

2.a.9. Financing	All references to adaptation actions that involve "new financing or insurance strategies to prepare for future climate disturbances" (Biagini et al. 2014). This includes also the ways in which financing is obtained for the transport infrastructure.
2.a.10. Technology	All mentions of adaptation actions that involve "develop or expand climate-resilient technologies" (Biagini et al. 2014)
2.b. Adaptation institutional arrangements	All mentions of the different adaptation planning institutional arrangements in Bogotá made by the interviewees or found in the analysed documents.
3. Barriers to adaptation	All mentions of barriers or opportunities for the effective adaptation planning of road infrastructure in Bogotá based on the categories presented by Lehmann et al (2015).
3.a. Information	This code collects all references to barriers or opportunities related to information quality and availability in Bogotá.
3.b. Resources	This code collects all references to barriers or opportunities related to resources availability in Bogotá.
3.c. Incentives	This code collects all references to barriers or opportunities related to incentives in which decision-makers have to act in Bogotá.
4. Climate change	All mentions of climate change.
4.a. Climate change effects	All references to climate change effects in Bogotá and impacts on the transport infrastructure of the city made by the interviewees or found in the analysed documents.
4.b. Climate change perceptions	Evidence of the perceptions and thoughts that the interviewees have regarding climate change and its effects.
5. Decentralisation	All references to the institutional decentralisation of government in Bogotá and the problems or benefits related to it.
6. Decision support tools	All references to decision-support tools and their use in adaptation and transport planning.
6.a. Indicators	All mentions of indicators in adaptation or transport planning. This includes their existence, their use, or the need for them.
7. Development	All references to interviewees' perceptions of what should be the focus, models, ideas or plans for the future development of the city.
8. Development Plan	All references to the mayor's Development Plan document and its influence.
9. Environmental management	All mentions of environmental management practices and policies in the different organisations of the city.
10. Flagship projects	This code collects all references to the flagship infrastructure projects in Bogotá mentioned by the interviewees or documents analysed.
10.a. Lagos de Torca	All mentions of the project "Lagos de Torca" in Bogotá.
10.b. Metro de Bogotá	All mentions of the project "Metro de Bogotá" in Bogotá.
10.c. Quinto Centenario	All mentions of the project "Quinto Centenario" in Bogotá.
10.d. Red Vial Vital	All mentions of the project "Red Vial Vital" in Bogotá.
11. Information systems	All references related to information systems used by decision-makers in Bogotá or the need for them.
12. Memorable quotes	This code collects the most memorable quotes for future referencing according to the author of this thesis.
13. Mitigation	All mentions of mitigation actions and practices in Bogotá.
14. Non-climatic challenges	All references to additional present and future challenges in Bogotá caused by non-climatic processes.
14.a. Informal urban spaces	All references to informal urban spaces challenges in Bogotá.
15. Planning cycle	All the references to the adaptation planning cycle and its different phases according to the EAAC framework in Bogotá.
15.a. Problem structuring	This code collects all the references to the "Problem structuring and establishing of the arena" phase of the planning cycle according to the EAAC framework.
15.b. Agenda formulation	This code collects all the references to the "Developing the adaptation agenda, vision and pathway" phase of the planning cycle according to the EAAC framework.

15.c. Implementation	This code collects all the references to the "Implementing adaptation options" phase of the planning cycle according to the EAAC framework.
15.d. Evaluation and monitoring	This code collects all the references to the "Evaluating, monitoring and learning" phase of the planning cycle according to the EAAC framework.
16. Political pressures	All mentions of political pressures that affect decision-making processes in Bogotá.
17. Risk management	All references to risk management in Bogotá.
18. Scales of adaptation	This code collects all references related to the different scales of adaptation presented in the EAAC framework.
18.a. No adaptation	This code collects all references to the overt decision to not adapt.
18.b. Resistance	This code collects all references to adaptation characterized by "increased and concentrated investment in existing development pathways, infrastructure, institutions and practices" (Pelling et al. 2015)
18.c. Incremental	This code collects all references to adaptation characterized by "marginal changes in infrastructure, institutions and practices that foster flexibility and fulfil capacity while not directly threatening systems' integrity" (Pelling et al. 2015)
18.d. Transformation	This code collects all references to adaptation characterized by "fundamental change to the functioning of systems" (Pelling et al. 2015)
19. Spatial interactions	This code collects all references regarding the different interactions that Bogotá has at different spatial scales.
19.a. Interactions with the national level	All references of the interactions that Bogotá has with the national level.
19.b. Interactions with the regional level	All mentions of the interactions between Bogotá and the regional level. This include references to the concept of Bogotá-region.
19.c. Local level	All mentions of the interactions between Bogotá district government and the localities.
20. Spatial Planning	This code collects all references regarding the spatial planning processes, documents and philosophies followed by the city of Bogotá.
20.a. Spatial Planning documents	All references to the spatial planning documents of the city and their use.
20.b. Eco-urbanism	All mentions of eco-urbanism and its use in spatial planning in Bogotá.
21. Stakeholders	This code collects all references to the stakeholders of the transport sector of Bogotá and its adaptation planning.
21.a. Academia	All mentions of academia.
21.b. Acueducto	All references to "Empresa de Acueducto y Alcantarillado de Bogotá" (Water Company of Bogotá).
21.c. Alcalde Mayor	All references to the city's mayor.
21.d. Alcaldías Locales	All references to the local mayoralties.
21.e. Community	All references to the community.
21.f. Concejo Bogotá	All references to the City Council.
21.g. Construction materials providers	All references to construction materials providers.
21.h. IDIGER	All references to IDIGER (District Risk Management and Climate Change Institute).
21.i. IDU	All references to the IDU (Urban Development Institute).
21.j. Jardin Botánico	All references to the city's Botanical Garden.
21.k. NGOs and International agencies	All references to NGOs and international agencies.
21.l. Private engineering companies	All references to private engineering companies.
21.m. Secretaría Ambiente	All references to the District Environmental Secretary.
21.n. Secretaría Hacienda	All references to the District Treasury Secretary.
21.o. Secretaría Movilidad	All references to the District Mobility Secretary.
21.p. Secretaría Planeación	All references to the District Planning Secretary.
21.q. Transmilenio	All references to Transmilenio.
21.r. UMV	All references to UMV (Special Administrative Unit for Road Maintenance and Rehabilitation).
21.s. Utility companies	All references to utility companies (not including the Water Company).

22. Sustainable development	All references to sustainable development.
23. Sustainable transport	All mentions of sustainable transport.
24. Transport planning	All mentions of the processes, documents and philosophies of Bogotá's transport planning.
24.a. Transport planning documents	All references to transport planning documents of Bogotá.
24.b. Construction	All mentions of the construction of new transport infrastructure in Bogotá.
24.c. Maintenance	All mentions of the maintenance of transport infrastructure in Bogotá.
24.d. Planning principles and prioritisation	The planning principles and prioritisation methods used in the transportation planning processes of Bogotá.
24.e. Transport institutional arrangements	All references to the different institutional arrangements that guide transport planning in Bogotá.

Appendix 8 – Additional evidence supporting the analysis presented in Chapter 6 and 7.

This appendix provides additional evidence that supports the analysis presented in Chapter 6 and Chapter 7 of this thesis. This appendix is divided into two sections, one for each analysis chapter. The additional evidence is provided for each corresponding footnote following the same numbering presented in the main text.

Chapter 6 footnotes

6. INT24b explains here which organisation in the city oversees the management of information regarding climate change and its associated risks:

In order to manage information [related to climate change] […] I mean, we do not manage [this kind of information] here [in the District Mobility Secretary], but we would need to find an indicator specific to adaptation in the transport sector because the Secretary should not begin to develop hazard maps of the city because for that we have IDIGER and IDIGER is who manages that kind of information (INT24b).

In her interview, INT8 explains the role that IDIGER has in the development of the Urban Master Plan and confirms their responsibility for the creation and management of information regarding risks in the city:

We [IDIGER] need to generate the risk management inputs for the ordinary review of the Urban Master Plan. In the current Urban Master Plan, the one from 2000, we generated some hazard maps for flooding, for landslides, for earthquakes, and something small was done for technological risk. Right now, there is a law, a national decree (which is the [Decree] 1807 from 2014) that defines how risk management should be incorporated in urban master plans. Then, we need to comply with the technical requirements from the decree and we need to update the maps we have (INT8).

7. INT37 explains the need for a baseline for adaptation decision-making in the city:

It is clear that the city has currently no clarity about the quantification of impacts and I think that needs to be the first step, no? It means telling the city 'hey, look, you need to do a baseline today […] and what can we foresee in the future from that?'(INT37).

8. The following quote shows INT20's answer to the question "how do you think road infrastructure in the city will be affected by climate change?":

Climate change at this time would have two impacts in the city since our city has the connotation of being a city that has mixed geography. We have here a flat area, which is the Savannah area, and we have several mountain areas that imply completely different developments. Then, the construction in the hillsides must contemplate the management of rainwater and the stability of the road we are building so there are no movements or faults that generate stability problems and problems with landslides. The other issue is the construction of roads in the flat area, in the Savannah, where those stability conditions are not affected by landslides but are dependent only on the management of rainwater and the management of the stability of the soil, but is a matter that is easier to manage as there is not the need to construct additional works to maintain the road (INT20).

The following quote shows INT7's answer to the question "how do you think road infrastructure in Colombia will be affected by climate change?":

[Climate change will affect] negatively [the infrastructure in the country]. We are seeing it right now with the variability of the weather, with the effects of the latest el Niño and la Niña phenomena. Obviously, the La Niña phenomenon is affecting us more because of the increase in rainfall, the intensity of rain, and that generates that we have very high risks in terms of landslides and flooding (INT7).

9. INT23 explains the damages suffered by road infrastructure during dry periods in Bogotá:

Now, when the droughts happen. When it is the time when there is no rain, then the soil becomes completely dry. We have seen this mainly in the north of the city where complete roads have failed due to the dryness of the soil. So, there are places in which there are expansive clays which in rainy season absorb a lot of water and expand, and when the dry season comes, they become dry and retract. This generates several failures [in the roads], I mean, I have seen longitudinal failures and you can also spot subsidence and unevenness in the roads (INT23).

10. Refer to the quote in the main text.

11. Refer to the quote in the main text.

12. The following quote shows INT21's answer to the question "who must develop the adaptation strategy for the road sector in Bogotá?":

It must be developed by the [District Mobility] Secretary […]. Yes, we [IDIGER] should not develop it. […] There is something very important here in the Law 1523, I think it is article 12, that tells us that the owner of the infrastructure or of the territory is the owner of the risk, yes? […] Therefore, in

the case of the transport sector, the responsible for the [risk management] are the organisations that I mentioned are part of the transport sector (INT21).

13. The following quote shows INT21's answer to the question "so, there is not yet an adaptation strategy for the road infrastructure of the city?":

No (INT21).

14. INT15a and INT2 explain who is responsible for the "green" infrastructure of the city:

And we have the institutional arrangements. We have the Botanical Garden, […] which is no longer just working in the garden itself but now governs the city's gardens and trees (INT15a).

It is equally necessary that the Botanical Garden and the District Environmental Secretary perform constant maintenance of the green areas of the city (INT2).

INT33 explains how the new Sewer Master Plan of the city establishes the responsibility of Bogotá's Water Company over SUDS:

I was fortunate to be responsible for the development of the principal component of the Sewer Master Plan for the city. […] This Master Plan was developed to answer the question which is the strategy we can follow to adapt to climate change. The Master Plan has four basic programmes. […] The fourth programme is oriented specifically towards adaptation to climate change, which we have called the integral rainwater management programme, which is nothing else than the plan to transform the sewer system of the city into a sustainable urban drainage system (INT33).

15. The main objective of the RVV study commissioned by the District Mobility Secretary was:

To update the Vital Road Network of Bogotá D.C. and develop its implementation framework regarding the technical, financial and legal components, including criteria related to climate change adaptation and resilience of the mobility system of the city (Report RVV).

16. INT21 shows that some professionals from IDIGER are critical of the adaptation approach chosen by the District Environmental Secretary:

[Ecosystem-based adaptation] is a vision from the District Environmental Secretary, but us in IDIGER, as we are the coordinators of the system, we have discussed enough the necessity of [adaptation] not only being ecosystem-based adaptation, yes? But that we rather should incorporate a vision that is a bit more holistic (INT21).

Refer to note 54 in this appendix for further evidence.

17. INT32 explains how climate change considerations are being incorporated into the new Urban Master Plan:

Climate change is incorporated as part of the general diagnosis of the environmental component of the city, but it is defined as a problem which we need to tackle with concrete actions. Those actions can be put under the umbrella of climate change adaptation, but we are trying to put that under the conceptual framework of urban ecoefficiency because we think this framework proposes concrete actions that can make the urban organism more efficient. Actions like sustainable urban drainages, […] [or] managing adequately the environmental structure of the city (INT32).

18. INT21 and INT11a mention here other types of actions regarding new kinds of pavements:

Which other measures can I remember? We had proposed in the previous [risk management and climate change] plan how to begin making roads more permeable, but that is a measure that was proposed without having any money to invest in it. Just imagine trying to change all roads in Bogotá when we actually don't even have a road system in satisfactory state (INT21).

We are trying with the department of new technologies [in the IDU] to develop asphalt-rubber mixes. We are hoping to make long life road pavements for effectively counter the effects of water over roads. […] Water is what mainly affects pavements and we need roads that last longer (INT11a).

19. INT23 explains the use of innovative slope management techniques when he was the director of UMV:

I was the director of UMV […] and during that period, in the rural road network of Bogotá, we applied a lot something called bioengineering in places where, because of climate change and the presence of geological faults, we couldn't provide traditional hard infrastructure solutions. […] So bioengineering was applied in more than 250 unstable sites. […] The result was very positive because bioengineering focuses on the management of drainage. […] We used native vegetation, and, at this moment, you can pass next to these sites and you will not recognise the measures. We were able to adapt the problem to nature (INT23).

20. INT17 explains the need to incorporate adaptation considerations into the Urban Master Plan:

That's why in Bogotá, in spite of what we have in terms of risk management and the model we want to keep in which there is a specific chapter for adaptation, it is not easy to have an adaptation plan per se if adaptation is not a part of the Urban Master Plan (INT17).

21. INT26 explains how adaptation considerations can be included in the Urban Master Plan to make them effective:

You know how the political-administrative dynamics are here, but what we are trying to do is adding the adaptation proposals to the structural component [of the Urban Master Plan]. […] There are some short-term, medium-term and long-term components [in the Urban Master Plan]. The structural components are those for the long term, those that cannot be changed by any government. (INT26)

22. Refer to the examples given in the main text.

23. INT15a suggests that Partial Plans and Master Plans have a history of being manipulated and because of this they have not been useful for planning in the city:

The Urban Master Plan is operationalised through the Master Plans, the Partial Plans and similar documents. This has also been a very complex problem because each government makes different decrees thinking, for example, that the north of the city should be developed in a certain way, and the west should be developed in this other way, and there are administrations that says: 'no, let's not do either. Let's change the past decrees because it is part of my government powers to change decrees'. So, the Partial Plans and the Master Plans have also no important or serious objective for you as a citizen to know if this city in the next 10 or 15 years will have a clear goal when the city celebrates its 500 years anniversary (INT15a).

24. Refer to the examples given in the main text.

25. INT24b explains the process of the legal adoption of the RVV:

We need to start the legal adoption of the RVV. As I was telling you, there is a proposed draft for the decree, and it must be reviewed and validated by the secretary from the Legal Secretary and then give it to the mayor's office for it to be signed. That is the process I am telling you will take us some time, at least until next year, until the decree is signed (INT24b).

26. INT5-2 explains here how the District Risk Management and Climate Change Plan – Bogotá 2015-2050 is being changed by Enrique Peñalosa's administration:

It is not that they tell something different, it is that it is not mentioned, I mean, a part of that reality is observed, yes? So, you cannot say that Bogotá is not complying or that the administration is not complying with the regulations, what happens is that if the regulations do not work for me, I modify them and start [with my projects]. So, the city's administration has been a year and a half, two years, modifying [the District Risk Management and Climate Change Plan] so it is adapted to what they need. In other words, their philosophy is that if I need bigger shoes, I do not buy bigger shoes, I cut my toes, so my feet fit in the shoes I have. But this is legal, you see? (INT5-2).

They continue later explaining why the administration is trying to change this plan:

I believe that it is a very difficult topic. […] One of the elements is the pressure created by the private sector, the construction sector, for housing development in the city, because there are other many elements and variables that can create economic development in the city, the topic of employment, etc. So, the most interested, for example, in the modification of the [District Risk Management and Climate Change Plan] was the construction sector (INT5-2).

27. INT22 explains how the current institutional arrangements in the city hinder innovations:

For me is that there is a fear to face change, fear of transformations. It is preferable to have some conventional methods which we have always used, that we know very well, are seen as easy to implement again, but changes and transformations are something perceived as complex. Even the control organisations themselves punish these attempts for change (INT22).

28. INT21 and INT24b explain that adaptation is not part of the legal competences of most organisations in the District, making adaptation planning a complex process:

We in [IDIGER] are very weak in implementing measures because if [there is new hazard or risk information] and I am asked which measures to implement, I will say that I do not know. I don't know. Not because I don't know about the topic, I don't know because in reality telling the organisations of the district that we need to do this and that is a complex process because if it is not in their competences it is not done (INT21).

The obstacle [for implementing the RVV] is being able to push it forward in the city's agenda because all these normative processes take some time and let's say that the organisational topic and the matter of defining well the competences of each of the organisations in this topic is difficult for all those organisations that are not dedicated to the topic of climate change as they do not have it in mind (INT24b).

29. INT30 explains the influence of the Development Plan over the administration of localities in Bogotá:

The environmental matters, particularly those related to climate change in the localities, the importance given to them is very conditioned to the proposal of the Development Plan (INT30).

In another example, INT20 explains the influence of the Development Plan over the prioritisation of technical work for the road infrastructure of the city:

The development of the road network is dependent on the District Development Plan that is proposed by each mayor when they begin their government every four years. Then, based on the Development Plan, we prioritise which roads are going to be constructed and maintained and according to that, we begin the bidding processes to comply with the Development Plan (INT20).

Refer to note 71 in this appendix for a further example.

Chapter 7 footnotes

30. The private consultancy that worked on updating the RVV explains in their report that:

Organisations like UMV, [the Special Administrative Unit for Public Utilities], [Colombian Civil Defence] and [the District Planning Secretary] did not provide information, in this case, and how it was explained before, we proceeded to search for secondary information (Report RVV).

31. The following quote shows INT8's answer to the question "are there already good information systems in the city?":

I believe that the city has improved, but I think we are still lacking a lot. I think that we need platforms, I think we need to be connected in an inter-organisational manner to be able to understand how each organisation contributes to [information management]. It is part of what we need to do. So, one could say, [the District Planning Secretary] should consolidate all information from all organisations. And then we would have the instrument, but that is not how it works (INT8).

32. As part of the development of Bogotá's Public Policy on Eco-urbanism and Sustainable Construction, the city identified its main problems for sustainability. It was identified that one of the causing factors of the problem of "Difficulty for the administration to act", is:

The lack of coordination between sectors and unions: Academia (research), private sector (projects), public organisations (planning, regulation and control) (Eco-urbanism) (Alcaldía Mayor de Bogotá 2014b).

33. INT5, who demonstrated in many parts of her two interviews that she politically opposes the administration of Enrique Peñalosa, explains how some sectors of IDIGER that are not politically close to the mayor have not received some information:

We do not know yet, when I say "we" I mean some sectors from IDIGER, we do not know yet the results, for example, of the proposed risk zoning [for the Urban Master Plan]. What we know is that a very important modification has been done to the flooding hazard maps precisely so things like "Ciudad Río" [a Partial Plan seeking to develop urban projects in the banks of the Bogotá river] can be developed because if you do not modify the zoning you would not be able to construct next to the river (INT5-2).

They have not received this information as these sectors from IDIGER do not share the political interpretations of risk from the mayor and his political allies.

34. Refer to the example provided in the main text and note 26 in this appendix.

35. All the sources quoted in this footnote present evidence for the information barriers described in the main text and examples of this evidence are presented in notes 36 to 51.

36. INT2 explains what would be for him the ideal way in which the city should keep an up-to-date database of the condition of its road network:

So, a diagnosis [of the physical state of road infrastructure in the city] started to be done a year ago and they are going to present the results in December [2016]. I think that we should be doing the following: we need to get out a diagnosis contract, yes? Constantly. As I imagine you have seen this kind of contracts in Europe. I am the city's engineer. The city's engineer is contracted, and he receives a workload every month. 'Hey, please make this diagnosis, do this, keep an updated database', and I will give these results to the construction area, telling them what they need to do, the routine maintenance, the periodic maintenance. Let's go to this part of the city and we begin to work there like this. Unfortunately, we are not doing things like this (INT2).

INT2 later adds in his interview that this and other problems with proper maintenance in the city are due to lack of financial resources allocated for this purpose.

37. INT2 explains that a diagnosis of the road network of the city has been taking too long and that the information given by the diagnosis loses validity because of this:

Right now, a diagnosis is being finished. They have been taking a year to do the diagnosis. You know that diagnosis loses validity in two or three months (INT2).

38. Refer to note 26 in this appendix.

39. INT10 explains the following about decentralization in the administration of transport infrastructure in Bogotá:

Apparently, a big institutional problem in Bogotá is that there is too much fragmentation in the organisations that administer the infrastructure in the city and that is why planning is not working well in the city (INT10).

40. Refer to note 31 in this appendix.

41. INT26 explains which are for him the main factors that hinder adaptation in Bogotá:

So, the main issues are ignorance, [lack of] institutional technical capacity, lack of financial resources to promote knowledge and implement that knowledge, […] [lack of] normative support for

the tasks needed, and deficiencies in academia and education in order to investigate deeper this topic (INT26).

42. INT14 explains the situation of the city regarding the modelling of its water systems:

I must insist that we have done only baby steps regarding modelling. I say it because we have just about more than 230 bodies of water in the city and from those 230, approximately, just about half of them have any kind of modelling and have their parameters defined for a return period of 100 years (INT14).

43. The following quote shows INT25's answer to the question "how is climate change being included in the work of the Centre for Environmental Information and Modelling of Bogotá?":

We [the District Environmental Secretary] have a group for climate change, what happens is that those groups need as input catalogued information, organized information, like the one generated by the Centre for Environmental Information and Modelling. We do calculations of the emissions of all components, for instance, the industrial emissions, the ones related to urban trees, of waste […] This comes from an analysis of which are the most important contributions made by the city, and through this analysis what we look for are proposals and alternatives that allow in a correct way to decrease the emissions associated with climate change (INT25).

44. The following quote shows INT37's answer to the question "have you observed that adaptation is being considered by Bogotá for its road infrastructure?":

Not as resilience against climate change, I think it is not being considered, but that depends also of which [are our conditions], of which are the effects that we have normally in Bogotá as part of climate change, and as they are not evident yet because they haven't happened, I feel that inside the planning of road infrastructure we are not considering climate change. […] As I was telling you, in the strategic planning in the city this is not being considered, we have not yet considered from a risk perspective what is the best way to incorporate this resilience to climate change (INT37).

45. INT3 explains the lack of well-maintained weather stations in Colombia:

Here in Colombia long ago something called IMAT worked before IDEAM and they had weather stations everywhere. And all of them worked and they had an eye on them. Nowadays we have much less coverage than in those days. And the weather stations I have seen give me the impression that they are not in good shape. They are not checking that the instruments work well or are well-calibrated. For me that should be basic, having weather stations, trying to have the maximum number of stations and also in rivers to have adequate measures of their levels (INT3).

46. INT24b explains how the natural uncertainty of climate change and other factors make adaptation a complex task for the District Mobility Secretary:

When one wants to evaluate adaptation you need to evaluate also risk, flooding risk, rainfall risk, climatic models, the effects over vulnerable populations, and as you can see it already becomes a multidimensional problem in which many times we do not have information, and if it exists we do not know it or we do not know how to deal with it. Therefore, it becomes a much more complex problem (INT24b).

INT11a also comments on the complexity of dealing with climate change due to its associated uncertainty:

For example, whatever you analyse today tomorrow might change and with this topic of climate change, there is no one that has the absolute truth about if it is going to rain or not tomorrow (INT11a).

47. INT11a comments why he thinks Bogotá and Colombia do not have better information about the risks associated with climate change:

It would be nice if Bogotá and Colombia, in general, had already some areas diagnosed, I mean, a very serious and diligent study that says 'you should not design infrastructure in this way here and you should design in this way there'. […] So, most likely there are already studies, but we need to invest even much more money. I think that maybe that is the drawback (INT11a).

This quote also shows an example of an actor that is not well informed about which agencies are producing information about climate change and if there is the existence of this information. Another example of this can be found in note 46 in this appendix.

48. Refer to note 47 in this appendix.

49. Refer to note 41 in this appendix.

50. The following quote shows INT31's answer to the question "what is Bogotá currently doing regarding climate change action?":

I will say that very little, you know. [The administration of the city is] even going against basic criteria of climate change, such as building on the edge of the Bogotá river (INT31).

51. Refer to the examples provided in the main text.

52. Refer to note 9 in this appendix.

53. The following quote shows INT28's answer to the question "how would you define what adaptation actions are?":

Adaptation actions? (Interviewer: 'Yes'). Well, they are the actions that [the IDU] is beginning to take into account to manage the changes that are being generated by climate change, I mean, to be able to keep up with them, so we could ideally reduce the impacts that are being generated or manage them. That is how I understand it (INT28).

This shows that INT28 has apparently a good understanding of adaptation and what is the nature of adaptation actions. However, when immediately asked about which adaptation actions are being promoted by the IDU, INT28 begins to describe some types of environmental management action:

[The IDU] is always following regulations and makes the necessary demands to contractors. There are very general things, for example, like the management of construction materials and construction debris. […] Another example is the use of asphalt-rubber mixes (INT28).

54. INT12a describes the work done by the District Environmental Secretary in terms of adaptation to climate change:

Regarding adaptation, we work from the Management Department with the formulation of two ecosystem-based adaptation plans. Why ecosystem-based adaptation? Well, because it is compatible with the mission of this organisation. There are obviously different adaptation approaches, but for us, due to our mission we are more focused on ecosystem-based adaptation and inside the Development Plan we have some goals and some investment goals which are the formulation and implementation of two high impact ecosystem-based adaptation projects (INT12a).

55. Refer to the quote by INT21 in note 28 in this appendix.

56. INT2 explains about the need for more financial resources for the maintenance of road infrastructure in Bogotá:

Ok. So, I was telling you were are very limited in terms of financial resources. We are talking about a need of 11 billion Colombian pesos to be able to maintain and update the infrastructure. […] The resources we receive right now are not enough, they are about 100 thousand million Colombian pesos, that's all. So, [the city government] establishes some prioritisation models that definitively are not supported in any technical criteria (INT2).

57. The following quote shows INT14's answer to the question "what is limiting the implementation of systemic actions to infrastructure problems in Bogotá?":

Let's say that there is the first limitation. If you put a group of experts together, for sure the first thing they are going to point out is that there is a resources problem. They will say that there is no money for developing certain topics because there are other needs in the city that need to be attended. So, I will say that there is not only a lack of resources but in general, there is a problem with the conception of planning from the decision-makers (INT14).

In his interview, INT29, an engineer working in a private company, explains why he thinks that the IDU does not invest properly in the maintenance of road infrastructure in the city:

I think that they distribute the resources wrongly. They have too much bureaucracy and they waste the money in non-representative stuff, because the resources that the city collects were for it to have the road infrastructure in a perfect state and roads with excellent traffic, but the resources are either badly distributed or there is too much corruption or there is too much bureaucracy and all resources are gone in that. And later, there is too little left for real investment (INT29).

58. The following quote shows INT2's answer when asked why one of Bogotá's main roads keeps getting damaged and if it is because there is not enough technical knowledge about it in the IDU:

No, of course not. What I say is that we are not lacking technical knowledge what we are lacking is policies. We need a policy that truly says: "I will put resources for maintenance" (INT2).

59. INT15a explains the lack of a sustainable financial scheme for transport infrastructure maintenance in the city:

We do not have a sustainable programme for maintenance. […] When you ask: 'what financial sustainability does the road network of the city have?' I say a very small one. The road network of the city only receives money from the taxes over fuel. […] Those taxes collect around 400 thousand million Colombian pesos, and we only receive about 50% of that, in other words, we only get 200 thousand million Colombian pesos to do some maintenance when the city has a need for 8 billion Colombian pesos. That amount of money becomes, of course, useless because those 200 thousand million are spent in just covering potholes because dealing with them is what is most urgent (INT15a).

60. Refer to note 56 in this appendix.

61. INT15a describes what he thinks is a major problem in the organisational structure of the IDU:

Here in this organisation, you would find that there is a power structure where there is a central authority in the head and then everyone is below it, where only one person has this power is very difficult to work, and the benefit of this is debatable. We have not been able to implement here a project management structure, so we are able to make quicker decisions and be more effective (INT15a).

62. INT2 explains how the lack of up-to-date information regarding the physical state of road infrastructure makes it complicated to invest optimally in its maintenance:

Here they created a contract for the diagnosis of the physical state of the road infrastructure of the city. It started in January [2016], and they haven't finished it yet [in December 2016]. I mean, what they have surveyed from January is very different from what we have right now. […] So, I receive the reports and they tell me: "this road has this condition, needs this budget and needs only routine maintenance". When I go and check the road it is full of potholes. I cannot do just routine maintenance there. So, we have already a gap there in information, and the famous reports they send me only about half of them have good information, and the budget allocated thanks to that information is not enough for the real conditions of the roads (INT2).

63. INT30 explains the challenge of providing infrastructure in parts of the city that have an informal origin:

There is a very well-known neighbourhood, a very popular neighbourhood that has an informal origin, which is the Bilbao neighbourhood in Suba. This neighbourhood in a study we did in 2002, a study about the design of roads in the locality of Suba, established that in order to leave the road network in Bilbao in a perfect state it would cost us two times the annual budget of the entire locality. And we are talking that the locality has more than 200 neighbourhoods. So, here is where you can observe the huge necessities we have and the importance of not only doing contracts for building new roads, but also to do proper maintenance to the roads, which ultimately is cheaper, but there is not the habit of doing that (INT30).

64. INT15a explains why politicians do not try to create new taxes that can be used for investing in the road infrastructure of the city:

As a political candidate, I believe, if you are telling people 'we need to create a new tax in this city for the road network and we need to charge tolls for some roads with high traffic in the city' you will lose in the elections, you will lose because that is not popular, but that is the real necessity that the city has because as it is today the financial income is very bad, speaking only about infrastructure, is very bad against the real needs (INT15a).

65. Refer to the evidence provided in the main text.

66. Refer to the example provided in the main text.

67. The following quote shows INT38's answer to the question "what are the barriers that the city needs to overcome in order to begin thinking of climate change adaptation?":

I believe that the current administration, particularly the [District Mobility Secretary], is conscious about [adaptation]. I think that the principal obstacles are political, of time and of money. What do I mean by political? I mean that we have right now more important things to solve than adaptation to climate change, things that are more urgent and of more impact. And after that comes the fact that there is no time, I mean, that there is no technical staff, technical staff dedicated to that, and there is also no money. I think those are the principal obstacles (INT38).

68. INT12b explains that the current District Risk Management and Climate Change Plan – Bogotá 2015-2050 is being modified because originally it had overly ambitious goals:

[The District Risk Management and Climate Change Plan – Bogotá 2015-2050] is a very complete plan that right now is being updated and put in sync with the Development Plan, because the original risk management and climate change plan was ambitious in the sense that the city did not have the necessary funding at the time to be able to achieve all the high goals proposed for 2020, 2030 and 2050 (INT12b).

69. INT29 why it is challenging to have long-term planning of infrastructure in Bogotá:

Unfortunately, the mayors, as there is no continuity between them, some projects that are started by one are later thwarted by the next one. The next mayor does not continue the project and simply says 'that project is not what the city needs, it needs this other project' and if he does not finish it during his government, then the next mayor comes and says the same [and changes the project again]. So, there is no long-term planning of projects (INT29).

70. Refer to the examples provided in the main text.

71. INT19 expresses the need to change the national laws so Urban Master Plans become legally binding and are not superseded by the Development Plans:

For us is fundamental that the national law changes so that the Development Plans have to implement what the Urban Master Plans establish, so that Urban Master Plans become legally binding in more detail, because if they are not more binding we would never be able to have long-term policies. So, what happens today? […] The Development Plan of the administration that coincided with the development of the new Urban Master Plan is absolutely coherent with it. Then the next Development Plan will move away a bit from the Urban Master Plan and then the next one has nothing to do with it. So, we need the Urban Master Plan to actually be legally binding (INT19).

72. INT13 explains how complicated it can be to work on a neighbourhood road due to complicated institutional arrangements in the city:

It is also a headache to be able to intervene, for example, a road in a neighbourhood because responsibilities are not clear in the organisations. […] So, for instance, this neighbourhood road has to be fixed by the local mayoralty, but the local mayoralty can hire the UMV for doing this. But, something that no one knows, is that the UMV cannot work on the sidewalk. For example, the sidewalk is damaged: the sidewalk can only be intervened by the local mayoralty or the IDU, or the utility companies, or who knows who. So, it is a big problem to intervene a whole road and nobody can do it at the end (INT13).

73. INT18 explains the lack of real community participation in decision-making processes in the city:

That is also a huge limitation in adaptation policies here in Bogotá, processes are top-down. […] Fabio Sambrano is one of the authors that has worked more on the topic of popular participation, and he has analysed how most of the community participation in Colombia is extractive. What do [the government agencies] do? They invite people to a nice snack, they make them talk, they extract information from them, some priorities, they say goodbye and never they include really what people have proposed in these processes (INT18).

74. INT36 explains the lack of strong control institutions that regulate urban development in the city:

Bogotá, just to give you the scope of the magnitude, from its 39 thousand hectares more than 10 thousand are constructed in an informal way, a quarter of the territory has no property titles and of course no urban licences. It is a phenomenon where urban planning does not exist and where it is evident that roads are a phenomenon of chance […]. This puts in evidence the presence of a weak State that has no control and that, for now, one cannot see that it even has the will to become stronger. [We have a city] without urban police control, because the one that exists is pathetic, useless, 'a posteriori' and of very little use and effectiveness (INT36).

75. Refer to notes 26 and 34 in this appendix.

76. Refer to note 28 in this appendix.

77. INT26 explains the need for regulations and norms to make some actors take action regarding adaptation:

Not everything would need regulations to be developed, right? But in the public sector if I do not have regulations or norms that support me, then I do not do it, and that is a big issue. This is because if there are no regulations then it is not necessary, it will not be applicable, and when you do not have a need then the problems start and public servants leave the topic behind, they ignore it and prioritise other matters, not necessarily in that topic, and that is what happens in transport here (INT26).

78. Refer to note 41 in this appendix.

79. INT30 explains that climate action will have an important role in a local mayoralty just if the local mayor is a champion of the topic:

The environmental matters, particularly those related with climate change in the localities, the importance given to them is very conditioned to the proposal of the Development Plan, but I believe that it is more related with the importance that the manager of the local fund, the local mayor, gives to it (INT30).

80. Refer to note 69 in this appendix.

81. Refer to note 74 in this appendix.

82. INT31 explains the incongruity between the size of the population in Bogotá and the size of the staff administrating the city:

For example, Bogotá is almost like a country itself. For instance, the locality of Suba has more than a million inhabitants, which is almost as big as Uruguay, and it has a local mayoralty with only 10 public servants and I do not know how many contractors are checking that the construction companies comply with urban norms and construction regulations (INT31).

83. Refer to note 65 in this appendix.

84. Refer to note 63 in this appendix.

85. Refer to the evidence provided in the main text and in notes 86 to 89 in this appendix.

86. INT22 explains his experience trying to promote new technologies in the city when he worked with IDIGER:

Technology changes are required with climate change because we cannot continue using the same techniques. So, for example, those changes are difficult, they were difficult to accept. There was a huge resistance in Bogotá to them (INT22).

87. INT4 explains in the following quote which technologies private companies can use when working for the public sector:

We cannot use other types of tools or techniques because contractually we are not allowed, yes? Because that means more costs. […] So, the techniques we use, all of them, are standardized by the public organisations we work with (INT4).

88. Refer to note 86 in this appendix.

89. INT22 explains that there was strong opposition to technological changes in the way the city was going to maintain the road network when he was working for the Gustavo Petro's administration because:

The matter was not only about the way in which hiring was done, but what really was behind it, what you can see there, was the business opportunity that was behind that and the interests of some individuals of guaranteeing that the technology used for maintaining the road network was exclusively one and no other (INT22).