A Streetcar Named Progress: Systems Analysis of Sustainability Transitions for Low-Carbon Urban Transport

by

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Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Matthew Flower Date: 24 October 2019

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Abstract

Cities represent a promising opportunity for climate change mitigation, however current research suggests that they are not realising their full climate action potential. Research is urgently required that investigates specifically *how* to generate enduring change around low-carbon urban outcomes, in addition to developing the evidence base around effective and appropriate interventions for decarbonising urban systems. The IPCC and other international organisations have identified transport as an urban system high on the priority list for decarbonisation. Urban transport's sectoral emissions profile is already significant, and demand for transportation in cities is set to grow as the global trend toward urbanisation continues.

Hence, this study focuses on the decarbonisation of urban transport systems, with the medium-sized city of Canberra, ACT, Australia as its case study. To underpin the modelling and analysis in this study, a fuzzy cognitive map (FCM), was developed on the basis of interviews with various city-level actors in Canberra. The FCM itself is an important output of this study. It offers the literature, and policymakers, knowledge about the complex relationships between transport policy interventions and their outcomes, as well as providing a strong basis for further qualitative and quantitative analysis. This study's FCM identifies a broad range of climate policy interventions for low-carbon transport across four themes – vehicle electrification, transport infrastructures, urban development, and market forces. Moreover, it identifies the triggers, linkages, feedbacks, dynamics, and causal influences on the 'core transitions engine' of these interventions.

A key finding of this study is that city governments have an unequivocally important role throughout low-carbon transition processes in urban transport systems. Although interventions led by industry bodies may provide city governments with mechanisms for implementing climate policy interventions with less expenditure of their own political and financial capital, leveraging mechanisms that rely primarily on the private sector to progress climate policy interventions is often neither effective nor appropriate. As an example, this study found that prioritising the outcomes of light rail projects to benefit private urban developers risks generating perverse outcomes for low-carbon transport.

Notwithstanding the above caveats, this study finds that the private sector does have jurisdiction over certain interventions for low-carbon transport which have the capacity to be both effective and appropriate. The main example identified by this study is the building up of 'electric car culture', which supports the mainstreaming of buying an electric car. However, even here, city governments have a role in facilitating the private sector's transport intervention by providing associated infrastructures (e.g. charging facilities and other planning provisions). Otherwise, the effectiveness of the private sector's intervention is noticeably reduced.

In terms of practical implications for policymakers, this study identified five key leverage points which represent effective city government –led interventions for low-carbon urban transport, as well as an accompanying discussion regarding their appropriate implementation. These leverage points relate to the intervention themes of vehicle electrification, transport infrastructures, and urban development.

This study contributes to the urban climate policy and sustainability transitions literatures, by adding to the evidence base of how to build low-carbon transport systems that promote sustainable urban futures

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Glossary, Terms, and Abbreviations

ACT – Australian Capital Territory

Active Travel – walking, cycling, and other human-powered forms of movement for transportation purposes

Driver/Trigger – A factor or event which causes an action to be taken

Edge – (in graph theoretic terms,) a link between two nodes

FCM – Fuzzy Cognitive Map (Kosko, 1986)

Graph – (in graph theoretic terms,) a mathematical representation of nodes and edges

Infrastructure – Services (e.g. a bus service) or Facilities (e.g. light rail tracks)

Intervention – an action, or a mechanism used to direct the outcome or effects of a given action

IPCC – Intergovernmental Panel on Climate Change

Low-carbon transition – the process of decarbonising systems in human societies

LP – Leverage Point

Meet travel needs – The capacity of a transportation mode to support the journeys which make up a life – e.g. work, education, recreation, shopping

MLA – Member of the Legislative Assembly (ACT Government)

Mobility – Transport

Mode – A form of travel (i.e. bus, light rail, car as driver, walking, cycling)

Node – a point in a graph, which may represent a concept or variable

Positive inertia – An emergent property of a system, wherein sustainable outcomes have become embedded within (‘locked in’ to) a system, creating a sustainable development trajectory that is difficult to sway away from (Irvine and Bai, in press)

Shared vision – the capacity of the community at large to ‘buy-in’ to a strategy, plan, or series of interventions

Sustainable Modes – Non-car modes of transportation

Transit – Public transport modes (i.e. buses, light rail etc.)

Urban intensification – The co-location of homes, jobs, and activity centres in dense urban nodes

Chapter 1: Introduction

1.1 Urban Transport: An Opportunity for City-led Climate Action

The Intergovernmental Panel on Climate Change (IPCC) presents strong evidence stating that unmitigated climate change will have increasingly widespread and irreversible impacts on natural and human systems around the world, including a warming planet, threats to human health, security, and livelihoods, more frequent and intense extreme weather, and destruction of ecosystems (IPCC, 2014a). It is also clear that human-induced greenhouse gas (carbon/GHG) emissions are a dominant cause of global warming, which leads to climate change (IPCC, 2014a). However, evidence points to reduced climate-related risks to natural and human systems under scenarios where the total extent of global warming is more limited, in particular, 1.5°C instead of 2°C (IPCC, 2018). Thus, despite some amount of climate change being inevitable, the opportunity to limit its impacts offers a powerful reason to act.

In terms of assessing opportunities for mitigating climate change, it is important to recognise that we live in an urban century (Elmqvist, 2018; Mi *et al.*, 2019). Global populations, resource use, and emissions are increasingly concentrated in urban areas (Hoornweg *et al.*, 2016). Around 55% of the world's population already live in urban areas, with this number projected to reach 68% by 2050 (UN DESA, 2018). The ways in which we manage the carbon footprint of urban populations, for both existing residents and those moving into cities as a result of urbanisation, will have a defining impact on global sustainability and prosperity (Mesener, 2017; Bai *et al.*, 2018). If carbon emissions are not successfully decoupled from the population growth and resource-use pressures of urbanisation, the Paris Agreement's 1.5°C warming target will be exceeded (McPhearson *et al.*, 2016; Bai *et al.*, 2018; Solecki *et al.*, 2018; Victor *et al.*, 2018).

High hopes have been expressed about the capacity of city governments, and other city-level actors, to take action on climate change, particularly given the reticence of many national governments to lead the way (Watts, 2017; CitiesIPCC, 2018; van der Heijden *et al.*, 2019). Cities themselves are also indicating their willingness to stand up and be leaders (Bulkeley *et al.*, 2012). Over 2000 cities are signatories to the Global Covenant of Mayors for Climate and Energy, a city climate action network (Kona *et al.*, 2018). A hundred cities, some of them the world's largest, committed to net-zero carbon emissions by 2050 at the UN Climate Summit in September 2019 (UN Secretary-General, 2019). Yet van der Heijden *et al.* (2019) cautions against treating cities as something of a panacea in the fight against climate change, as many scholars argue that cities still lack the capacity to bring about enduring transitions toward sustainable and low-carbon urban futures (Castán Broto *et al.*, 2019; Hölscher *et al.*, 2019; Huxley *et al.*, 2019; van der Heijden *et al.*, 2019; Wolfram *et al.*, 2019).

Against this backdrop, cities face complex and interrelated challenges in their efforts to mitigate climate change, spanning equity, resilience, infrastructural and economic development, and urban ecological restoration, among others (McPhearson *et al.*, 2016). These challenges cut across the boundaries of urban systems, from transport to urban development and energy, each of which may be locked into their own unsustainable development trajectories (Markard *et al.*, 2012; Köhler *et al.*, 2019).

Among these urban sustainability challenges, the IPCC recognises that decarbonising urban transport systems is a priority (IPCC, 2018). In 2010, urban transportation accounted for 11.2% of all global end-use energy (IEA, 2012; IEA, 2013). Around 75% of all transport emissions are generated by private road transport (SLoCaT, 2018). Meanwhile, continued growth in demand for passenger and freight transport threatens to outweigh existing mitigation measures (IPCC, 2014b). This presents challenges for transitions toward low-carbon transport systems, given that many cities in OECD countries remain 'locked-in' to private car travel (Berger *et al.*, 2014). The ability of the global transport sector to meet its emissions reductions targets is coupled to the outcomes of efforts to mitigate urban transport emissions (Creutzig *et al.*, 2015). Thus, research into how to decarbonise urban transport systems is urgently needed (Mi *et al.*, 2019).

Full decarbonisation of urban transport will require the overhaul of several related sub-systems, including the propulsion technologies of the vehicles themselves, and their associated infrastructures and energy systems (Berger *et al.*, 2014; IPCC, 2014b; IPCC, 2018). Successful transitions, i.e. enduring change, toward low-carbon urban transport will therefore depend on policy and infrastructure interventions that can address all unsustainable aspects of the transport system (Berger *et al.*, 2014). This study considers an 'intervention' to be one of two things: (1) an action (e.g. the decision to build a light rail system, or to redesign the bus network), or (2) a mechanism that produces a directed outcome (ensuring that the light rail system provides equitable coverage of a city, or that the new bus network makes better use of operational resources).

1.2 Research Scope

This study has two main aims. Aim 1 is to identify how city actors can create enduring change toward low-carbon urban transport systems, that is, helping low-carbon outcomes to become self-reinforcing. Aim 2 is to develop policy-relevant insights about the effectiveness and appropriateness of different city-led interventions for low-carbon transport. In order to address these aims, three research questions have been developed. An overarching research question frames the study. Research questions RQ1 and RQ2, corresponding to *Aims 1 and 2*, respectively, form the basis of the analytical work.

Overarching research question:

- How, and to what extent, can city-level actors create meaningful progress toward decarbonising urban transport systems?

Analytical research questions (RQs):

- RQ1: In what ways do the activities of city governments and private sector bodies shape the dynamics of low-carbon transitions within urban transport systems?
- RQ2: How do different scenarios, which represent packages of city government policy and other city-level interventions, affect progress toward low-carbon urban transport objectives?

To underpin this study's response to these aims and research questions, two methodological considerations will be followed: the use of systems approaches (methodological consideration 1), which relate primarily to RQ1, and the development of quantitative storylines based on scenario analysis (methodological consideration 2), which relate primarily to RQ2. Section 2.2 expands on the rationale for these aims and methodological considerations.

1.3 Research Approach and Theoretical Grounding

This research is designed around a case study focusing on Canberra, Australia. Canberra was chosen because of its recognition as a leader in urban climate change mitigation, including in the urban transport sector.

In terms of research methods, this study uses the Fuzzy Cognitive Map (FCM) technique (Kosko, 1986). Integrating both qualitative and quantitative approaches, the FCM is a form of decision support and systems thinking tool which facilitates the formal modelling of mental models depicting causal relationships (Özesmi and Özesmi, 2004; Jetter and Kok, 2014; Doukas and Nikas, 2020). FCMs help to illustrate the interlinkages between variables in complex systems, and have the capability to quantitatively model different scenarios, such as those relating to urban climate policy interventions (Jetter and Kok, 2014; Olazabal and Pascual, 2016).

Analytically, this study draws on concepts from the field of sustainability transitions (Geels, 2002). Within this field, this study will apply the newly-defined concept 'positive inertia' (Irvine and Bai, in press) as an analytical framing for interpreting the final FCM. The concept of positive inertia refers to the situation wherein low-carbon outcomes have become 'locked-in' to a city's development, and it has become difficult to sway from a sustainable trajectory (Irvine and Bai, in press).

1.4 Thesis Outline

This study has seven chapters. Chapter 2 provides a rationale for aims and methodological considerations, reviews relevant concepts in sustainability transitions and low-carbon urban transport, and expands on FCMs. Chapter 3 provides a rationale for the choice of Canberra as the case study city, and explains the research methods, data collection, and data analysis approaches used in this project. Chapter 4 presents the FCM for Canberra's low-carbon mobility transition. Chapter 5 presents quantitative modelling results of policy intervention scenarios based on the FCM. Chapter 6 discusses key findings and insights from the study in light of the research questions, before evaluating limitations, and opportunities for further work. Finally, Chapter 7 offers concluding remarks.

Chapter 2: Literature Review

This chapter provides an overview of the literature and research gaps as they relate to the study of urban sustainability transitions. The importance of sustainability transitions within urban transport systems in particular, as well as the value of complex systems methods to the study of urban processes, will be highlighted. In addition, the rationale for this study's aims and methodological considerations will be discussed with respect to emerging research agendas identified in the literature.

2.1 Sustainability Transitions

Much of the current literature which focuses on societal transitions toward low-carbon futures is part of the field known as 'sustainability transitions' (Geels, 2002; van den Bergh *et al.*, 2011; Markard *et al.*, 2012; Geels *et al.*, 2017; Köhler *et al.*, 2019). A sustainability transition is the process of socio-technical systems – e.g. transportation or energy – undergoing radical change, wherein unsustainable practices are replaced by the emergence of more sustainable production and consumption patterns (Markard *et al.*, 2012).

The main objectives of a sustainability transition could be considered as meeting the needs of future world populations whilst meeting people's basic needs and maintaining the planet's crucial life-support systems; this could include reducing GHG emissions, reducing land cover change, or promoting biodiversity (Parris and Kates, 2003). In conjunction with these objectives, the core aim of sustainability transitions research is to explain, and provide context for, how society can realise radical changes in the way it fulfils these needs (Köhler *et al.*, 2019). Thus, low-carbon transitions can be considered a particular type of socio-technical transition (Geels *et al.*, 2016; Geels *et al.*, 2017); this study will focus on low-carbon transition.

Research into sustainability transitions is also about examining the (dynamic) stability and (radical) change of socio-technical systems (Geels, 2012). Thus, 'triggers' are relevant to this discussion. Triggers are events and factors which catalyse various actors to take action, or otherwise establish initial momentum, towards addressing a problem or issue (Bai *et al.*, 2010; Irvine and Bai, in press).

Sustainability transitions generally involve a wide range of actors, from individual consumers, to academia, civil society, and public and private sector organisations (Geels *et al.*, 2017). Each has particular interests and values, and varying levels of power and agency, thus possess differentiated capacities to enable or constrain transition processes (Geels, 2014; Avelino, 2017; Huxley *et al.*, 2019). Socio-technical systems also consist of multiple elements, such as technologies and infrastructures, cultural values, and individual behaviours, that develop in co-evolutionary ways (Köhler *et al.*, 2019). These processes of co-evolution can reinforce each other, creating unsustainable path dependencies (Geels, 2012; Berger *et al.*, 2014).

Sustainability transitions are therefore contested and have open-ended outcomes, which may play out over timeframes of multiple decades (Köhler *et al.*, 2019). Thus, an ongoing research challenge is to identify patterns and typologies in the transition processes of socio-technical systems across time and space (Geels and Schot, 2007; Köhler *et al.*, 2019). Moreover, it clear that cities are, and will continue to be, a key arena for tackling climate change and other global sustainability challenges – and that these challenges represent wicked problems requiring intensive further study (Clark, 2003; Grimm *et al.*, 2008; Solecki *et al.*, 2018; Wolfram *et al.*, 2019).

2.2 Emerging Research Needs for Urban Sustainability Transitions

With respect to advancing sustainability transitions in cities, many scholars are calling on the urban research field to foster scientific leadership in the design and evaluation of global urban policy (McPhearson *et al.*, 2016; Acuto *et al.*, 2018; CitiesIPCC, 2018). The design of effective urban climate policy requires cities to draw from a strong evidence base, which can be significantly strengthened by fit-for-purpose research (McPhearson *et al.*, 2016; Acuto *et al.*, 2018; CitiesIPCC, 2018; Wolfram *et al.*, 2019). Otherwise, not only will cities fail to make the necessary emissions reductions to enable the meeting of Paris Agreement targets, but it will not be possible to meet the urban sustainability goals of multilateral forums such as UN-Habitat and the New Urban Agenda (McPhearson *et al.*, 2016). Additionally, Hughes (2017) argues that researchers need to further unpack the political dimensions of urban climate policy. This confirms the relevance of RQ1, since one of these dimensions is the identification of key mechanisms and actions pursued by various actors to enable or constrain the design and implementation of urban climate policy (Hughes, 2017).

Fulfilling the mandates proposed by McPhearson *et al.* (2016), Hughes (2017), and Acuto *et al.* (2018) will require addressing the research gaps that exist across many aspects of urban governance and urban climate action research, as well as keeping up with city actors' constantly evolving engagement with climate policy (McPhearson *et al.*, 2016; Hughes, 2017; Acuto *et al.*, 2018; CitiesIPCC, 2018).

2.2.1 Urban Climate Policy Design

A key research gap in the design of urban climate policy is that urban climate governance activities often fail to create enduring change within urban systems (van der Heijden *et al.*, 2019; Irvine and Bai, in press). There are a range of explanations, including the breakdown of collaborations between different levels of government or city governments and other local actors, as well as the adoption of conflicting policy priorities or pathways by new city governments (van der Heijden *et al.*, 2019; Irvine and Bai, in press). Creating change that endures is critical to the success of sustainability transitions, as a lack of continuity in urban climate policy interventions increases the risk that a city's development pathway could be steered away from sustainable trajectories (Elmqvist *et al.*, 2019; Irvine and Bai, in press). This underscores the relevance of *Aim 1*, which seeks to explore the issue of how cities can implement climate policy interventions that lead to enduring change in urban transport systems.

In addition, there is the problem that city-led policies and interventions for climate change mitigation often rely on an inadequate evidence base, or are otherwise not well integrated within broader efforts to achieve radical shifts in unsustainable urban systems (McPhearson *et al.*, 2016; Acuto *et al.*, 2018). On this basis, Acuto *et al.* (2018) calls for the building of a 'global urban science' that is capable of both doing the research needed to address urgent urban sustainability challenges, and building stronger interconnections between science and policy. Central to this is the development of new and better knowledge about effective and appropriate urban climate policy interventions, which can then be formulated as actionable advice for urban policymakers (Acuto, 2018; Acuto *et al.*, 2018). This underscores the relevance of *Aim 2*, which seeks to produce insights about the effectiveness and appropriateness of different city-led interventions for low-carbon urban transport.

2.2.2 Methodological Considerations

In terms of research methodologies for addressing aims 1 and 2, Bai *et al.* (2016) and CitiesIPCC (2018) argue for the application of systems approaches to the exploration of solutions for urban climate change mitigation. Cities are complex systems, and their behaviours can display emergent properties, as well as non-linear dynamics (Bai *et al.*, 2018). To capture the full complexity of these processes, it is valuable to conceive of cities as systems, composed of many networks and flows (Batty, 2013). Systems approaches can help generate knowledge on key interactions, interdependencies, causal relationships and resource flows between social, infrastructural, and natural systems, which then aid in the design and implementation of urban climate policy (Bai *et al.*, 2016; Bai *et al.*, 2018; CitiesIPCC, 2018; Ürge-Vorsatz *et al.*, 2018). Hence, *Methodological Consideration 1* of this study will be the use of systems approaches.

In addition, CitiesIPCC (2018) and van der Heijden *et al.* (2019) draw attention to the value of alternative research methods for opening up new directions in urban climate scholarship. Examples include FCMs (Kosko, 1986), which remain underexplored in studies that analyse human-technological ('socio-technical') systems such as transport and energy (Papageorgiou and Salmeron, 2012; Doukas and Nikas, 2020), as well as studies which model the consequences of current decisions on the future (Jetter and Kok, 2014). An important consideration for these methodologies is that they engage with storylines which are built on quantitative models, as these are able to provide more credible insights into the long-term implications of climate policy interventions (Doukas and Nikas, 2020). Moreover, quantitative storylines can help support decision-makers in the design and implementation of urban climate policy (Doukas and Nikas, 2020), for example, by suggesting appropriate prioritisation for urban climate interventions, or assessing the co-determinants and unintended consequences of urban change (Acuto *et al.*, 2018). Hence, *Methodological Consideration 2* of this study will be the use of research methods that offer quantitative insights into the long-term impacts of climate policy interventions.

2.3 Transitions toward Low-Carbon Urban Transport

'Sustainable Mobility' (i.e. sustainable transport), as a policy goal, was first introduced in a 1992 EU Green Paper (European Commission, 1992). Yet, three decades on, the world has still not achieved widespread change toward sustainable transportation (IPCC, 2014b; SLoCaT, 2018; Holden *et al.*, 2019). Globally, transport is the third-largest GHG emitter; transport emissions in Oceania are staying steady, they are decreasing in Europe and North America, and increasing in the rest of the world (SLoCaT, 2018).

One explanation for this lack of progress is that creating a low-carbon transport system requires a highly multifaceted approach. Berger *et al.* (2014) highlights that advancing sustainability transitions within transport necessarily requires the overhaul of multiple sub-systems – including the transport vehicles themselves, infrastructure, and energy systems. Moreover, debates over the meaning of 'sustainable mobility' as a goal, i.e. what constitutes a desirable transport future, can also dilute the ambition of system actors (Berger *et al.*, 2014; Gössling *et al.*, 2018). Sustainability transitions in transport also rely heavily on user adoption, which in turn depends on behaviour change; this is difficult enough before considering the diversity of users, who each have different needs (Berger *et al.*, 2014). This highlights the particular challenges of decarbonising urban transportation (Holden *et al.*, 2019).

In their systematic literature review on sustainability transitions toward low-carbon urban transport, Nikulina *et al.* (2019) found that most studies focused on planning aspects – asking "who" and "what" questions that relate to stakeholders, actions, and priorities. Planning is indeed relevant to transitions, as planning can enable or constrain transition efforts through a variety of mechanisms (Carroli, 2018). However, planning research does not address the core aim of sustainability transitions research – examining *how* to achieve transitions toward sustainable mobility, and critically, how to accelerate this process (Geels *et al.*, 2017; Köhler *et al.*, 2019; Nikulina *et al.*, 2019). Of the 154 texts (articles, books, and manuscripts) identified by Nikulina *et al.* (2019), only 7 could be considered relevant to future-oriented sustainability transitions in personal mobility. Given the current laggard state of the sustainable transport transition and the limited available literature, transport presents an important and urgent focus area for further research within the broader theme of urban sustainability transitions.

2.4 Methods and Concepts for Complex Systems Analysis

2.4.1 The Fuzzy Cognitive Mapping (FCM) Approach

The Fuzzy Cognitive Map (FCM), first proposed in Kosko (1986) and Kosko (1988), is a modelling technique that is consistent with both *Methodological Considerations 1* and *2* of this study. FCMs extend the cognitive mapping methods developed by Tolman (1948) by making them computable (Jetter and Kok, 2014). Contemporary cognitive mapping methods are often referred to as 'causal loop diagrams' or 'influence diagrams', as discussed in Dyball and Newell (2014). Similar to cognitive maps (Dyball and Newell, 2014), FCMs are built on mental models, consider system dynamics such as feedbacks and causal relationships, and have the potential to uncover hidden patterns or unintended consequences that arise from dynamical system behaviours (Kosko, 1986; Kosko, 1988; Özesmi and Özesmi, 2004; Jetter and Kok, 2014).

FCMs are represented by graphs which are signed, weighted, and directed, consisting of two key elements: variables that represent measurable concepts, and weighted directional links (edges) between variables that represent causal relationships of varying strengths (Kosko, 1986; Jetter and Kok, 2014). Unlike cognitive maps, FCMs contain causal relationships which are "fuzzy"; while they are allowed to be given binary 'active' (1) or 'inactive' (0), the unique aspect of FCMs is that each causal relationship can be assigned a state in-between 0 and 1 (Jetter and Kok, 2014). This gives rise to so-called 'fuzzy causality'. The information about the presence and absence of causal relationships between every pair of variables, as well as their link strengths (edge weights), is captured in an adjacency matrix (Kosko, 1986).

A particular strength of FCMs is that they can be used to explore potential futures (Jetter and Kok, 2014; Olazabal and Pascual, 2016). FCMs facilitate the development and testing of any number of scenarios representing different sets of policies and interventions. These are captured by varying the input vector of drivers to the system; the input vector's numeric values correspond to the size of the perturbation in each modelled variable (Jetter and Kok, 2014; Olazabal and Pascual, 2016; Zhang and Jetter, 2018). The perturbations in each variable then propagate through the FCM, according to the presence and weights of the causal relationships in the FCM (Kosko, 1986; Jetter and Kok, 2014). Thus, the output of FCM scenario modelling offers quantitative insights into the dynamic properties, possible future states, and instabilities of modelled systems (Jetter and Kok, 2014; Gray *et al.*, 2015). This makes them suitable for studying the 'core puzzle of transitions' – (dynamic) stability and (radical) change (Geels, 2012). Because of these capabilities, the use of FCMs support *Aims 1* and *2* of this study, as well as the broader goals of sustainability transitions research.

FCMs can be generated in a number of ways. Kosko (1986) conceived of FCMs as tools for building knowledge, wherein the aggregate knowledge-base represented by an FCM is arrived at by combining the cognitive maps of multiple knowledge sources (see figure 2.1, reproduced from Olazabal *et al.* (2018)).

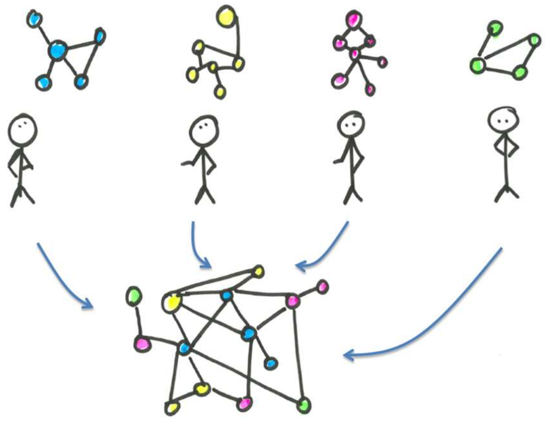

Figure 2-1: Graphic representation showing that an FCM is an aggregation of the individual cognitive maps produced by different people or knowledge sources. Reproduced from Olazabal *et al.* (2018).

Jetter and Kok (2014) identify that the literature suggests three main methods for eliciting knowledge to build FCMs: the modeller acting as the expert, holding participatory workshops or interviews with experts, and modeller-led analysis of documents. These methods can be combined to overcome issues of data or expert availability, as well as to balance the merits of each approach (Jetter and Kok, 2014). Özesmi and Özesmi (2004) make the comment that the analysis of many kinds of environmental problems can be improved through modelling people's knowledge.

In terms of research into sustainability transitions, the review paper Doukas and Nikas (2020) identifies just four FCM studies relevant to transportation. Of these, only one is within the domain of urban transport. The study, Shiau and Liu (2013), modelled sustainable transport at the city level in Japan. They present an FCM with 10 variables, which relate to the emissions intensity of vehicles, transport infrastructure in remote areas, the mobility of the elderly, and traffic accidents. However, with respect to academic reviews of city-led climate change mitigation strategies (cf. Deetjen *et al.*, 2018; Reckien *et al.*, 2018), there are notable absences in the variable set considered by Shiau and Liu (2013). These include variables that the literature considers pertinent to the decarbonisation of urban transport, such as compact urban development (Ewing and Cervero, 2017; Nelson, 2017), active travel – i.e. walking and cycling (MacMillen *et al.*, 2010; Pucher and Buehler, 2017), and economic disincentives for car travel (Ubbels and Verhoef, 2006; Li and Hensher, 2012; Elvik and Ramjerdi, 2014). Another issue is that while Shiau and Liu (2013) address *Aim 2* of this study, they do not address *Aim 1* at all.

Clearly, there is a dearth of FCM-based urban transport studies. Moreover, there are key limitations in the one available study, in that it omits modelling several potentially relevant variables, and does not address *Aim 1* of this study – which was developed on the basis of a critical emerging research need identified in the literature. Thus, these findings highlight a clear opportunity for further studies, like this one, which use FCMs to investigate the decarbonisation of urban transport systems (see chapter 3).

2.4.2 Positive Inertia

Within the domain of low-carbon urban transport, there are a range of different interventions which have the potential to progress the objectives of sustainability transitions (Walker, 2012; Berger *et al.*, 2014; IPCC, 2014b; Creutzig *et al.*, 2015). However, it is relevant to note that many such actions require continued investment and development to achieve meaningful progress toward low-carbon urban transport outcomes. For example, abandoning the development of light rail or bus rapid transit (BRT) service after only a small section is completed would likely have little impact on the travel patterns of an entire city. This is because public transport services generally need to form comprehensive networks in order to maximise their utility to the most number of people, and the largest variety of trips people may need to take, thus inducing travellers to shift toward the more sustainable public transport services (Mees, 2009; Walker, 2012; Mees, 2014).

The initial momentum for these transport policy or infrastructure interventions could take years to build up. In addition, this initial momentum must be maintained throughout the time lags between successive stages of a major transport infrastructure intervention, such as building a city-wide light rail network. Thus, delays in the process of implementing multi-stage policy or infrastructure interventions for sustainable transport make these interventions vulnerable to factors such as changing public attitudes and local government electoral cycles (Irvine and Bai, in press). Scholars posit that the development pathways of climate policy interventions must be made resilient and enduring, so that it is difficult for them to be destabilised by these kinds of external shocks (Elmqvist *et al.*, 2019; van der Heijden *et al.*, 2019; Irvine and Bai, in press).

On this basis, Irvine and Bai (in press) propose the new concept 'positive inertia'. Positive inertia is an emergent system property, which arises from the situation wherein sustainable, or low-carbon in the context of this study, outcomes have become self-reinforcing. Irvine and Bai (in press) explain that the emergence of positive inertia requires both an initial momentum, and for this initial momentum to become self-reinforcing through a series of positive feedback loop dynamics. The emergence of positive inertia increases the likelihood that the low-carbon objectives of climate policy interventions are fully realised, as positive inertia represents the difficulty of disrupting the transition toward a low-carbon future (Irvine and Bai, in press). Thus, the analysis of positive inertia, in the dynamics of transitions toward low-carbon urban transport, supports *Aim 1*.

2.5 Summary of Research Gaps

There is little doubt that advancing sustainability transitions in cities is crucial for meeting the ambitions of global climate change mitigation targets – i.e. the Paris Agreement, as well as agendas for urban sustainability, such as the New Urban Agenda (McPhearson *et al.*, 2016; Watts, 2017; Acuto *et al.*, 2018; Solecki *et al.*, 2018; Wolfram *et al.*, 2019). Moreover, it is clear that the decarbonisation of urban transport will be a crucial element of urban sustainability transitions (Creutzig *et al.*, 2015; IPCC, 2018; Mi *et al.*, 2019). Yet, within the literature on sustainability transitions for urban transport, very few studies examine *how* to bring about transitions toward low-carbon transport (Nikulina *et al.*, 2019).

Moreover, *Aims 1 and 2*, as well as *Methodological Considerations 1 and 2*, were identified in the literature as being key research gaps in the research and evidence base for urban sustainability transitions and urban climate policy interventions (McPhearson *et al.*, 2016; Acuto *et al.*, 2018; van der Heijden *et al.*, 2019; Irvine and Bai, in press). As outlined in this literature review, FCMs appear to be a research method which is well-suited to addressing these aims and methodological considerations. Yet, Doukas and Nikas (2020) were only able to find one FCM-based study relevant to sustainability transitions in urban transport – Shiau and Liu (2013), which has a number of limitations as discussed. This presents a clear opportunity for this study to adopt the FCM-modelling approach, and apply it to addressing the research gaps (aims) identified by this literature review.

Chapter 3: Case Study and Research Methods

This chapter introduces the case study and research methods for this study. First, a rationale is provided for the choice to focus on Canberra, Australia, and the ACT's governance arrangements are outlined. Following this, the methods applied to building and testing the FCM are discussed, including knowledge (data) capture, and undertaking quantitative scenario analysis on the basis of the FCM.

3.1 Canberra, Australia as the Case Study City

The primary reason for choosing Canberra, in the Australian Capital Territory (ACT), as the case study is that Canberra's climate action leadership at the city level is recognised by both national (Corbell, 2015) and international (Rattenbury, 2016) organisations. A medium-sized city with a population of around 420,000 people (ACT Government, 2019c), Canberra has committed wholeheartedly to decarbonisation. To exemplify, the ACT Legislative Assembly acknowledged a climate emergency in May 2019 (ACT Legislative Assembly, 2019), and has a legislated target for net-zero emissions territory-wide by 2045 (ACT Government, 2017). As of October 2019, the ACT has also achieved its 100% net renewable energy target (Rattenbury, 2019). Additionally, the ACT Government recognises transport as a critical sector for decarbonisation to meets its net-zero emissions goals (ACT Government, 2017), which is relevant to the scope of this study. This ambition is a clear part of the territory's strategic transport plan *Moving Canberra 2019-2045* (ACT Government, 2018) and climate change plan *The ACT Climate Change Strategy 2019-25* (ACT Government, 2019a). The *ACT Climate Change Strategy* is the key government strategy charting the course to a net-zero carbon future, and encompasses the critical actions from sector-related strategies such as *Moving Canberra.*

Canberra's leadership in climate action makes it highly suitable as a case study choice, since Canberra has motivated city-level actors who are actively engaged in progressing urban sustainability transitions. This means that they are building up knowledge, experience, and best practices which may generate relevant insights for other cities which, as the introduction and literature review have identified, may be struggling with putting their climate action aspirations into the creation of tangible, enduring change in their unsustainable urban systems.

A second reason is that transport-related case studies of small-to-medium sized cities are critically underrepresented in the urban climate solutions literature (Lamb *et al.*, 2019), despite cities of this size being home to some of the most pressing urban challenges (McPhearson *et al.*, 2016; Lamb *et al.*, 2019). That Lamb *et al.* (2019) identifies redressing this gap in case study knowledge as a priority strengthens the case for this study to focus on transport in Canberra.

3.1.1 Governance Arrangements in the ACT

Canberra, the primary urban area of the ACT and Australia's capital city, has a unique governance structure. The ACT Government has a single elected decision-making body, the Legislative Assembly, composed of 25 Members of the Legislative Assembly (MLAs) who are elected every four years (Access Canberra, n.d.). Meanwhile, the ACT Government's functions are split amongst a number of directorates. Collectively, the ACT Legislative Assembly and ACT Government's directorates are responsible for governance and service provision at both the local government and state/territory levels (Access Canberra, n.d.). Within the transport domain, the ACT Government is responsible for operating, planning, and investing in the road, public transport, and active travel systems; they are the operator of all ACT public buses, and procure private operators for the running of light rail services (Transport Canberra, n.d.).

3.2 Building the Fuzzy Cognitive Map (FCM)

To engage with this study's research questions, aims, and methodological considerations, this study adopts the FCM approach as its core research method. The method for building the FCM used by this study, hereafter referred to as the study FCM, is consistent with the approaches outlined in Jetter and Kok (2014) and Olazabal *et al.* (2018). These include the following key steps: clarifying the project objectives, planning and executing a knowledge elicitation strategy, aggregating, calibrating, and testing the FCM, and using the final FCM model for scenario modelling and interpretation of the FCM's system dynamics (Figure 3-1).

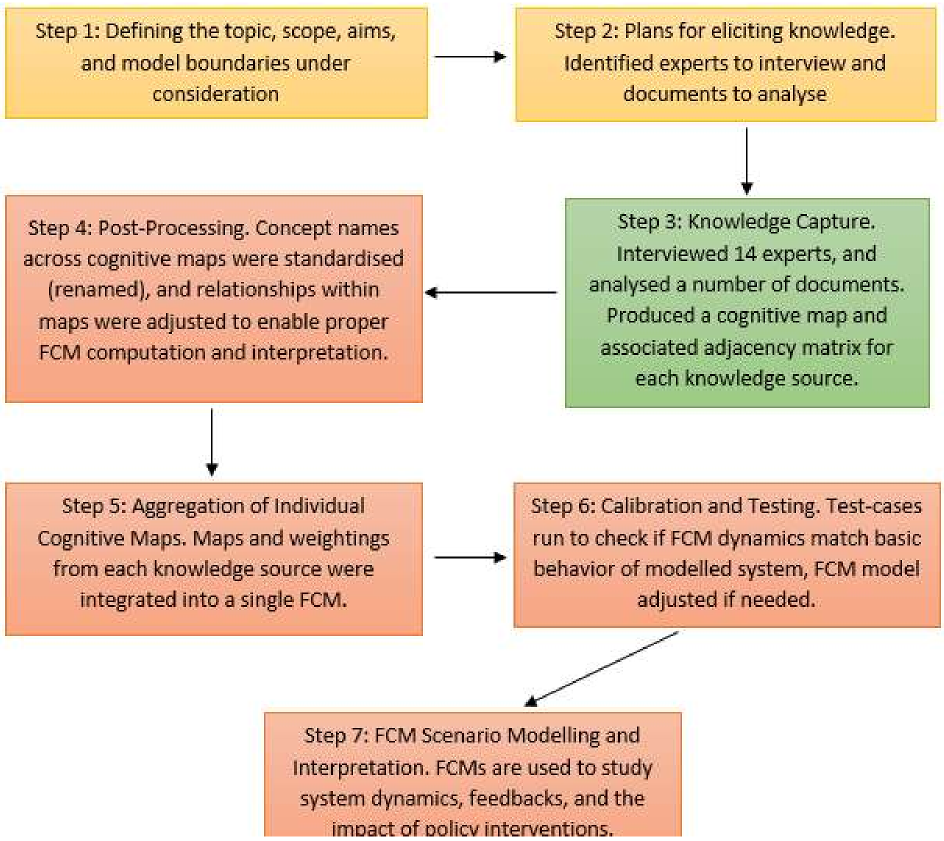

Figure 3-1: Flowchart of research method followed for building the study; method and steps adapted from Jetter and Kok (2014) and Olazabal et al. (2018).

3.2.1 FCM Step 3: Knowledge Capture

Step 3 of the FCM-building process (Figure 3-1) requires knowledge to be captured, to be used as knowledge sources for the FCM. Many FCM modelling studies use some form of respondent interviewing, each including between 7 and 46 individual cognitive maps (Jetter and Kok, 2014). Jetter (2006) identifies snowball sampling as a widely-used and legitimate technique for identifying potential interviewees in FCM studies. Snowball sampling is a form of purposive sampling, wherein an initial set of interviewees are identified, and these interviewees are asked to provide names of other relevant interviewees from within their networks (Mack *et al.*, 2005).

In total, this study had 14 interviewees (Table 1). This was composed of two groups. Firstly, an initial set of interviewees was selected, which spanned ACT Government directorates related to transport, planning, and the environment, MLAs, academics specialising in climate change and urban planning, as well as independent advisors to the ACT Government. Note that some of the initially selected interviewees did not agree to an interview. Secondly, further interviewees were identified through snowball sampling; at the end of each interview, interviewees were asked if they were willing to provide the contact information for other relevant people who might be available to be interviewed.

Interviews were conducted face-to-face, and worked with a pen and blank sheet of A3 paper. Each interview began with the interviewee being introduced to the study's aims and objectives, as well as the research methods used (causal loop diagrams and FCMs). Then, a set of 'starting concepts' were outlined (Jetter and Kok, 2014), to prompt interviewees to begin suggesting further concepts and linkages. By the end of each interview, respondents had developed an individual cognitive map (Appendix 2) with associated comments on the strengths of various linkages. These were used as inputs to steps 4-7 of the FCM-building process (Figure 3-1). In general, interviews lasted between 45 and 90 minutes, with each interviewee introducing roughly 10-30 concepts (variables). Therefore, the interviews proceeded in line with the expectations of Özesmi and Özesmi (2004) and Jetter and Kok (2014).

The data collection aspect of this research was approved under ANU Human Research Ethics Committee Protocol 2019/344.

Table 1: List of Interviewees in this study

Interviewee Identifier	Role(s)	Organisational Affiliation
MLA-1	(Former) Member of the Legislative Assembly (MLA): Deputy Chief Minister, Minister for Capital Metro, Minister for Environment and Climate Change, Minister for Planning	Australian Labor Party
MLA-2	Member of the Legislative Assembly (MLA): Shadow Minister for Transport	Canberra Liberals
MLA-3	Member of the Legislative Assembly (MLA): Transport Spokesperson	ACT Greens
D-1	(Former) Director General – Transport Canberra and City Services Directorate; (Former) Director General – Capital Metro Agency	ACT Government
D-2	(Former) Director General – Environment, Planning, and Sustainable Development Directorate	ACT Government
D-3	Director, Strategic Planning and Policy - Environment, Planning, and Sustainable Development Directorate	ACT Government
D-4	Sustainability Manager - City Renewal Authority	ACT Government
D-5	Sustainability and Land Release Manager – Suburban Land Agency	ACT Government
A-1	ACT Commissioner for Sustainability and the Environment	Independent Statutory Position
A-2	(Immediate Past) Chair, ACT Climate Change Council	Advises the ACT Minister for Climate Change and Sustainability
A-3	Political Advisor – Transport	ACT Legislative Assembly
Dev-1	Sustainability Manager – Ginninderry	Riverview Projects (ACT) Pty Ltd
P-1	Urban Planning Academic	University
P-2	Retired Professional Planner	National Capital Authority; ACT Planning Authority

3.2.2 FCM Steps 4 & 5: Data Treatment, Homogenization, and Aggregation

Once knowledge has been captured, there a number of crucial steps in translating this knowledge into a final FCM. This study followed the suggestions of Olazabal *et al.* (2018) for maintaining the transparency and reproducibility of this process.

Firstly, interviewees' individual cognitive maps were augmented with additional comments, based on written notes and audio recordings from the interviews. Secondly, to improve the consistency of concept names among the individual cognitive maps, common terminology was selected for commonly-mentioned concepts, facilitating the standardisation of concept names across all 14 individual cognitive maps. This included the grouping or un-grouping of certain concepts. All changes were tracked in a spreadsheet to ensure the integrity of this process. Finally, the individual cognitive maps were aggregated. This was done in three steps: (1) iteratively adding all causal relationships between concepts from the individual cognitive maps into a single aggregated FCM, (2) checking the coherency of the causal relationships in the FCM against interviewees' individual maps and interview notes, and (3) removing as well as adding new causal relationships until the final FCM and individual cognitive maps were conceptually consistent.

3.2.3 Edge Weights in the Study FCM (Adjacency Matrix)

In order for the final FCM derived from the steps above (the 'study FCM') to be computable, all causal links must have given edge weights (the adjacency matrix A in FCM terminology). To this end, the full table of edge weights in the Study FCM can be found in Appendix 2. The primary source of data for assigning edge weights was a critical analysis of the interview data – individual cognitive maps, notes, audio recordings, and follow-up conversations with interviewees.

For each assignment of edge weight, a careful process was followed. First, factors which contribute to increasing the strength of the weights were recorded and analysed. Then, factors which might reduce these influences were considered. Careful attention was paid to the magnitude of change that variable A might have on variable B, in the context of this study's focus on urban transport across Canberra.

To exemplify, the link between sustainable transport infrastructure (x18) and ability of sustainable modes to meet needs (x26) was classified as +0.4. This link is positive because new the intervention x18 is designed to improve people's ability to get around using sustainable modes (x26). Interviewees suggested that infrastructure-based interventions, such as light rail, have a strong effect on x26, because they significantly improve the quality and usefulness of the public transport service (a sustainable mode). However, in Canberra's case, the ACT Government's focus is on capital intensive infrastructure such as light rail. Thus, this limits or reduces the strength of this causal relationship, because each new unit of infrastructure only serves a small proportion of the urban population. This means that the value of x26 is not as strong as it would be if x26 was being influenced by a unit of infrastructure intervention which has a city-wide impact.

3.3 Quantitative Modelling for Scenario Analysis

In order to fulfil *Aim 2* and *Methodological Consideration 2* of this study, scenario modelling was performed on the study FCM (step 7 in Figure 3-1).

There are a number of tools and software packages for modelling the dynamic behaviour of FCMs (Felix *et al.*, 2019). However, some of the tools which supported scenario modelling did not appear to be publically available or readily accessible (FCM Designer, FCM Tool, ISEMK, and FCM Expert). In the case of Mental Modeler, a free online FCM design and modelling tool which has a few options for running scenarios, the tool's documentation provided no explanation of the mathematical functions underpinning the scenario modelling tools (cf. Gray and Cox, n.d.). In an effort to maintain analytical rigor and avoid a 'black box' modelling tool, it was decided to adapt well-understood mathematical approaches for the modelling of scenarios on the study FCM.

This study will therefore use control theory as the quantitative underpinning for its scenario modelling. The robust control framework allows the quantitative examination of how feedbacks affect system behaviour (Engelberg, 2015). It has previously been applied in sustainability science (Anderies *et al.*, 2007), and provides a means of generating the kinds of FCM scenario modelling outputs presented in Jetter and Kok (2014) and Zhang and Jetter (2018).

The building block of control theory in sustainability science is that almost any governance system can be represented by a feedback loop (Anderies *et al.*, 2007), as depicted in Figure 3-2.

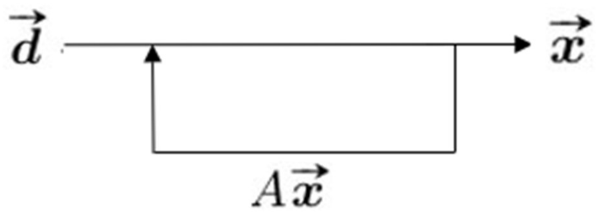

Figure 3-2: Simple Feedback Design in Control Theory

The vector of perturbations $\vec{d}$, generally referred to as 'drivers' in the systems thinking vocabulary or 'external signals' in engineering, leads to a change in the vector $\vec{x}$ (i.e. $\Delta\vec{x}$), where $\vec{x}$ is a vector containing all variables present in the FCM. The vector $\vec{d}$ represents quantitative changes in the value of $\vec{x}$, driven by an external signal such as a policy intervention or change in travel behaviour. Meanwhile, the feedback mechanism $A\vec{x}$ also acts on $\vec{x}$, where A is the adjacency matrix of the FCM (containing the weights w of each pairwise causal relationship between variables) and x is as before. In this way, $A\vec{x}$ captures the dynamical systems property that $\vec{x}$ is causally influenced by changes to other variables in the FCM.

$$d = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix} \quad x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad A = \begin{bmatrix} w_{x1\to x1} & w_{x2\to x1} & \cdots & w_{xn\to x1} \\ w_{x1\to x2} & w_{x2\to x2} & \cdots & w_{xn\to x2} \\ \vdots & \vdots & \ddots & \vdots \\ w_{x1\to xn} & w_{x2\to xn} & \cdots & w_{xn\to xn} \end{bmatrix}$$

Hence, the mathematical expression for the 'signals', or 'drivers' and 'feedbacks', acting on a single variable x is as expressed in equation 1a. Solving for x, the new value of x given A and d is as per equation 1d. This expression assumes that x has come to equilibrium in response to the driver d.

$$d + ax = x \tag{1a}$$

$$d = x - ax \tag{1b}$$

$$d = x(1 - a) \tag{1c}$$

$$x = \frac{d}{1 - a} \tag{1d}$$

In matrix notation, the mathematical expression of the drivers and feedbacks, i.e. signals, acting on the vector of variables $\vec{x}$ are given in equation 2a. Note that I is the identity matrix. Thus, the size of the change in $\vec{x}$ given A and d, with respect to the system's equilibrium state, is as expressed in equation 2d.

$$\vec{d} + A\vec{x} = \vec{x} \tag{2a}$$

$$\vec{d} = \vec{x} - A\vec{x} \tag{2b}$$

$$\vec{d} = (I - A)\vec{x} \tag{2c}$$

$$\Delta\vec{x} = (I - A)^{-1}\vec{d} \tag{2d}$$

In order to provide a reference point for $\Delta\vec{x}$, all elements of x are normalised, such that all values in $\vec{x}$ have the value of 1 prior to being perturbed by the drivers $\vec{d}$. The driver values $\vec{d}$ and variable changes $\Delta\vec{x}$ are both relative to the pre-perturbation $\vec{x}$ values (which are all equal to 1). Thus, $\Delta\vec{x}$ can be interpreted as the decimal change with respect to the value 1, and can be converted directly to a percentage.

For a concrete example to motivate the above mathematical discussion, consider Figure 3-3, which depicts a simple feedback system with three variables x, corresponding drivers d, and four edges with weights w.

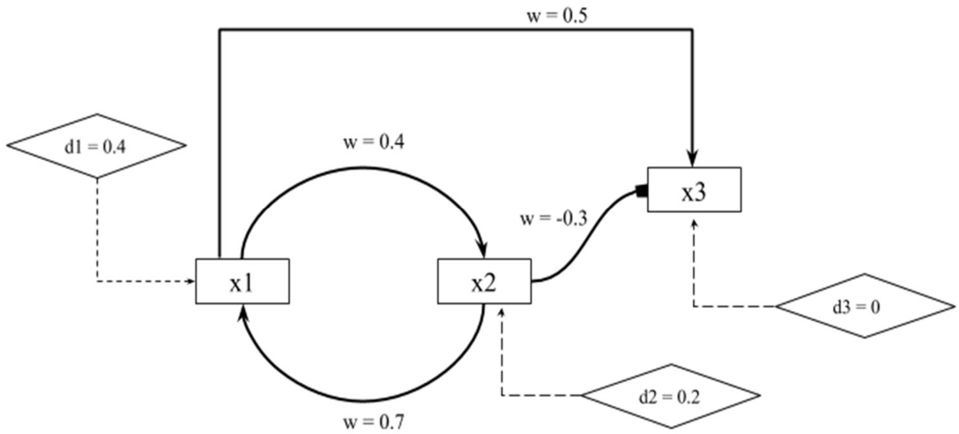

Figure 3-3: Simple example system with drivers d, variables x, and edge weights w.

The mathematical expression for the Δx in this example system, using equation 2d, is given below.

$$\Delta \vec{x} = (I - A)^{-1} \vec{d}$$

$$\Delta \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0.7 & 0 \\ 0.4 & 0 & 0 \\ 0.5 & -0.3 & 0 \end{bmatrix} \right)^{-1} \begin{bmatrix} 0.4 \\ 0.2 \\ 0 \end{bmatrix}$$

In this study, the method for quantitatively estimating the output of a scenario is based on an implementation of equation 2d in Microsoft Excel. System behaviour under different scenario conditions is represented by different input vectors $\vec{d}$ (for example, d_A, d_B, and d_C), where each d corresponds to a particular set of policy interventions which generate a certain quantitative change in $\vec{x}$.

$$d_A = \begin{bmatrix} 0.1 \\ 0.3 \\ 0.4 \end{bmatrix} \qquad d_B = \begin{bmatrix} 0.2 \\ 0.3 \\ 0.8 \end{bmatrix} \qquad d_C = \begin{bmatrix} 0 \\ 0.4 \\ 0.4 \end{bmatrix}$$

The weights in the adjacency matrix A for the study FCM were chosen based on the evidence collected during the knowledge capture process (see section 3.2.1), corresponding to Step 3 of the FCM-building process illustrated in Figure 3-1. The identity matrix I is an $n \times n$ matrix, where n is the number of variables in the FCM, and the vector $\vec{x}$ contains all variables present in the FCM.

Regarding the mathematical representation of 'interventions', defined in section 1.1 as (1) actions or (2) directed outcomes, the former is mathematically represented as a driver in the vector

$\vec{d}$, and the latter is represented as a non-zero entry in the adjacency matrix A (equivalent to the presence of a causal link in the systems diagram Figure 4-1) .

Chapter 4: Qualitative Results

This chapter discusses the qualitative aspects of this study's results – the 'aggregated cognitive map' (systems diagram), presented in Figure 4-1. Note that the legend provided as part of Figure 4-1 applies to all FCM-related figures in this study, with additional legend items as noted. The aforementioned systems diagram (step 3 in Figure 3-1) is a precursor result to the full study FCM (step 5 in Figure 3-1). This chapter's main aim is to engage with RQ1: *In what ways do the activities of city governments and private sector bodies shape the dynamics of low-carbon transitions within urban transport systems?*

To address this aim, the chapter will explore the key structures of the systems diagram. First, key variables that directly affect the urban transport system's carbon footprint – the 'core transitions engine', will be examined. To clarify, the carbon footprint referred to in this study are the operational carbon emissions of the transport system. The discussion in this chapter will then be guided by a focus on the various climate policy interventions for low-carbon urban transport, as identified by this study's interviewees. For each intervention, system drivers, ingoing and outgoing causal linkages, as well as the feedbacks they participate in will all be discussed. Moreover, the roles of different city-level actors, such as city governments and private sector bodies, will be identified and commented on. Finally, the chapter will conclude with a review of the key qualitative results of this study.

4.1 Core Transitions Engine

As discussed throughout the opening chapters, the goal of this study is to model the low-carbon transitions of urban transport systems, specifically Canberra's. The decarbonisation of the urban transport system is represented in the study FCM by reducing the value of the variable "carbon footprint of transport system" (x8). The variables and feedbacks surrounding this core goal variable can be considered as the 'core transitions engine', i.e. the set of variables which directly drive the sustainability transition toward a low-carbon urban transport system.

Within the 'core transitions engine', interviewees identified five variables that directly influence urban transport's carbon footprint (x8). Two variables relate to private vehicle travel, namely car as default journey mode (x3) and electric car ownership rates (x4), respectively. Another variable relates specifically to electrifying the transit (bus, light rail, and any other public transport mode) fleets (x7). In addition, two variables relate to travel behaviours surrounding sustainable travel modes: modal shift (x5), referring to people who switch modes e.g. car to bus, and individual utility of sustainable modes (x2), which concerns how people value sustainable modes e.g. convenience, travel time, reliability, comfort, and value-for-money (Walker, 2012).

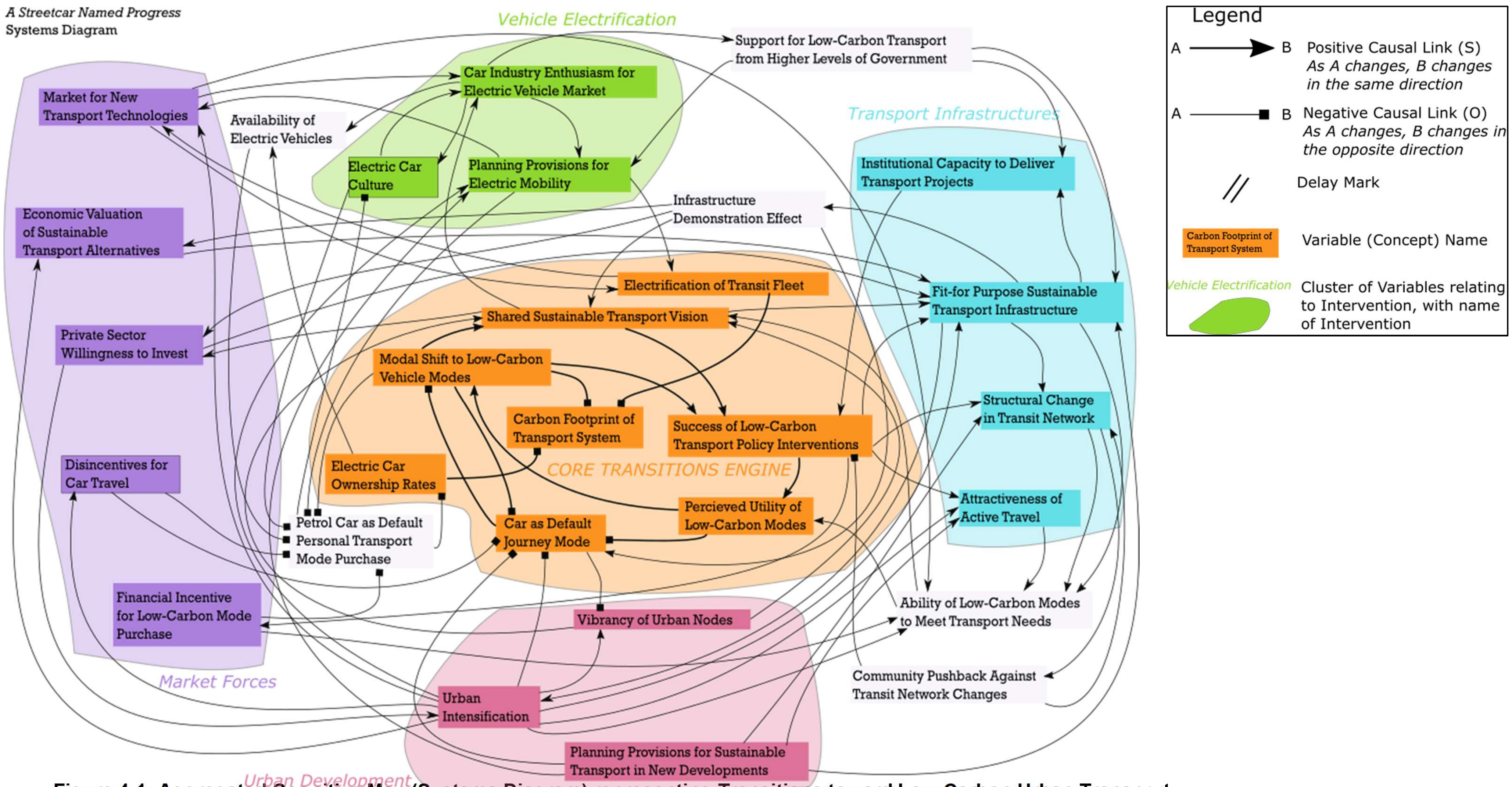

Figure 4-1: Aggregated Cognitive Map (Systems Diagram) representing Transitions toward Low-Carbon Urban Transport

The ‘core transitions engine’ also contains a number of feedback loops. The (desirable) reinforcing dynamics of the main feedback loop occur when individuals’ perceived utility of sustainable modes (x2) increases, thus decreasing car as default journey mode (x3), triggering modal shift to sustainable vehicle modes (x5), which builds shared vision around sustainable transport (x6), leading to increased success of sustainable transport initiatives (x1), and feeding back to x2 again. There is an additional link from individual utility of sustainable modes (x2) directly to modal shift (x5), which provides a ‘shortcut’ for the main feedback loop. Finally, there is also a link from modal shift (x5) to car as default mode (x3).

In order to reduce the value of x8, and thus progress sustainability transitions toward low-carbon urban transport, interventions for urban transport will need to target some part of this ‘core transitions engine’. Interventions which target the ‘core transitions engine’ will also cause changes in other system variables; if these are desirable, they can be considered co-benefits (Creutzig *et al.*, 2012; Kwan and Hashim, 2016), otherwise, they are unintended consequences (Acuto *et al.*, 2018).

4.2 Climate Policy Interventions for Low-Carbon Urban Transport

4.2.1 Vehicle Electrification

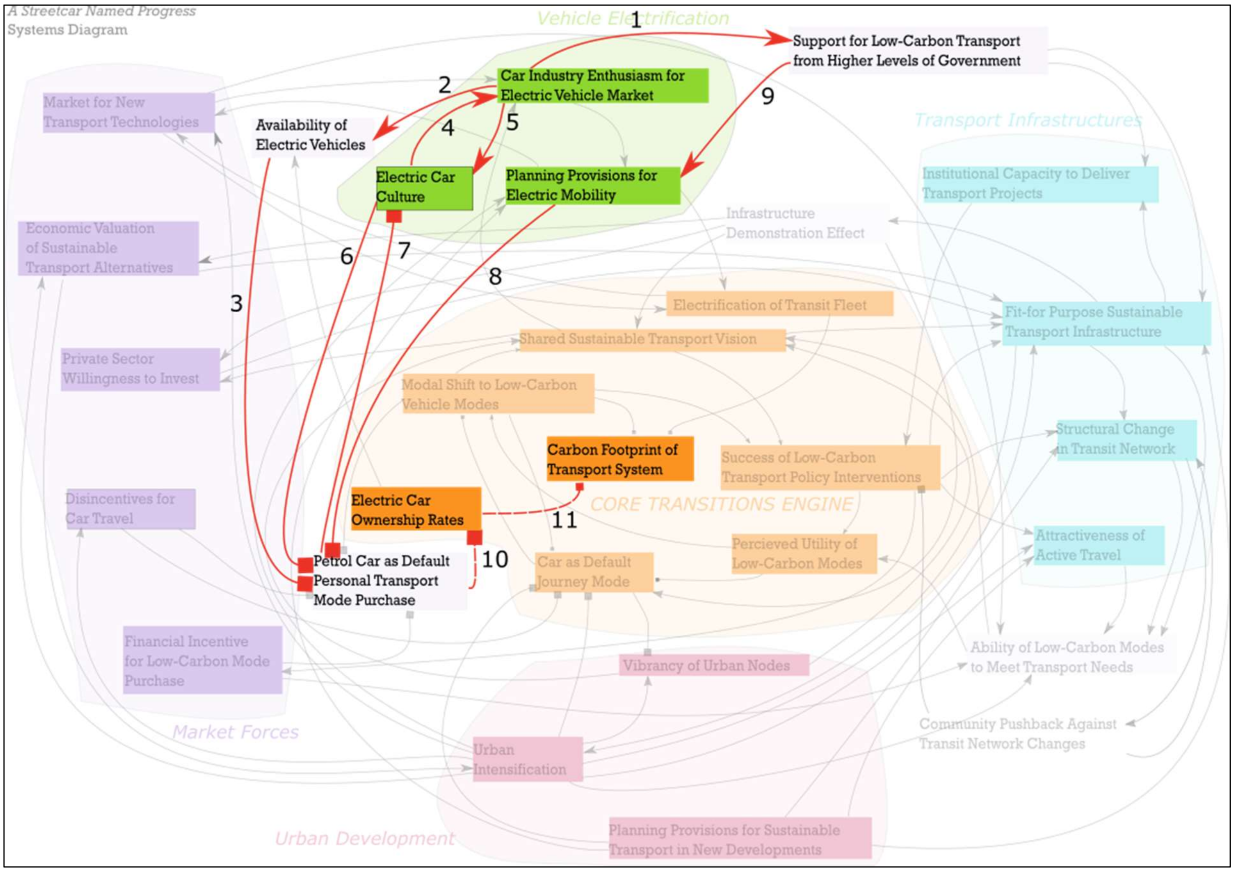

Figure 4-2: Systems Diagram, highlighting variables and linkages identified by interviewees as relevant to electric cars, within the intervention theme of 'vehicle electrification'

Table 2: Description of Key Feedback Loops in Figure 4-2

Feedback Loop No.	Links in Loop	Variables in Loop
R1	4-5	x15, x12
R2	6-7	x12, x10

Concerning electric cars, it was somewhat surprising to find that interviewees broadly viewed the car industry as an actively positive agent in the transition process. It is surprising because, among other reasons, car manufacturing companies are traditionally seen as helping to 'lock-in' private car dependence – which has hitherto been a highly unsustainable form of transportation (Moradi and Vagnoni, 2018). It is also surprising because previous work, such as Marletto (2014), has suggested that the electricity industry (electricity producers and grid managers) would be the ones to drive transitions toward electric vehicles.

Interviewee A-3 outlines several causal impacts which stem from the car industry's enthusiasm for electric vehicles (x15). These are: (1) increasing the availability of electric cars, (2) promoting a motoring culture around electric mobility, (3) proposing new electric vehicle technologies to the ACT Government for replacing their car fleets, and (4) lobbying the Federal government to support electric cars through appropriate infrastructure, regulation, and subsidies (Figure 4-2). It is also relevant to note that as electric car culture (x12) grows, this feeds back into driving further car industry enthusiasm for electric cars (x15).

Interviewee A-1 explained that part of what motivates the car industry to be enthusiastic about electric mobility is their increasing sensitivity to the expiring 'social license to operate' for fossil-fuel cars, as well as growing shared vision around sustainable transportation. Another important aspect is the feed-back from more consumers buying non-petrol cars (x10), shown in loop R2 (Table 2, Figure 4-2). Meanwhile, interviewee A-3 notes that the ACT Government's clear signals of intent to buy more low-carbon vehicles is the key driver for car companies to 'knock on the door' of the ACT Government.

Electric cars link to the core transitions engine via links 10 and 11 in Figure 4-2.

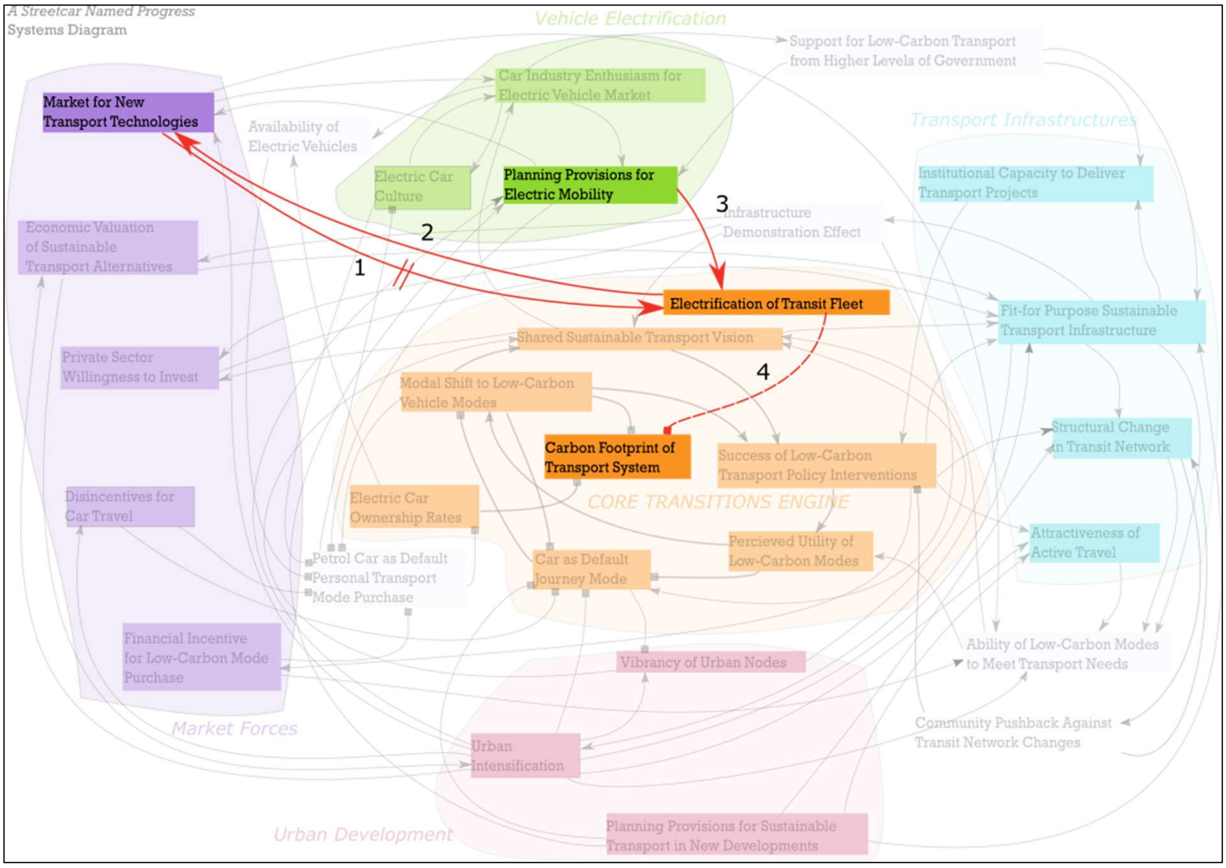

Figure 4-3: Systems Diagram, highlighting variables and linkages identified by interviewees as relevant to electric transit fleets

Table 3: Description of Key Feedback Loop in Figure 4-3

Feedback Loop No.	Links in Loop	Variables in Loop
R3	1-2	x7, x17

Another vehicle class the ACT Government is looking to electrify is its public bus fleet. Results of the ACT's 12-month benchmarking trial of battery electric and hybrid buses were released in September 2019 (Steele, 2019). The results found that, compared to diesel buses, the battery electric buses had 61% less CO_2 emissions and 27% lower whole-of-life economic costs. However, these electric buses were not able to operate around one-third of the peak hour bus trips they were scheduled to, mostly due to breakdowns and other operational issues (this compares to a 0.8% failure rate for diesel buses). The implication is that current electric bus technologies are not adequate (especially in terms of reliability) for the demands of the ACT's public transport network. Interviewee A-3 notes that the ACT has much higher safety and reliability standards for electric buses than many places which have already achieved high levels of bus fleet electrification, such as Shenzhen, China. A-3 adds that the supply chain for the types of electric buses suited to the ACT does not yet exist. Thus, A-3 suggests that the electric bus supply chain needs to develop electric bus technologies suitable for the ACT, before the ACT can adopt electric buses more widely.

To this end, A-3 suggests that the ACT is helping to drive a market for electric public transport vehicles in Australia by signalling that they are looking to buy low-carbon buses and that eventually, the ACT will only be willing to buy electric vehicles. Such planning provisions for electric mobility helps, in small part, to enlarge the market for new transport technologies in Australia (Figure 4-3). As the availability of electric buses which meets ACT standards grows, the ACT's bus fleet will become increasingly electrified, further strengthening the Australian market for new transport technologies such as better electric buses. Thus, the reinforcing feedback loop R3 is formed (Table 3, Figure 4-3).

However, A-3 notes that there is a delay between the market size growing and electrification of ACT buses, for two main reasons. Firstly, it takes time for R&D and for supply chains to mature (UITP, 2016). Additionally, while the ACT is attempting to progressively replace older diesel buses, increases in the number of timetabled bus services in Canberra is absorbing the addition of new lower-emission buses, leading to old diesel buses remaining in the fleet. Thus, full electrification of the fleet is likely to take many years, unless something is done to accelerate the process. Nonetheless, the ACT Government remains committed to a zero-emissions bus fleet (Steele, 2019).

Electric transit fleets link to the core transitions engine via link 4 in Figure 4-3.

4.2.2 Transport Infrastructure

One of the main interventions for low-carbon mobility currently being pursued by the ACT Government is the building of new sustainable transport infrastructure, in particular, the Canberra Light Rail network (ACT Government, 2018). However, MLA-1 notes that building up the initial momentum to implement infrastructure interventions can take copious amounts of time, as well as political leadership. Light rail had been proposed for Canberra since the city's 1913 Walter Burley Griffin Plan, however the 20th century saw no progress on rapid transit in the ACT. Interviewee MLA-1 describes the ACT Government's attempts to establish a Bus Rapid Transit (BRT) system in the early 2000s, which was abandoned when they discovered that "BRT had no friends – not a single stakeholder group supported it". The ACT Government returned to the drawing board and proposed an integrated light rail network instead, which MLA-1 added "at least had some supporters". This became a starting point for the ACT Government's push to deliver light rail; the first light rail service finally began carrying passengers in April 2019.

Interviewees suggest that developing sustainable transport infrastructure causally influences four variables: (1) structural change in transit network (2) attractiveness of active travel, (3) infrastructure demonstration effect, and (4) institutional capacity to deliver transport projects (Figure 4-4). Altogether, interviewees highlighted the participation of sustainable transport infrastructure in a four key feedback loops (Table 4).

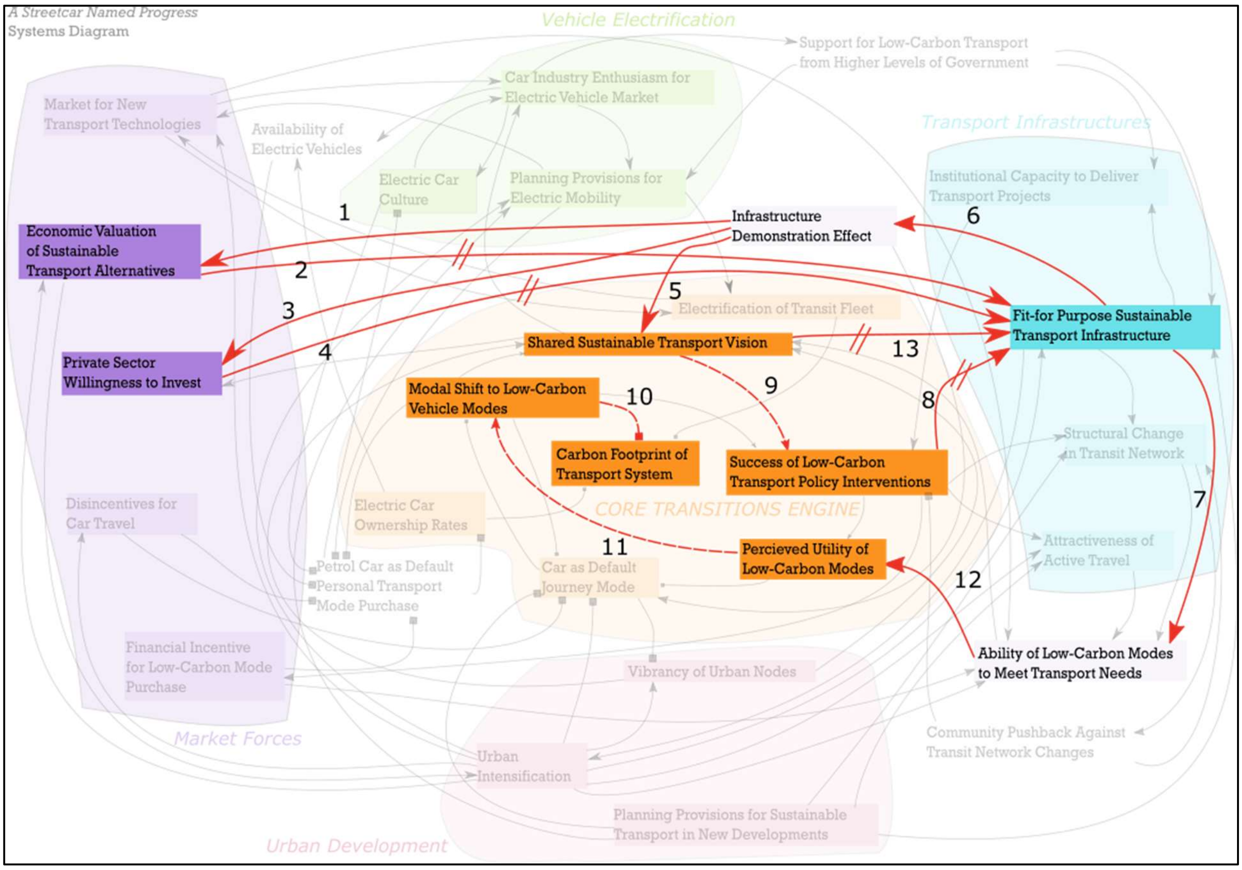

Figure 4-4: Systems Diagram, highlighting variables and linkages identified by interviewees as relevant to fit-for-purpose sustainable transport infrastructure, within the intervention theme of transport infrastructures

Table 4: Description of Key Feedback Loops in Figure 4-4

Feedback Loop No.	Links in Loop	Variables in Loop
R4	6-5-13	x18, x11, x6
R5	6-5-9-8	x18, x11, x6, x1
R6	6-1-2	x18, x11, x13
R7	6-3-4	x18, x16

Seven interviewees (D-1, D-2. D-4, MLA-1, A-1, A-2, P-1) discussed the feedback loop wherein sustainable transport infrastructure contributes to a demonstration effect, driving shared vision around sustainable transport, in turn leading to development of more sustainable transport infrastructure – loop R4 (Table 4, Figure 4-4).

As MLA-1 explains, light rail's initial demonstration effect involved changing people's perceptions of public transport – "that it could be for everyone". D-1 adds that light rail helped attract first-time public transport users, and gave many people a newfound appreciation for the freedom public transport can offer when moving around the city. MLA-1, D-1, and A-1 describe how this fosters conversations about the future – what Canberra residents want their city to look like, how people want to move, and what kinds of transport projects should get funded. This shared vision feeds back to building more sustainable transport infrastructure, as well as contributing to the success of broader efforts for low-carbon mobility – loop R5 (Table 4, Figure 4-4). Interviewee D-2 suggests that the demonstration effect (through the realisation of wider economic benefits) also has the effect of improving the economic valuation of sustainable transport infrastructure projects, which leads to more similar projects being selected – loop R6 (Table 4, Figure 4-4). A number of interviewees added that the demonstration effect also encourages the private sector to assist in building new sustainable transport infrastructure - loop R7 (Table 4, Figure 4-4). This is relevant because the ACT Government is pursuing a Public-Private-Partnership (PPP) model for building light rail (ACT Government, 2019b).

Sustainable transport infrastructure links to the core transitions engine through two pathways – via links 5 and 9, as well as via links 12, 11, and 10 (Figure 4-4).

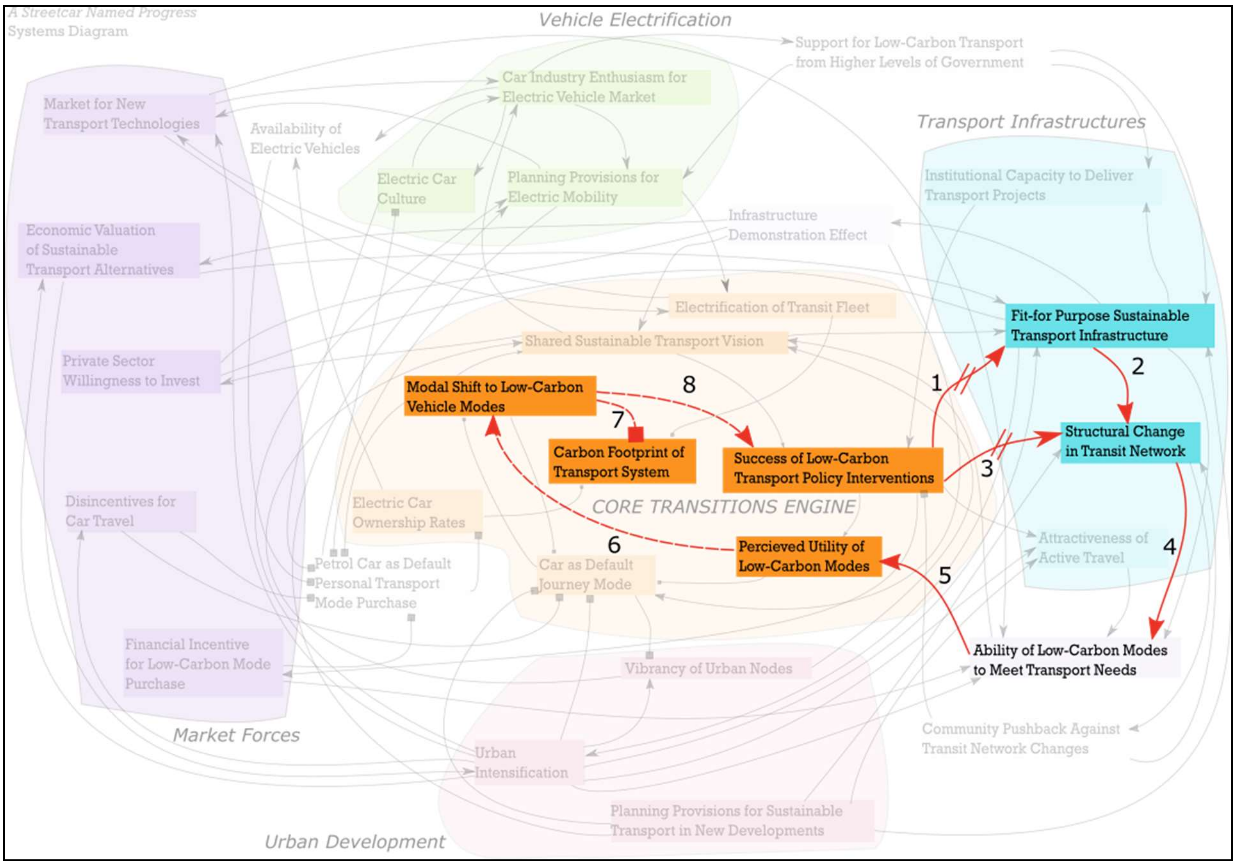

Figure 4-5: Systems Diagram, highlighting variables and linkages identified by interviewees as relevant to structural changes in the transport network, within the intervention theme of transport infrastructures

Table 5: Description of Key Feedback Loops in Figure 4-5

Feedback Loop No.	Links in Loop	Variables in Loop
R8	4-5-6-8-2	x23, x26, x2, x5, x1
R9	4-5-6-8-1-2	x23, x26, x2, x5, x1, x18

The second mode-shift strategy implemented by the ACT Government is structural changes to the transit network (bus and light rail routes). Compared to developing new sustainable transport infrastructure, this intervention requires less time, financial capital, and political capital. Interviewees suggest that this action causally influences the ability of sustainable modes to meet the travel needs of Canberra's residents. They outline improvements such as a growing network of 'rapid' bus services, improved frequencies, a more legible network, and later trips on nights and weekends. This in turn causes sustainable modes to have greater utility to individuals, leading to modal shift, increasing the success of the transition efforts, and feeding back to more structural change – loop R8 (Table 5, Figure 4-5). It may also induce improvements to sustainable transport infrastructure, which feeds back to structural change in the transit network as well – loop R9 (Table 5, Figure 4-5).

Changes in the transit network links to the core transitions engine via links 5, 6, and 7/8 in Figure 4-5.

4.2.3 Market Forces

Three of the five interventions in the market forces cluster – market for new transport technologies, economic valuation of sustainable transport, and private sector willingness to invest – have already been addressed in Figure 4-3 and Figure 4-4. This is because they are triggered by feedback loops which are causally linked to interventions in the other thematic clusters.

Causal linkages relating to the remaining two variables in this cluster – disincentives for car travel and financial incentives for the purchase of low-carbon modes (Figure 4-1) – were mentioned by a number of interviewees but detailed feedbacks and triggers were not discussed in detail. Hence, the dedicated discussion of interventions in this cluster is brief.

4.2.4 Urban Development

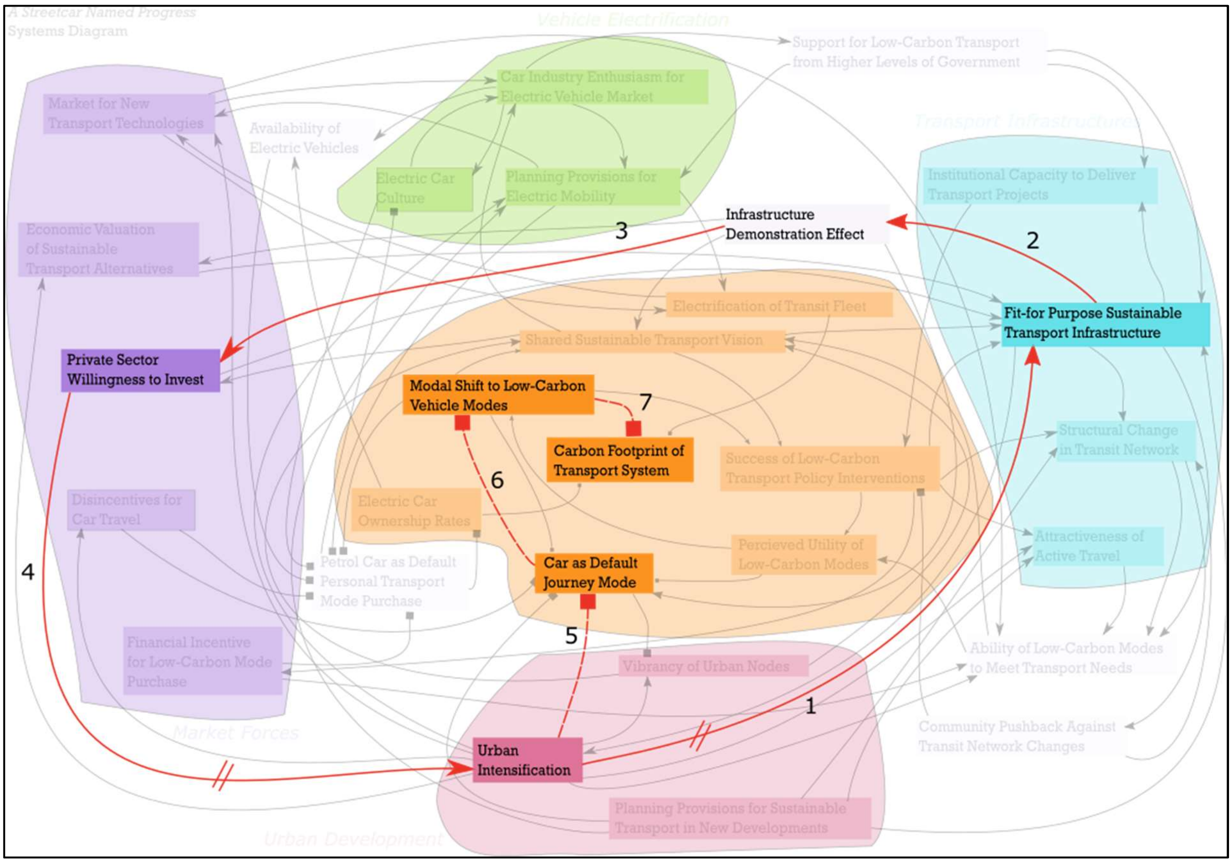

Figure 4-6: Systems Diagram, highlighting variables and linkages identified by interviewees as relevant to urban intensification, within the theme of urban development

Table 6: Description of Key Feedback Loop in Figure 4-6

Feedback Loop No.	Links in Loop	Variables in Loop
R10	1-2-3-4	x29, x18, x11, x16

Urban intensification, also known as compact development, is a policy intervention that often specifically targets reducing people's overall need for travel, including their choice of private cars as their default journey mode (Ewing and Cervero, 2017; Nelson, 2017).

As interviewee D-3 explains, urban intensification involves the co-location of housing, employment, and activity centres, as well as providing access to high-quality public transport. Interviewees identified that urban intensification drives development of sustainable transport infrastructure to service it, leading to a demonstration effect that increases private sector willingness to invest, which leads back to urban intensification, thus forming the feedback loop R10 (Table 6, Figure 4-6).

Urban intensification links to the core transitions engine via links 5, 6, and 7 in Figure 4-6.

4.3 Review of Qualitative Results

Qualitative results in this chapter all relate to the systems diagram shown in figure 5.1, which depicts the aggregation of interviewees' mental models regarding the low-carbon transition processes operating within Canberra's transport system.

An important high-level result (result 1) is that the process of decarbonising urban transport is linked to a 'core transitions engine', which encompasses a number of variables and feedbacks that directly affect urban transport's carbon footprint (x8). The various interventions for low-carbon transport influence the core transitions through a number of different causal pathways (result 2).

Moreover, many climate policy interventions for low-carbon urban transport display a high degree of interconnectedness with other variables (result 3). To exemplify, urban intensification (x29) has nine outgoing links and two ingoing links, sustainable transport infrastructure development (x18) has five outgoing links and seven ingoing links, and planning provisions for electric mobility (x19) has three outgoing links and four ingoing links. In addition, each policy intervention participates in a number of positive reinforcing feedback loops (result 4). It is also apparent that many variables from outside the transport domain, such as the economic assessment of major infrastructure projects (x13) as well as the vibrancy of urban nodes (x32), can have direct influences on the transition toward a low-carbon urban transport system (result 5). Overall, the systems diagram illustrates the inherent complexity of the processes implicated in transitions toward low-carbon urban transport; the aggregation of interviewees' mental models resulted in the identification of 30 relevant variables, as well as 85 causal linkages (result 6).

The interviews also drew out several insights regarding system drivers for low-carbon transport interventions. It was uncovered that each category of policy intervention has specific kinds drivers which help to spark their implementation (result 7). For example, city residents' desire for "better ways to move", as well as demographic preferences for denser living and better public transport, can help to trigger the development of new sustainable transport infrastructures (x18) such as light rail.

Interestingly, it was found that not all drivers were related to citizens' desires, or other external pressures that led to implementation of low-carbon transport policy interventions by city governments; drivers could also relate to city governments putting pressure on industry into instigating private-sector-led interventions of their own (result 8). Interviewees talked about how the ACT Government's signalling of planning commitments to electric mobility (x19) is helping to trigger initial momentum toward expanding the size of the Australian electric vehicle market, encouraging the car industry to increase the local availability of electric vehicles. This introduces the proposition that private sector bodies may have an important role to play in progressing transitions toward low-carbon transport systems at the city level (result 9).

In summary, this chapter presented qualitative results in three key areas: the complexity and interrelationships of interventions aiming to progress transitions toward low-carbon urban transport, drivers and triggers for these interventions, and the roles of different city-level and private sector bodies in the transition process.

Chapter 5: Quantitative Results

Chapter 4 presented a systems diagram that captures relevant variables and causal linkages involved in transitions toward low-carbon urban transport, the key qualitative underpinning of this study. This chapter builds on the aforementioned systems diagram, by including the FCM elements (adjacency matrix, drivers) which make the systems diagram computable, forming the key quantitative underpinning of this study.

The core aim of this chapter is to use the FCM to model the impact of the policy interventions proposed by the *ACT Climate Change Strategy 2019-25* (hereafter, *Climate Change Strategy)* on low-carbon transport objectives, with particular focus on the carbon footprint of the transport system (variable x8). Consequently, this chapter engages with RQ2: *How do different scenarios, which represent packages of city government policy and other city-level interventions, affect progress toward low-carbon urban transport objectives?* To address the above aim, this chapter will model a couple of scenarios corresponding to the *Climate Change Strategy*. The key quantitative results from this chapter will then be summarised.

5.1 Scenario A: The ACT Climate Change Strategy

Scenario A uses the study FCM to model the quantitative impact of the policy interventions mentioned in the transport section of the *Climate Change Strategy* (ACT Government, 2019a). In order to represent these interventions in the mathematical form described in section 3.3, each numbered action in the *Climate Change Strategy*'s transport section was mapped to a particular variable in the study FCM (Table 8). Each variable was then assigned a corresponding value in the vector $\vec{d}$, which was based on an estimate of how much change in that variable would be caused by the actions which were mapped to that variable (Table 7). These estimates are generated on the basis of the interviews (notes, systems diagrams, audio recordings, and follow-up conversations).

The vector $\vec{d}$, representing the conditions of Scenario A (Table 7), and the adjacency matrix A for the study FCM (Appendix 2) are then used in equation 2d to calculate $\Delta\vec{x}$ (illustrated in Figure 5-1).

$$\Delta\vec{x} = (I - A)^{-1}\vec{d} \qquad \text{(2d)}$$

Table 7: Actions from the *Climate Change Strategy*, and corresponding variables and values in the vector $\vec{d}$

ACT Action No.	Variable Name in Systems Model	Variable No.	Value in **d**
3.1, 3.2, 3.20	Financial Incentives for Ownership of Sustainable Transport Modes	x24	+ 0.4
3.3	Urban Intensification	x29	+ 0.3
3.4, 3.14	Fit-for-Purpose Sustainable Transport Infrastructure	x18	+ 0.5
3.5	Structural Change in Transit Network	x23	+ 0.2
3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.22	Attractiveness of Active Travel	x27	+ 0.4
3.12, 3.13, 3.15, 3.16, 3.18, 3.19	Disincentives for Car Travel	x33	+ 0.4
3.21, 3.23	Planning Provisions for Electric Mobility	x19	+ 0.4

On the basis of equation 2d, the potential reduction in the carbon footprint of Canberra's transport system (x8) is around 70% (Figure 5-1). The other two variables representing undesirable outcomes, car as default journey mode (x3) and petrol car as an individual's default personal mode purchase (x10), both decreased by around 75% (Figure 5-1). All variables in $\Delta\vec{x}$ are shown in Figure 5-1.

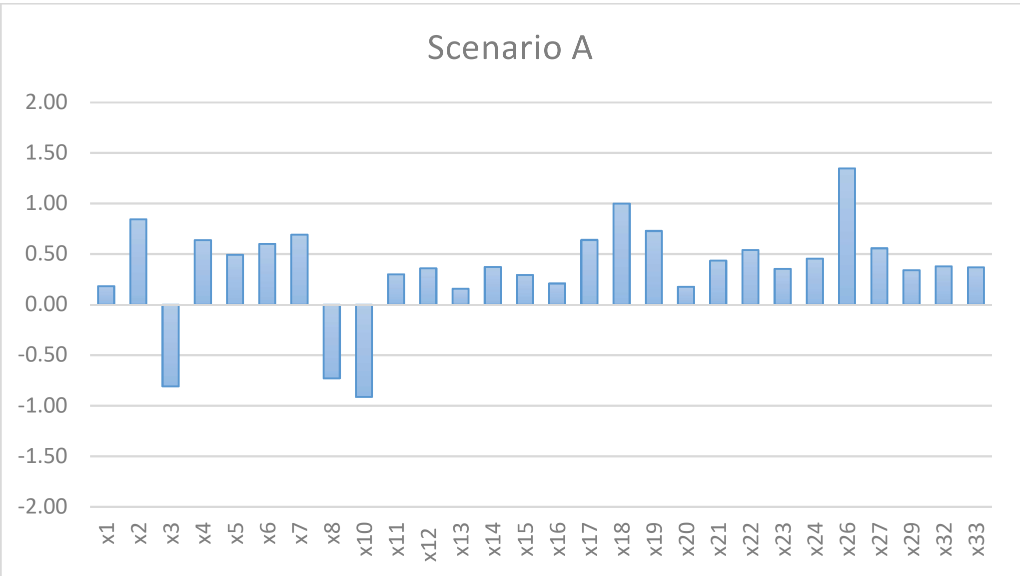

Figure 5-1: Δx under Scenario A

To test which transport actions, i.e. policy interventions, in the *Climate Change Strategy* might be most influential in reducing the carbon footprint of Canberra's transport system (x8), a sensitivity analysis was conducted. This tested the influence of policy interventions in Scenario A on the variable x8 (carbon footprint of urban transport), with respect to the FCM and systems diagram. For each intervention, the relevant value in $\vec{d}$ was set to zero (i.e. the intervention has no effect on its respective variable), the new value of the variable x8 was recorded and compared to the baseline (Scenario A with no modifications), and $\vec{d}$ was reset to test the next intervention.

This sensitivity analysis (Table 8) suggests that, when removed, the interventions with the largest effect on the value of x8 were the following four: sustainable transport infrastructure (x18), planning for electric mobility (x19), financial incentives for sustainable modes (x24), and urban intensification (x29).

Table 8: Sensitivity Analysis of Policy Interventions under Scenario A

Changes to Driver Set in Scenario A	New Value of V8	% Change in V8 (vs. Baseline)
Baseline – Scenario A	*-0.730*	*n/a*
x18 (Infrastructure) removed	-0.629	-14%
x19 (Planning for Electric Mobility) removed	-0.493	-32%
x23 (Transit Network) removed	-0.708	-3%
x24 (Financial Incentives) removed	-0.619	-15%
x27 (Active Travel) removed	-0.684	-6%
x29 (Intensification) removed	-0.482	-34%
x33 (Disincentives) removed	-0.667	-9%

5.2 Scenario B: ACT Collaboration with the Private Sector

The premise of Scenario B is based on the proposition expressed by result 9 (section 4.3), that the private sector may have an important role to play in the transition toward low-carbon urban transport. Scenario B includes all the drivers present in Scenario A, and adds non-zero driver values in the vector $\vec{d}$ (table 5) for the following three variables: economic valuation of sustainable transport projects (x13), car industry enthusiasm for the electric vehicle market (x15), and private sector's investment appetite (x16).

Table 9: Scenario B, including added private sector related actions

ACT Goal No.	Variable Name in Systems Model	Variable #	d-value
3.1, 3.2, 3.20	Financial Incentives for Ownership of Sustainable Transport Modes	x24	+ 0.4
3.3	Urban Intensification	x29	+ 0.3
3.4	Fit-for-Purpose Sustainable Transport Infrastructure	x18	+ 0.5
3.5	Structural Change in Transit Network	x23	+ 0.2
3.6, 3.7, 3.8, 3.9, 3.10, 3.11	Attractiveness of Active Travel	x27	+ 0.4
3.12, 3.13, 3.15, 3.16, 3.18, 3.19	Disincentives for Car Travel	x33	+ 0.4
3.21	Planning Provisions for Electric Mobility	x19	+ 0.4
n/a	Economic Valuation of Sustainable Transport Alternatives	x13	+ 0.3
n/a	Car Industry Enthusiasm for Electric Vehicle Market	x15	+ 0.2
n/a	Private Sector Willingness to Invest	x16	+ 0.3

Under Scenario B, the potential reduction in x8 is around 95% (Figure 5-2), which is 25% greater than the potential reduction found under Scenario A. This suggests that private sector involvement in transitions can potentially be effective, and augment the interventions led by the public sector.

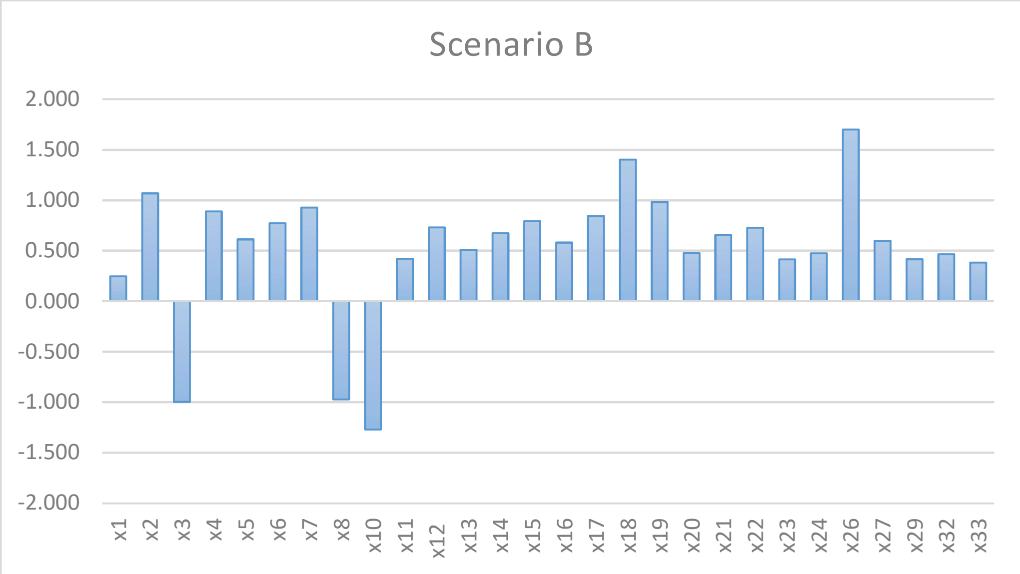

Figure 5-2: Δx under Scenario B

5.3 Review of Quantitative Results

Quantitative results in this chapter relate to the scenario modelling conducted on the study FCM, with respect to Scenarios A and B.

A key finding was that the *Climate Change Strategy* (Scenario A) will create a meaningful degree of progress towards reducing the operational carbon footprint of Canberra's transport system (x8); this study estimates a potential reduction in x8 of around 70% (result 10). Modelling also suggests that the effectiveness of the *Climate Change Strategy* can be increased by around 25% if the private sector actively contributes to the transition process by driving change in variables x13, x15, and x16 (result 11). The differential impact on variable x8 between scenarios A and B may depend on factors such as the level of private sector involvement, their motivations for being involved in transition processes, and how strongly they drive change in system variables.

Moreover, a sensitivity analysis was conducted, to determine the relative effectiveness of individual policy interventions in Scenario A. The sensitivity analysis found that there were four policy interventions which were particularly effective at reducing the value of x8 (result 12). In decreasing order of effectiveness, these were the development of new sustainable transport infrastructures (x18), provision of financial incentives for sustainable transport (x24), planning for electric mobility (x19), and urban intensification (x29). This suggests that certain interventions may be higher priority than others, particularly if financial or political capital is limited.

In summary, this chapter presented quantitative results of scenario modelling which related to the *Climate Change Strategy*.

Chapter 6: Discussion

This chapter builds on the qualitative results from chapter 4, and the quantitative results from chapter 5, to discuss key findings and underlying themes arising from this study. Some further quantitative analysis will also be conducted. The aim of this chapter is to engage with *Aims 1 and* 2, RQ1 and RQ2, as well as the overarching research question, which are restated in Table 10.

Firstly, results 1-9 (pertaining to RQ1) will be discussed in relation to initial momentum, the emergence of self-reinforcing dynamics around low-carbon urban transport outcomes and positive inertia (Irvine and Bai, in press). Whereas Chapter 4 discussed system structures and feedbacks in a broad and 'ideal' sense, this chapter 'zooms in' on specific links in feedback loops, and how they may enable or constrain the emergence of self-reinforcing dynamics.

Secondly, results 10-12 (pertaining to RQ2) will be discussed in the context of further quantitative analysis to be conducted in this chapter. This further analysis will identify key policy-relevant insights, and policy levers, for effective and appropriate interventions to progress transitions toward low-carbon urban transport systems.

Table 10: Restatement of Aims, Research Questions, and Methodological Considerations

	1	**2**
Overarching research question: How, and to what extent, can city-level actors create meaningful progress toward decarbonising urban transport systems?		
Aim	To identify how city actors can create enduring change toward low-carbon urban transport systems	To develop policy-relevant insights about the effectiveness and appropriateness of different city-led interventions for low-carbon urban transport
Analytical Research Question	In what ways do the activities of city governments and private sector bodies shape the dynamics of low-carbon transitions within urban transport systems?	How do different scenarios, representing different sets of urban climate policy interventions, affect progress toward low-carbon urban transport objectives?
Methodological Consideration	The use of systems approaches	The development of quantitative storylines

6.1 Enduring Change for Low-Carbon Transport Outcomes

Positive inertia is a desirable emergent property of systems that engender low-carbon outcomes (Irvine and Bai, in press), as it means that the dynamics of low-carbon transitions have become self-reinforcing and more difficult to break away from (see section 2.4.2). The emergence of positive inertia is therefore a crucial prerequisite of 'enduring change'. Qualitative results from Chapter 5 found that Canberra's policy interventions for low-carbon transport have various drivers (which can contribute to building up initial momentum for implementing particular interventions), and form part of positive reinforcing feedback loops. These are the two necessary conditions for the emergence of positive inertia (Irvine and Bai, in press). Hence, this raises the question of how initial momentum and feedbacks can be leveraged in order to engender positive inertia, and how these insights might be relevant to places outside Canberra.

The following discussion explores how (i.e. in which parts of the study FCM) different actors can contribute to creating the conditions for the emergence of positive inertia around low-carbon transport outcomes, by triggering initial momentum in feedback loops, as well as supporting the mechanisms which allow positive feedback loops to become self-reinforcing.

It addresses *Aim 1,* RQ1, and *Methodological Consideration 1* of this study (Table 10). The focus will be on the following outcomes: electrification of transit fleet (x7), petrol car as default transport mode purchase (x10), the ability of sustainable modes to meet travel needs (x26), and urban intensification (x29). These outcomes correspond to the policy interventions identified by section 5.3 as being the most effective for reducing the urban transport system's overall carbon footprint.

There were several key findings. It appears that mechanisms relating to citizens (e.g. shared vision) represented challenges for the emergence of positive inertia, whereas market-based mechanisms (such as private sector investment) represented opportunities. This is consistent with the proposition in result 9 from chapter 4, that the private sector may have a critical role to play in creating enduring change toward a low-carbon urban transport system.

6.1.1 Transit Fleet Electrification

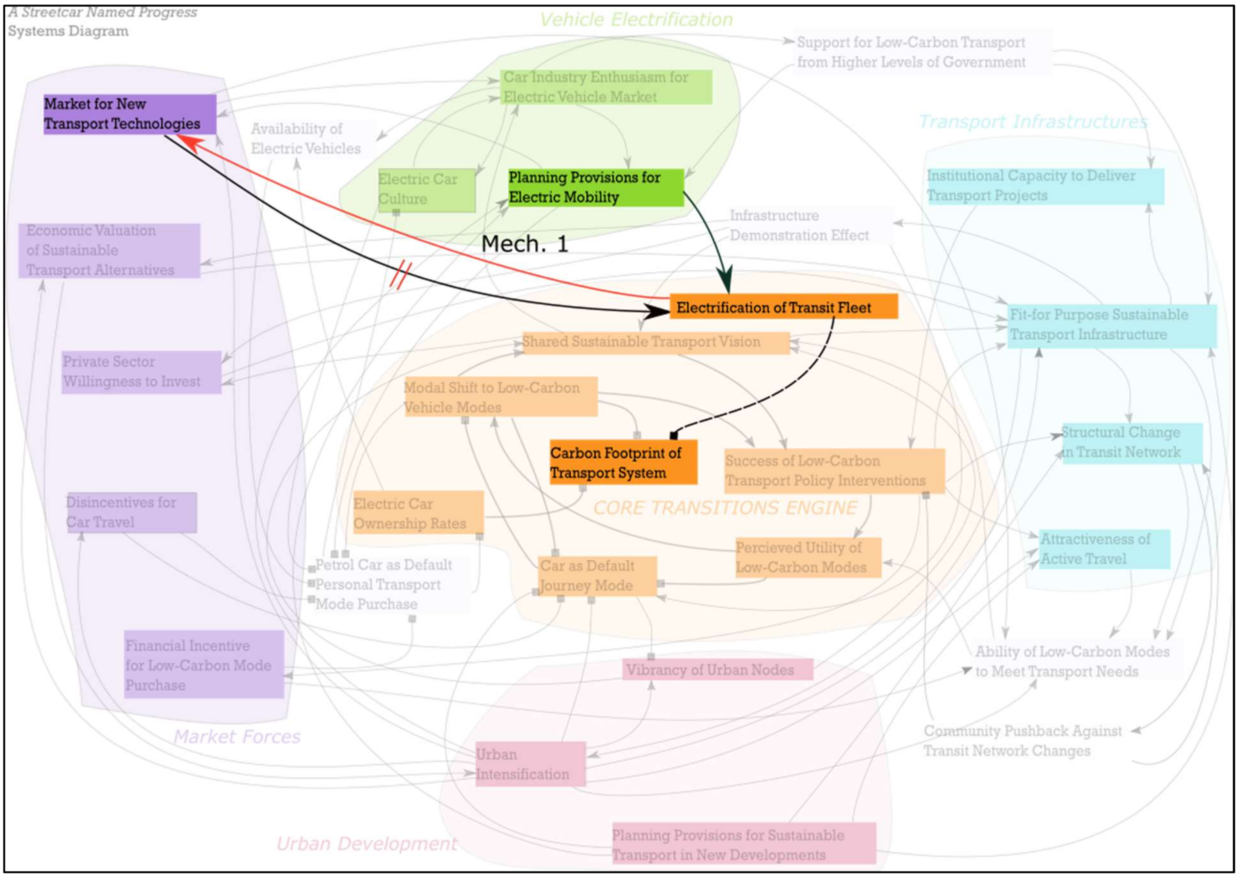

Figure 6-1: Mechanisms which are (at present) Enabling (Green) or Constraining (Red) the emergence of self-reinforcing dynamics relating to Electrifying Transit Fleets

Interviewee A-3 identifies a key enabling mechanism (mechanism 1) for electrifying transit fleets as city government signalling to industry their intention to transition toward an electric transit fleet (Figure 6-1). This is important for building up an initial momentum to increase the market for new transport technologies such as electric buses. Without this initial momentum, A-3 suggests that the feedback loop dynamics shown in loop R3 (Table 3, Figure 4-3) will take a long time to eventuate, given the delay in appropriate vehicle technologies coming online in the Australian market (see delay mark in Figure 6-1).

6.1.2 Ability of Sustainable Modes to Meet Travel Needs

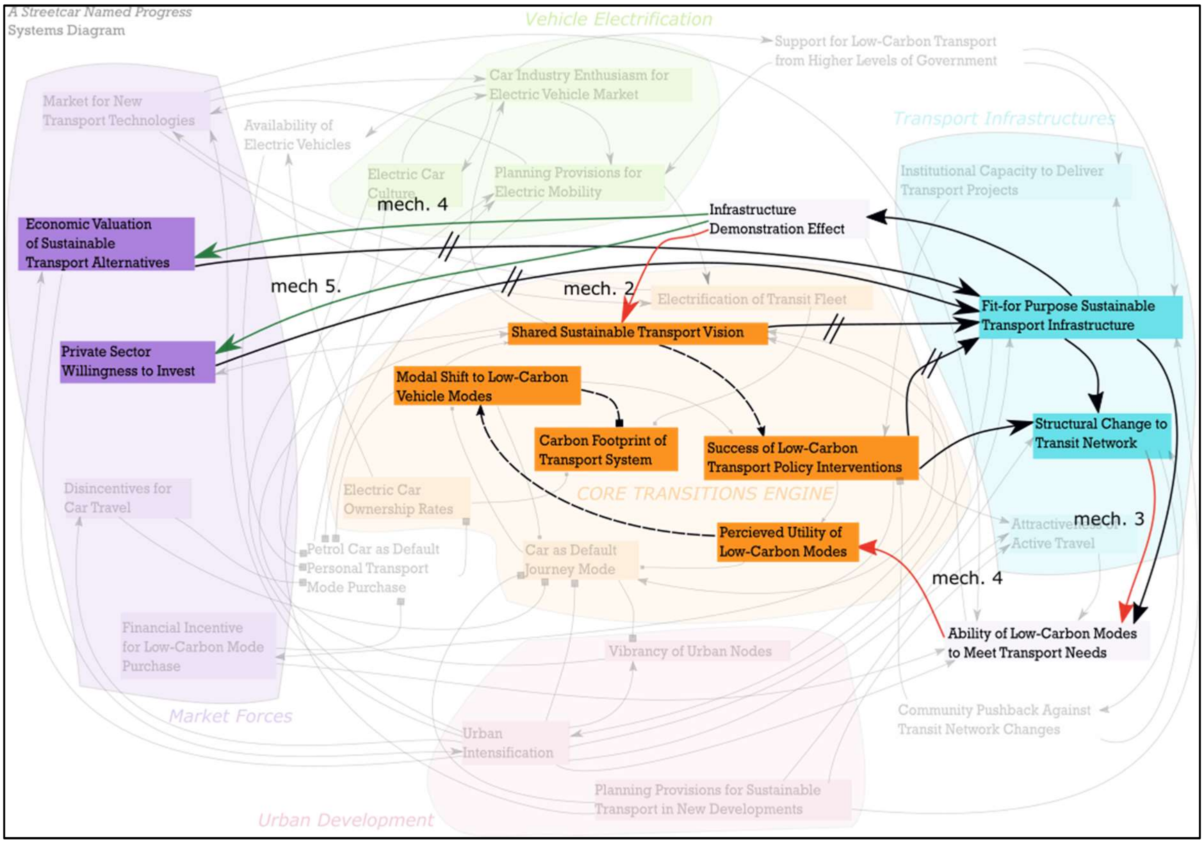

Figure 6-2 Mechanisms which are (at present) Enabling (Green) or Constraining (Red) the emergence of self-reinforcing dynamics relating to Ability of Low-Carbon Modes to Meet Transport Needs

The emergence of self-reinforcing dynamics around the outcome "ability of sustainable modes to meet individuals' travel needs" (x26) are enabled or constrained by a number of key mechanisms (Figure 6-2). Three mechanisms related to individuals and the community were identified: (2) the demonstration effect of sustainable transport infrastructure (x11) fostering a sense of shared vision around its benefits (x6), (3) structural change to transit networks (x23) generating widespread community support (x22), and (4) increased potential for sustainable modes to meet people's needs (x26) having tangible impacts on individual's travel behaviour and perceived utility of sustainable modes (x2). A further two market-based mechanisms for building positive inertia were identified, both causally influenced by the demonstration effects of new sustainable transport infrastructure (x11): (5) improving the economic valuation of sustainable transport projects (x13), and (6) increasing private sector willingness to invest (x16).

With respect to mechanism (2), interviewee MLA-2, representing the Opposition in the ACT's Legislative Assembly, notes that light rail's introduction and further plans have generated scepticism and opposition from parts of the Canberra community. MLA-2 cites two main community complaints: that light rail will only serve a small proportion of Canberra residents, even after the full network is complete, and that it has led to unwanted changes to existing bus services in parts of the city unaffected by the light rail roll-out. This suggests spatial variation in shared vision – those in areas with new light rail services are more likely to be impressed, those without access remain unconvinced of its benefits.

Thus, mechanism (2) demonstrates that the relationship between variables x11 and x6 may represent a challenge for engendering self-reinforcing dynamics in the feedback loops R4 and R5 (Table 4). In order to overcome this issue, interviewee MLA-2 suggests that the shared vision forming around new transport infrastructure must truly be 'shared'; buy-in must be achieved from a critical mass of city residents, not just those who directly benefit from the new infrastructure.

Secondly, interviewees highlighted mechanism (3) as a potential challenge to these feedbacks becoming self-reinforcing. The nature of changes made to the transit network will affect its outcomes. MLA-2 points out that the new integrated transport network introduced alongside Stage 1 of light rail introduced problems for many existing users of the bus system: removal of several dedicated school services, removal of service in parts of some suburbs, perceived lack of genuine consultation, and high cancellation rates of weekend bus trips. Despite these concerns, patronage from the new transit network has increased across the board (in all districts across Canberra, in all time periods). However, it is possible that these patronage gains could be greater if some of these concerns were addressed.

Finally, with respect to mechanism (4), improving the potential for public transport to meet people's needs does not automatically translate to individuals placing higher value on sustainable travel options. Individuals must first recognise this increased potential; D-1 suggests this may occur when trying the network for themselves. D-1 suggests that individuals could also come across this increased potential through journey planning and maps apps, evolving technology touchpoints, or word-of-mouth.

Moreover, in addition to these citizens-related mechanisms, there are also clear market-based opportunities for engendering positive inertia. Interviewees D-2, MLA-1, MLA-3 and A-1 highlight the potential of mechanism (5), illustrating that new infrastructure's demonstration effect can show off the project's economic benefits, strengthening the business case for further infrastructure development. Moreover, MLA-3 and A-2 discussed the potential of mechanism (6), explaining that demonstrably strong performance of new infrastructures can encourage private sector investment in driving further infrastructure development, providing another mechanism for generating self-reinforcing systems dynamics which may give rise to the emergence of positive inertia. Thus, mechanisms 5 and 6 demonstrate that garnering public support, through the building up of shared vision, is not the only way to entrench the outcomes of new infrastructure development (x18) and the increased ability of public transport to meet people's needs (x26).

6.1.3 Petrol Car as Default Transport Mode Purchase

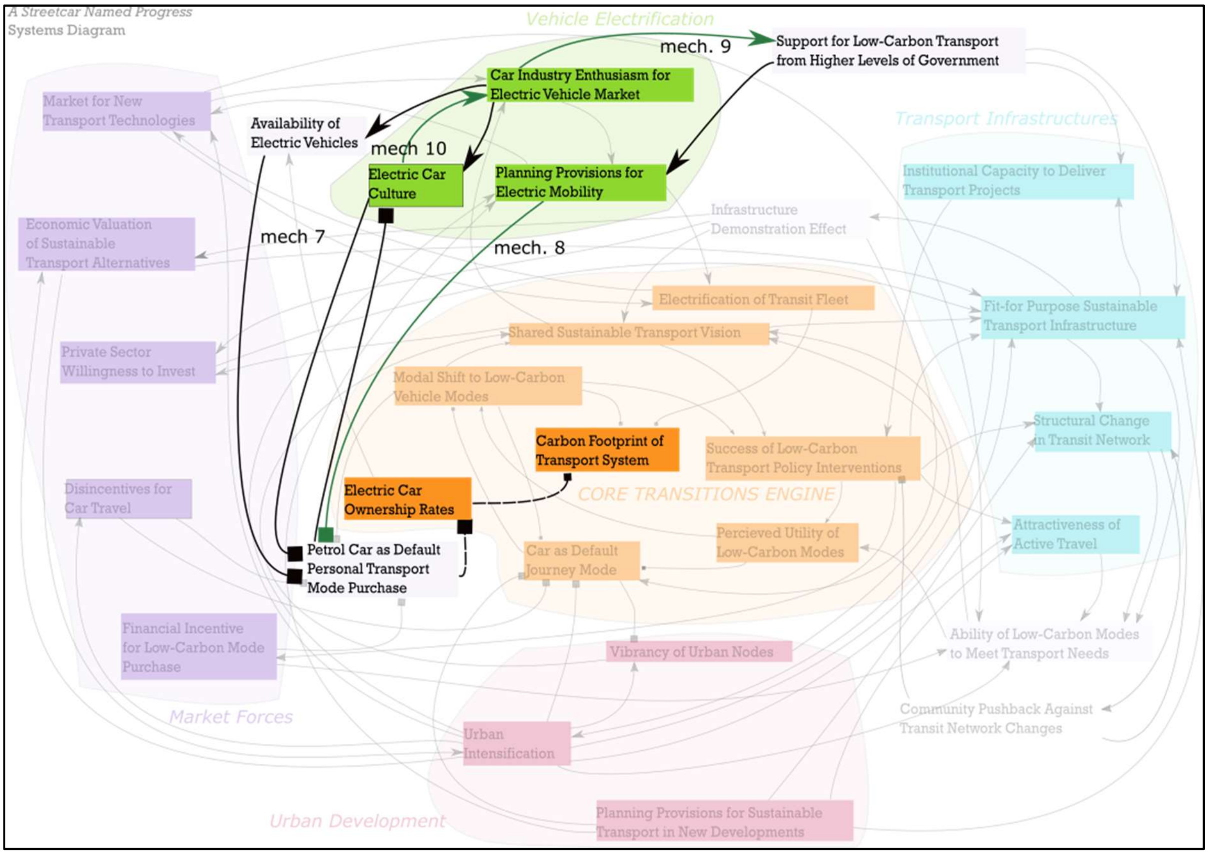

Figure 6-3: Mechanisms which are (at present) Enabling (Green) or Constraining (Red) the emergence of self-reinforcing dynamics relating to Petrol Car as Default Transport Mode Purchase

With respect to moving away from petrol cars being the default personal transport mode purchase (x10), there are a number of mechanisms which support this outcome. Mechanism (7) relates to the link between electric car availability (x14) and x10. Mechanism (8) relates to the link between planning provisions for electric mobility (x19) and x10. The link between the car industry's enthusiasm for electric cars (x15), and support for sustainable transport from higher levels of government (x20) is mechanism 9; the link between x15 and electric car culture (x12) is mechanism 10.

In terms of getting consumers to actually purchase electric cars, as opposed to petrol/diesel cars (x10), interviewee A-3 notes that mechanism (7) is currently very weak, and suggested that mechanism (8) may be more crucial for enabling the public adoption of electric cars. With respect to mechanism (9), interviewee A-3 commented that the car industry lobbies the federal government to support electric car adoption, including support for infrastructure and consumer subsidies.

6.1.4 Car as Default Journey Mode

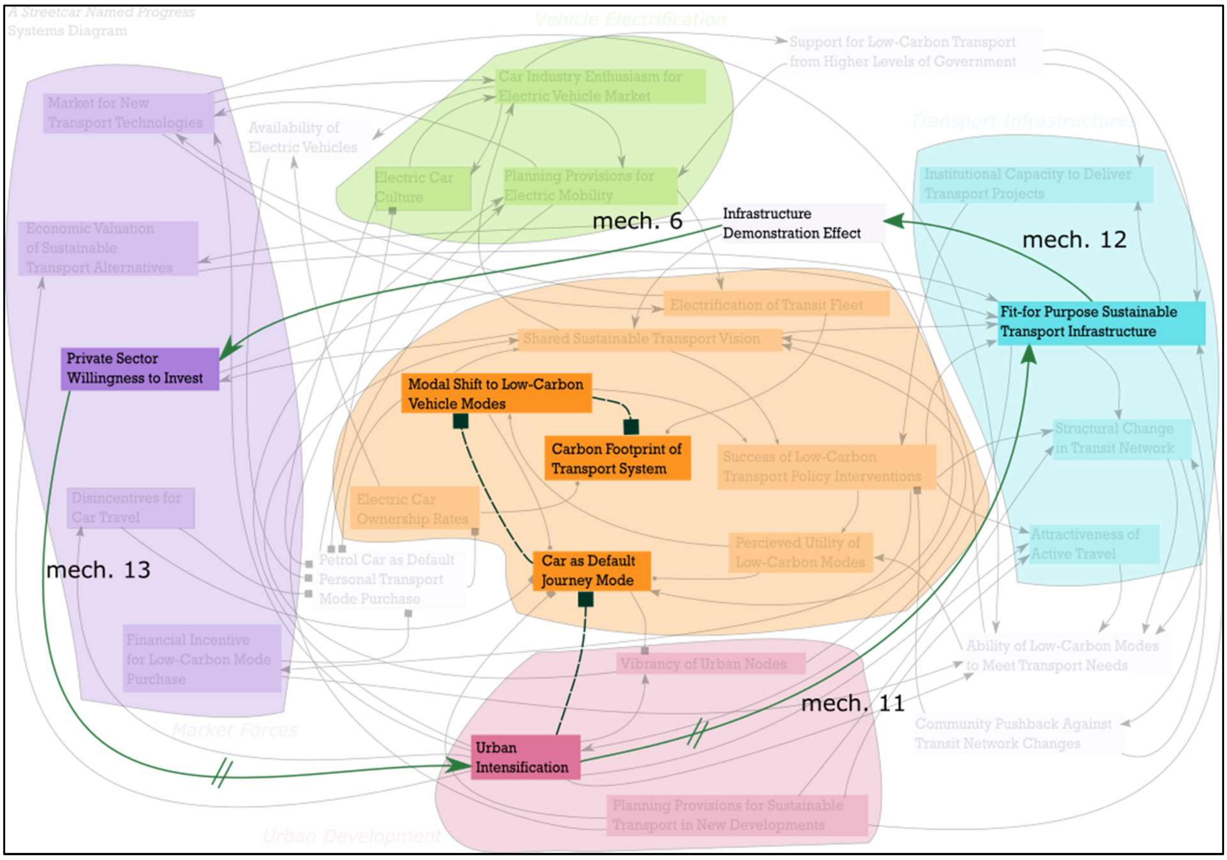

Figure 6-4: Mechanisms which are (at present) Enabling (Green) or Constraining (Red) the emergence of self-reinforcing dynamics relating to Urban Intensification

Interviewees suggest that the mechanisms 6 and 11-13 (links 1-2-3-4 in Table 6/Figure 4-6) form a feedback loop (Figure 6-4). They add that these mechanisms, forming a tight feedback loop, all represent opportunities for the emergence of self-reinforcing dynamics.

In terms of the operative aspects of the mechanisms, D-2 explains that new sustainable transport infrastructure (such as light rail) provides certainty to developers about future transport links and urban renewal, as well as potential land-value increase, contributing to their willingness to invest in building urban infill housing (intensification). D-3, D-4, and MLA-1 state that increased urban intensification triggers reviews of necessary transport policy interventions, which is highly likely to involve sustainable transport infrastructure.

What is noteworthy about the feedbacks involving urban intensification is that three of the four variables in the loop are actions – one led by governments (infrastructure), another led by the private sector (willingness to invest), and the last is the product of interactions between government and private sector developers (urban intensification). In addition, interviewees pointed out that housing preferences caused by demographic change – young people and older people are increasing favouring denser living – is helping to drive intensification. MLA-3 notes that these preferences demonstrate the promising business opportunity presented by urban intensification.

Thus, the emergence of reinforcing dynamics around urban intensification requires mechanisms which are under the jurisdiction of more than one act, suggesting some sort of co-operation or at least complementary interventions are needed. However, the flipside is that multiple different actors can contribute to building up initial momentum for interventions which involve urban intensification.

6.2 Effective and Appropriate Low-Carbon Transport Interventions

The following discussion contributes to the 'global urban science' proposed by Acuto *et al.* (2018), which calls for new and better knowledge regarding effective and appropriate urban climate policy, within the scope of this study's low-carbon urban transport focus.

This section expands on the mechanisms identified in section 6.1. Firstly, it quantifies particular mechanisms which are the most effective at creating transformative changes toward low-carbon transport outcomes; these mechanisms represent 'leverage points' in the system (Meadows, 1999; Abson *et al.*, 2017; Fischer and Riechers, 2019). Testing for leverage points involves removing individual links from the FCMs shown in Figures 6-1, 6-2, 6-3, and 6-4 (with system drivers as per $\vec{d}$ for Scenario A), recording the new value of the urban transport system's carbon footprint (x8), restoring the link, and testing another link. An arbitrary threshold of a 5% change against the baseline was used to classify a link as a leverage point; other links are omitted in the tables of results.

Secondly, it explores the 'appropriateness' of different applications of these mechanisms, i.e. potential caveats and unintended consequences. Findings from section 6.1 suggest that it may be 'easier' to create positive inertia by focusing on industry-based mechanisms rather than community-based ones (e.g. building shared vision), because the former present more as opportunities and the latter more as challenges/barriers. Whether such an approach is a good idea or not is a question this section will explore.

Throughout the discussion, *Aim 2,* RQ2, and *Methodological Consideration 2* of this study (table 10) will all be addressed. Five key leverage points - effective and appropriate interventions – for progressing transitions toward low-carbon urban transport systems were identified (Figure 6-5). The findings also indicate that a laissez-faire approach to relying on the private sector may have unintended consequences, as well as reduce the desirable impacts on low-carbon transport outcomes. Nonetheless, private sector involvement can still be beneficial if directed toward the 'right' outcomes. Thus, the discussion confirms a significant, and vital, role for city governments.

6.2.1 Vehicle Electrification

The adoption of electric cars appears to depend on two key leverage points (LPs). To identify these LPs, a sensitivity analysis was conducted on the highlighted links in Figure 6-1 and Figure 6-3.

LP1 is mechanism (5) from section 6.1.3, the link between planning provisions for electric mobility (x19) and whether people are buying petrol cars as default (x10). If this link were inactive, i.e. variable x19 has no causal influence on x10, the potential reduction in x8 would be roughly 14% less than the baseline (Table 11). A second LP, LP2, removes the influence of the motoring culture around electric cars (x12) entirely. This results in the strength of the links x15→x12, x12→x15, x10→x12, and x12→x10 all being set to zero. Under the conditions for LP2, the potential reduction in x8 would be around 11% less than the baseline (Table 11).

Table 11: Testing for leverage points relating to Vehicle Electrification

Link removed	Value of variable x8	% change compared to Baseline
Baseline	*-0.730*	*n/a*
x19→x10 (LP1)	-0.630	-14%
x15→x12, x12→x15, x10→x12, and x12→x10 (LP2)	-0.654	-11%
X4→x10	-0.706	-3%

Identification of the leverage points LP1 and LP2 shows that the most effective interventions for increasing electric vehicle adoption (x10), based on the mental models of the study's interviewees as captured in the study FCM, are planning provisions for electric mobility (x19) and creating a motoring culture around electric cars (x12). Additionally, this leverage points analysis (Table 11) is consistent with interviewee A-3's hypothesis that mechanism (4), relating to the availability of electric cars (x14), has a relatively weak influence on x10, and that other interventions are more crucial.

An important question to consider is which actors lead each of the interventions associated with LP1 and LP2. Interviewees A-1 and A-3 highlighted the private sector's role in fostering electric car culture (x12), through factors such as marketing, pricing, and availability of car models. Meanwhile, interviewees D-4, MLA-2, A-1, and A-3 referred to city governments as the key actor which would plan for electric mobility, including the use of policy levers such as introducing zoning requirements. However, interviewee Developer-1 notes that private developments, such as the Ginninderry project on Canberra's north-west urban fringe, are also involved with planning provisions for electric mobility (x19), through the provision of electric car charging stations.

Therefore, it appears that both city governments and private sector bodies have their own key ‘effective and appropriate intervention’ to promote electric vehicle adoption. City governments should broadly expand planning provisions for electric mobility across the urban area, such as zoning rules and publically-owned electric car charging facilities. Meanwhile, private sector bodies, namely the car industry, can positively impact low-carbon transitions in urban transport by promoting a culture and positive associations around electric cars, as well as increasing their availability.

6.2.2 Sustainable Transport Infrastructure

With respect to interventions involving new sustainable transport infrastructures, such as light rail, two LPs can be identified (on the basis of the highlighted links in Figure 6-2). LP3 is the link between sustainable transport infrastructure (x18) and the increased potential of sustainable modes to meet people’s travel needs (x26). If this link were removed entirely, i.e. variable x18 has no causal influence on x26, the potential reduction in x8 would be roughly 15% less than the baseline (Table 12). Meanwhile, LP4 is the same link as mechanism (1) from section 7.1.2, representing the relationship between new sustainable transport infrastructure (x18) and its demonstration effect (x11). If this link were to not exist, i.e. variable x18 has no causal influence on x11, the potential reduction in x8 would be around 10% less than the baseline (Table 12). Thus, LP3 results in a bigger reduction in the value of x8 than LP4.

Link removed	**Value of variable x8**	**Percentage change compared to Baseline**
Baseline	*-0.730*	*n/a*
x18→x26 (LP3)	-0.620	-15%
x18→x11 (LP4)	-0.654	-10%
x6→x18	-0.699	-4%

Table 12: Testing for leverage points relating to Infrastructure Interventions

The identification of leverage points LP3 and LP4 suggest that both demonstration effects (x11), and improving people’s ability to use sustainable modes to meet their travel needs (x26), are critical policy levers for ensuring that transport infrastructure interventions (x18) are effective at engendering the desired outcomes in terms of decarbonising transport (x8). However, Ramos-Santiago *et al.* (2015) and Wood and Brown (2019) point to analysis of streetcar (a type of rail-based public transport technology broadly similar to light rail) projects in the United States to highlight a potential caveat: many projects prioritised creating demonstration effects (x11) for private developers that catalyse urban development outcomes (x29), rather than focusing on providing ‘useful’ transportation (x26). It is certainly possible that a light rail project (x18) that promotes urban development (x29) also contributes to the goal of reducing the urban transport system's carbon footprint (x8), if the aforementioned development activity leads to the city becoming more compact (see Figure 6-4), however such an outcome is not assured. This raises the question of how, and to what extent, prioritising infrastructure outcomes in this way might affect the outcomes of transitions toward low-carbon urban transport (x8) – and whether such trade-offs are relevant in Canberra's experience.

Based on further quantitative modelling using the study FCM, it was found that a scenario where demonstration effects are prioritised for development purposes (AS1) results in around 12% less decrease in x8 (carbon footprint of the urban transport system) compared to the baseline, whereas prioritising useful transport outcomes (AS2) leads to an additional 4% decrease in x8 (Table 13). These scenarios were premised on the strength of the demonstration effect (x18 → x11) being kept constant, with the link strengths x11→x16, x11→x6, and x11→x26 being modified depending on which set of outcomes were prioritised. These results (Table 13) suggest that in the case of sustainable transport infrastructure interventions, prioritising urban development over transportation outcomes is clearly detrimental to the achievement of low-carbon urban transport outcomes.

Scenario	**(Amended) Link Weights**	**Value of variable x8**	**% change compared to Baseline**
Baseline	*x18→x11: 0.3;* *x11→x16: 0.3;* *x11→x6: 0.3;* *x18→x26: 0.3*	*-0.730*	*n/a*
AS1: Prioritise Demonstration Effect (x11) for Development	x18→x11: 0.3; x11→x16: 0.8; x11→x6: 0.0; x18→x26: 0.1	-0.645	-12%
AS2: Prioritise Useful Transport Outcomes (x26)	x18→x11: 0.3; x11→x16: 0.4; x11→x6: 0.5; x18→x26: 0.5;	-0.759	+4%

Table 13: Testing scenarios relating to the relative prioritisation of outcomes for sustainable transport infrastructure interventions

6.2.3 Urban Development

Concerning urban development, one additional LP can be identified (on the basis of the highlighted links in Figure 6-4). LP5 is the link between urban intensification (x29) and planning provisions for electric mobility (x19). If this link were removed entirely, such that variable x29 has no causal influence on x19, the potential reduction in x8 would be around 16% less than the baseline (Table 14). Note that LP4 is also relevant to feedbacks which involve urban intensification (x29).

Table 14: Testing for leverage points relating to Urban Development Interventions

Link removed	Value of variable x8	% change compared to Baseline
Baseline	*-0.730*	*n/a*
x18→x11 (LP4)	-0.654	-10%
x29→x19 (LP5)	-0.617	-16%

The identification of LP5, in conjunction with LP1, reiterates the critical nature of planning provisions for electric mobility (x19) in facilitating the decarbonisation of urban transport systems. Moreover, it affirms result 4 (section 4.3), which finds that urban interventions broader than just the transport domain (e.g. urban intensification) can also be crucial to the attainment of low-carbon urban transport outcomes.

6.2.4 Study FCM with Leverage Points

The study FCM, with leverage points highlighted for easy identification, is presented in Figure 6-5 below. Essentially, Figure 6-5 highlights the linkages identified in Figure 4-1 which are most critical for progressing sustainability transitions toward low-carbon urban mobility – so-called ‘effective and appropriate interventions’. Moreover, it represents the culmination of all the analysis and discussion undertaken throughout Chapters 4, 5, and 6.

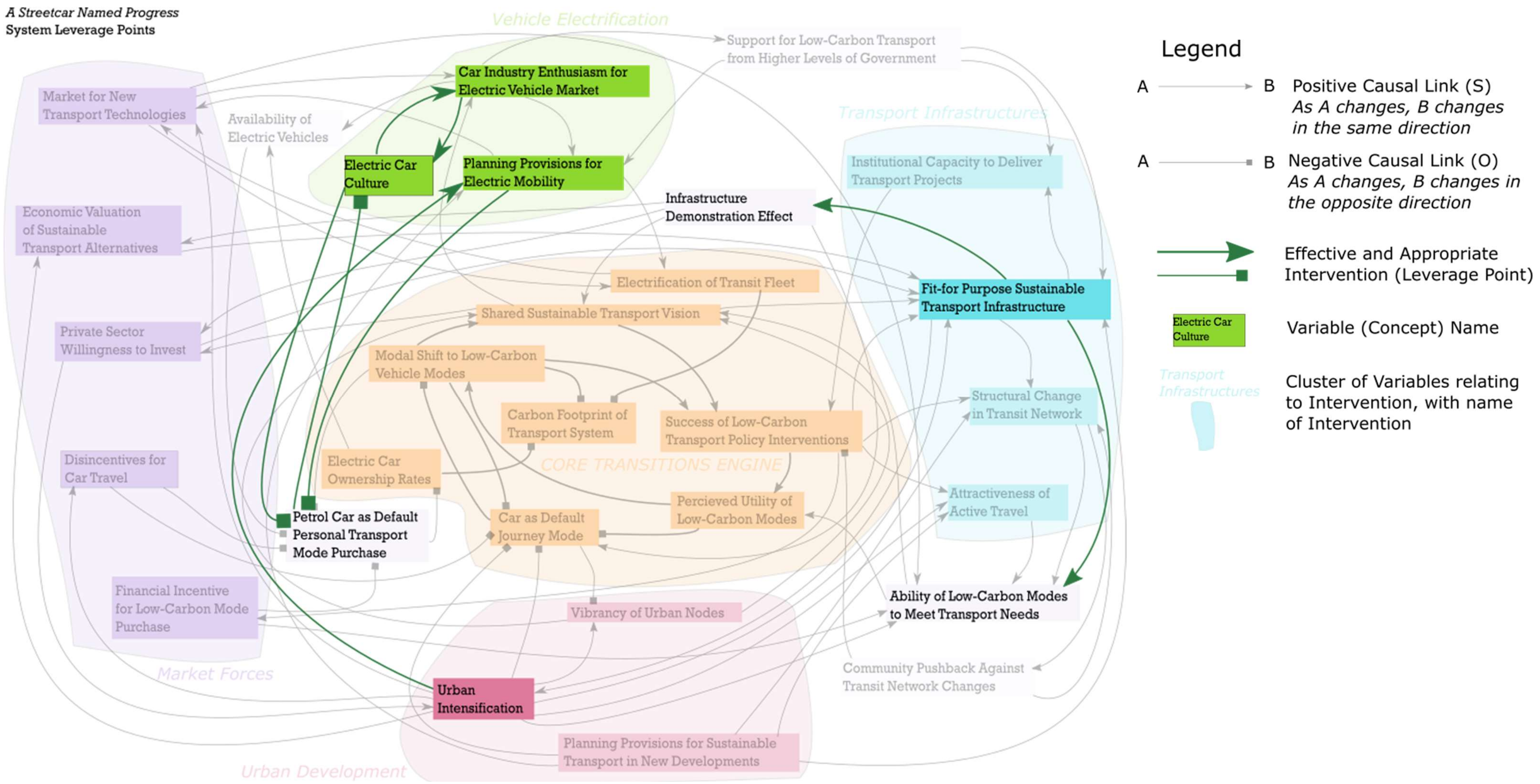

Figure 6-5: Study FCM (adapted from Figure 4-1), with the five identified Leverage Points highlighted in green

6.3 Practical Implications (Summary for Policymakers)

The quantitative modelling conducted by this study confirms that the actions in the transport section of the *ACT Climate Change Strategy 2019-25* will have a definite impact on reducing the carbon footprint of Canberra's transport system. Estimates from this study suggest that the carbon footprint will be reduced to around one-quarter of current levels. However, this is not quite meet the target of net-zero emissions from Canberra's transport sector (ACT Government, 2018).

To achieve the remaining one-quarter emissions reduction (compared to current levels), this study finds that leveraging market forces and collaborations with the private sector is a possible policy pathway. This would involve improving the economic valuation of sustainable transport projects, leveraging the private sector willingness to invest, and encouraging the car industry's enthusiasm for electric cars.

With respect to implications for cities more generally, this study identifies several mechanisms which provide pathways for low-carbon urban transport outcomes, such as the ability of sustainable modes to meet travel needs, to become self-reinforcing (Table 15). These mechanisms can be utilised to help 'lock-in' low-carbon urban transport outcomes during both the planning and implementation phases of climate policy interventions for low-carbon urban transport. Utilising these mechanisms could assist in making transitions toward low-carbon urban transport more resilient, contributing to enduring change that engenders low-carbon urban futures.

Table 15: Mechanisms for locking-in Low-Carbon Transport Outcomes (based on comments from interviewees)

Mechanism No.	Linkage	Mechanism	Key Partner
1	Electrification of Transit Fleet → Market for New Transport Technologies	City governments signalling to industry their intention to buy electric buses	Industry
2	Sustainable Transport Infrastructure → Infrastructure Demonstration Effect	Design new infrastructure to have tangible benefits, and clearly communicate these benefits when realised	Industry and/or Community
3	Structural Change in Transit Network → Community Pushback to Changes in the Transit System	Design-in equitable outcomes into transit network changes	Transport Canberra Directorate (ACT), transit agencies (other cities)
4	Potential for Sustainable Modes to Meet Travel Needs → Perceived Utility of Sustainable Modes	Ensure that travellers are aware of how sustainable modes have improved. Communication campaigns, information in maps apps and journey planners etc.	Transport Canberra Directorate (ACT), transit agencies (other cities)
5	Infrastructure Demonstration Effect → Economic Valuation of Sustainable Transport Projects	Ensure that projects are designed to have strong economic benefits and/or adjust cost-benefit analysis criteria; ensure benefits are realised post-implementation	City government agencies
6	Infrastructure Demonstration Effect → Private Sector Willingness to Invest	Ensure that infrastructure has a compelling return on investment (if targeting project investment partnerships); ensure that infrastructure provides certainty and economic benefits to developers (if targeting urban development outcomes)	City government agencies, Industry
7	Availability of Electric Cars → Petrol Car as Default Transport Mode Purchase	Potential to provide incentives (e.g. subsidies, property rates discount) for electric car purchases (note: city	City government agencies, Industry

Mechanism No.	Linkage	Mechanism	Key Partner
		governments may have limited jurisdiction here)	
8	Planning Provisions for Electric Mobility → Petrol Car as Default Personal Transport Mode Purchase	Provide effective electric car infrastructure to support and encourage individuals' decisions to buy electric cars	City government agencies
9	Car Industry Enthusiasm for Electric Cars → Support for Sustainable Transport from Higher Levels of Government	Lobbying efforts.	Industry
10	Car Industry Enthusiasm for Electric Cars → Electric Car Culture	Encourage car industry enthusiasm for electric cars – provide electric car infrastructure, procure electric car fleets for government use etc. (Note: city governments may have limited jurisdiction here)	Industry
11	Urban Intensification → Fit-for-Purpose Sustainable Transport Infrastructure	Design infrastructure into urban development planning; encourage and/or mandate private sector developers to contribute to infrastructure development	Industry
12	Fit-for-Purpose Sustainable Transport Infrastructure → Infrastructure Demonstration Effect	Design broader and tangible economic benefits into infrastructure projects (but take note of who these benefits are for, and what kinds of outcomes are prioritised)	City government agencies, Industry
13	Private Sector Willingness to Invest → Urban Intensification	Encourage private sector urban development efforts to be concentrated around transit corridors	City government agencies, Industry

Among the interventions for low-carbon urban transport identified by this study, a select few interventions emerge as the most effective and appropriate (Table 16). These so-called ‘leverage points’ could inform the prioritisation of interventions to be implemented or included in climate policy for low-carbon urban transport. Within this study’s context, leverage points refer to the individual interventions which have the biggest overall impact on reducing the urban transport system’s carbon footprint. To provide an indication of priority, the last column of Table 16 provides a ranking for each leverage point (1st being the leverage point with the largest impact).

Table 16: Leverage Points for the Transition toward Low-Carbon Urban Transport Systems

Leverage Point (LP)	Linkage	% Change in Carbon Footprint Reduction Potential of ACT Climate Change Strategy, if linkage is inactive
LP1	Planning Provisions for Electric Mobility → Petrol Car as Default Personal Transport Mode Purchase	-14% (3rd)
LP2	All links in- and out- of Electric Car Culture	-11% (4th)
LP3	Sustainable Transport Infrastructure → Potential for Sustainable Modes to meet Travel Needs	-15% (2nd)
LP4	Sustainable Transport Infrastructure → Infrastructure Demonstration Effect	-10% (5th)
LP5	Urban Intensification → Planning Provisions for Electric Mobility	-16% (1st)

Nonetheless, a key caveat when designing and implementing these mechanisms or interventions is the potential to produce perverse outcomes. Choosing the most politically or financially expeditious solution could in fact compromise the attainment of low-carbon transport outcomes. A key example from this study is that designing new sustainable transport infrastructure to primarily benefit private urban developers, as opposed to improve transportation outcomes, can decrease the effectiveness of decarbonisation efforts by more than 10% (Table 13).

6.4 Theoretical Implications (Contributions to the Literature)

This study aimed to make a contribution to an ambitious research agenda for urban climate scholarship, sketched out by McPhearson *et al.* (2016), Hughes (2017), and Acuto *et al.* (2018). Three key goals of this agenda, coined the 'global urban science' by Acuto *et al.* (2018), were the following: (1) new and better knowledge about effective and appropriate urban climate policy interventions (Acuto *et al.*, 2018), (2) providing science-based advice to policymakers (McPhearson *et al.*, 2016), and (3) improving understandings of the mechanisms and strategies used by various actors to enable or constrain urban climate policy interventions (Hughes, 2017).

In terms of goal (1), this study identified five leverage points relating to electric cars, sustainable transport infrastructures, and urban intensification, representing 'effective and appropriate' interventions. The broad themes of these leverage points – that they relate to cleaner vehicles, infrastructure, and compact development – are similar to the key findings identified in other studies (cf. Shiau and Liu, 2013; Ewing and Cervero, 2017; Nelson, 2017; Gössling *et al.*, 2018; Vagnoni and Moradi, 2018). However, the novel contributions of this study relate to the identification of effective interventions from a larger range of possible climate policy interventions than other studies, and that this study evaluates the appropriateness of different interventions for engendering desired low-carbon outcomes. Moreover, this study provides novel insights relating to the interactions between city governments and the vehicle manufacturing industry (Vagnoni and Moradi, 2018).

For goal (2), this study's main contribution is to advance the use of FCM techniques in the literature on low-carbon urban transport; Doukas and Nikas (2020) found that despite the suitability of FCM to this field, its application is currently very limited. Further comment on the method's limitations, and future work for improving the use of FCM techniques in low-carbon transitions research, are discussed in section 6.5.

Regarding goal (3), this study offers the insight that city governments have an unequivocally critical role in leading and directing transitions toward low-carbon urban transport systems, in order for such transitions to be successful. On one hand, this provides a counterpoint to recent research within the transport domain that uses the multi-level perspective – dominant in sustainability transitions studies (Köhler *et al.*, 2019) – as an analytical framework (Geels, 2012; Moradi and Vagnoni, 2018).

A main point of contention is the identification of *who* leads particular actions. Geels (2012) and Moradi and Vagnoni (2018) suggest that initiatives such as compact urban development and liveable streets are niche initiatives, led by social movements and/or community organisations. Yet, Canberra's experience has been that the ACT Government and private sector developers are leading these activities, driven by feedbacks between climate change concerns, maturing sustainable transport infrastructures, and demographic preferences for dense living. Additionally, Marletto (2014) proposed that electricity companies might lead vehicle electrification in cities; the ACT has found that the car industry is leading in this area, with the electricity sector playing a limited role.

A related point of contention is *what* kinds of effective interventions lie within the jurisdiction of city governments. Vagnoni and Moradi (2018) found that in an Italian context, the only factors with a direct effect on the urban transport system's carbon footprint were "strategies and plans". However, the leverage points identified in this study (Figure 6-5) show that city governments can also make effective contributions to transport decarbonisation efforts by advancing actions (infrastructures, urban intensification, planning provisions for electric mobility) as well as collaborating with the private sector to promote industry-led interventions (urban intensification, electric car culture, car industry enthusiasm for electric vehicles).

On the other hand, this study's findings are generally consistent with transitions studies that examined low-carbon transitions at the broader city (rather than urban sub-system e.g. transport) level, which emphasise the importance of city governments' leadership in transition efforts (Bai *et al.*, 2010; Bulkeley *et al.*, 2012; Peng and Bai, 2018). However, this study adds nuance to these conclusions, as it suggests that the city government role in transitions remains important throughout the transition.

In addition to its contributions to the emerging urban climate research agenda, this study also represents (to the best of the author's knowledge), one of the first applications of the 'positive inertia' concept proposed by Irvine and Bai (in press). This study's application of positive inertia uncovered some findings which can be used to enhance the development of the concept. Firstly, that the initial momentum in positive inertia can have different resistance, different drivers, and be built-up over different timescales. Secondly, that the conditions for positive reinforcing feedback loops to give rise to positive inertia may require interventions to ensure that particular linkages between variables in the feedback loop remain active. Thirdly, that there are a number of different positive feedback loops capable of locking-in low-carbon outcomes, presenting multiple pathways for the emergence of positive inertia – but relying on particular feedback loops may have perverse outcomes. An example of this is leveraging private-sector-development to promote improved accessibility to sustainable modes.

Finally, this study also found many commonalities between the Australian experience in transitioning transport systems to be low-carbon, and some American cities' experience at transitioning their transport systems, e.g. Atlanta, Cincinnati, Kansas City, and Tucson, in terms of trams/streetcars making a comeback as a public transport mode, new streetcar projects being leveraged as a catalyst for urban development, and people living far away from the footprint of new transit infrastructures being openly sceptical about their promised benefits (Wood and Brown, 2019). This suggests that there may be opportunities for learning and best-practice transfer between these two contexts.

An example is that Ramos-Santiago *et al.* (2015) attributes the strong relative transit performance of the streetcar in Portland, Oregon as linked to planning and operational decisions which situated the streetcar route alongside homes and jobs, connecting key destinations, and providing frequent service with long service hours. Early evidence from Canberra's light rail experience is consistent with Portland's, adding to the evidence base about what kinds of light rail projects create meaningful transportation outcomes. Moreover, U.S. researchers are mostly interested in the transportation and urban development roles of streetcars (Ramos-Santiago *et al.*, 2015), and not so much on their impact on low-carbon urban transport outcomes. In that context, this study offers the finding that many of the same determinants for transit performance also lead to reductions in the transport system's carbon footprint. Nonetheless, a caveat is that Canberra's light rail system runs on 100% clean energy.

6.5 Limitations and Opportunities for Future Work

Given that this study attempts to capture the dynamics of a complex socio-technical system – urban transportation – it is subject to what Newell and Proust (2017) refer to as the 'complexity dilemma'. While the full systems diagram may be considered to be too complicated to be an effective communication tool, isolating individual feedbacks risks ignoring dynamics that connect to other parts of the system. This study attempts to address these twin limitations through two approaches: (1) illustrating individual feedbacks in context of broader system dynamics, by highlighting where they are situated within the full systems map, and (2) quantitative modelling, which uses scenarios to balance ease-of-communication with interpretable results that account for all dynamics present in the full systems map.

The robustness of the quantitative modelling is also limited by the 'fuzzy' nature of the FCM method, as conceptual variables have 'fuzzy' definitions and relationships (Kosko, 1986). Moreover, the FCM is entirely based on the conceptual mental models of interviewees, which are undoubtedly subject to both conscious and unconscious biases. As a result, the findings of this study are presented with the understanding that they are based on the aforementioned mental models which cannot be considered to be completely objective.

Although outside the scope of this study, a suggestion for further work is to develop an FCM model based on a quantitative indicator framework. This would facilitate more precise definitions of the variables and link weights included in the model. An example of this can be found in Shiau and Liu (2013), which also applied FCMs to sustainable transport, albeit with a much smaller conceptual scope than this study.

The literature identifies a limitation of traditional FCMs as being their omission of time lags – i.e. knowledge about the temporal relationship between variables (Park and Kim, 1995; Nair *et al.*, 2019). Park and Kim (1995) point out that traditional FCMs assume that all causal effects occur in a single unit of time, suggesting that accounting for time lags would yield a more realistic map. Although this is also beyond the scope of this study, future work could explore augmenting the study FCM with time lags, bearing in mind the potential challenges in accurately estimating and representing time lags for each causal relationship (Park and Kim, 1995).

Chapter 7: Conclusion

The evidence is clear – action is urgently required to mitigate the worst effects of climate change. Yet, many national governments are laggards when it comes to climate action. Against this backdrop, the world's cities have emerged as a promising arena for pursuing climate change mitigation. Within cities, the urban transport system has been identified as a key priority area for reducing emissions for the purpose of mitigating climate change.

Therefore, this study adopted the overarching research question: *How, and to what extent, can city-level actors create meaningful progress toward decarbonising urban transport systems?* To address this overarching research question, this study defined two aims. Firstly, to identify how low-carbon urban transport outcomes can be made self-reinforcing. Secondly, to improve understandings of which interventions for low-carbon urban transport are the most effective and appropriate. The main methods used in this study were qualitative interviews, which were then modelled using Fuzzy Cognitive Maps (FCMs), a form of systems thinking approach. In order to ensure a manageable scope for the research, the city of Canberra, Australia was chosen as a case study.

With respect to the first aim, this study found that there are many different types, strengths, and characteristic timescales which determine the generation of initial momentum for interventions that lead to low-carbon transport outcomes. Moreover, a key finding is that there are many mechanisms which can assist in creating the conditions for these low-carbon transport outcomes to become self-reinforcing, once the initial momentum has been created. Some of these rely on community support, such as the building up of shared vision around sustainable transport initiatives. Others depend on leveraging market forces, such as the private sector's willingness to invest in sustainable transport infrastructure and compact development efforts.

The findings relating to the second aim build on the above. A key result was that both city governments and private sector bodies have jurisdiction over effective and appropriate interventions which can produce significant reductions in the overall carbon footprint of urban transport. This study identified four such 'leverage points', within the categories of vehicle electrification and infrastructure for sustainable transport modes. However, this study also identified several caveats relating to private sector involvement. In the case of electrifying private vehicles, despite the car industry's capacity to increase electric car availability and promote 'electric car culture', the city government's role in providing associated infrastructure has an even bigger effect on decarbonisation outcomes. Regarding the building of new sustainable transport infrastructures such as light rail, a city government that prioritises urban development interests risks decreases such infrastructure's ability to reduce the transport system's overall carbon footprint.

To comment on the 'to what extent' aspect of the overarching research question, the quantitative modelling in this study indicates that the transport actions contained in the *ACT Climate Change Strategy 2019-25* have the potential to reduce Canberra's urban transport emissions by around half of current levels.

In terms of contributions to the literature and addressing critical research gaps in urban climate scholarship, this study has generated new knowledge about effective and appropriate urban climate policy interventions, provided new insights on the roles of different actors in transitions toward low-carbon urban mobility, and applied the newly defined 'positive inertia' concept as an analytical framework. Moreover, this study has identified important areas for future research. A key focus could be the development of an accompanying quantitative indicator framework for the study's FCM, so as to provide more robust numerical estimates for the FCM's edge weights, and the impact of drivers on variables. Further participatory workshops should provide a more rigorous definition of the concepts (variables) in the FCM. Finally, a worthwhile focus would also be to consider how to best address the 'complexity dilemma' when modelling and presenting urban transition processes using systems tools such as FCMs, to balance complexity with comprehensibility.

In summary, this study recognises the role of both city governments and private sector bodies in implementing interventions that lead to the decarbonisation of urban transport. However, it cautions that a laissez-faire, or pandering, approach to private sector involvement may diminish the effectiveness of interventions made with the express goal of creating a low-carbon urban transport system. Thus, this study concludes that city governments have a crucial and non-negotiable role in transitions toward low-carbon urban transport, and suggests effective and appropriate interventions for city governments to fulfil this mandate.

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Appendix 1: List of Variables

Variable Number	Intervention Theme	Variable Description
x1		Success of Sustainable Transport Policy Interventions
x2		Individuals' Perceived Utility of Sustainable Transport Modes
x3		Car as Default Journey Mode
x4		Electric Car Ownership Rates
x5		Modal Shift to Sustainable Vehicle Modes
x6		Shared Vision around Sustainable Transport
x7	Vehicle Electrification	Electrification of Transit Fleet
x8		Carbon Footprint of Transport System
x10		Petrol Car as Default Personal Transport Mode Purchase
x11		Infrastructure Demonstration Effect
x12		Electric Car Culture
x13		Economic Valuation of Sustainable Transport Alternatives
x14		Availability of Electric Vehicles
x15	Vehicle Electrification	Car Industry Enthusiasm for Electric Vehicles
x16	Market Forces	Private Sector Willingness to Invest
x17	Market Forces	Market for New Transport Technologies
x18	Infrastructure	Fit-for-Purpose Sustainable Transport Infrastructure
x19	Vehicle Electrification	Planning Provisions for Electric Mobility
x20		Support for Sustainable Transport from Higher Levels of Government
x21	Infrastructure	Institutional Capacity to Deliver Transport Projects
x22		Community Pushback to Changes in the Public Transport System
x23	Services	Structural Change in Public Transport Network

x24	Market Forces	Financial Incentives for Ownership of Sustainable Personal Transport Modes
x26		Ability of Sustainable Modes to Meet Transport Needs
x27	Services	Attractiveness of Active Travel
x29	Urban Development	Urban Intensification (Co-location of homes, jobs, and services)
x30	Urban Development	Planning Provisions for Sustainable Transport in New Urban Developments
x32	Urban Development	Vibrancy of Urban Nodes
x33	Market Forces	Disincentives for Car Travel

Appendix 2: Edge Weights for Study FCM (Adjacency Matrix)

The adjacency matrix (Table 17) is defined such that, in a relationship A → B, the columns represent 'A' and the rows represent 'B'. The values are between 0 and 1. Empty cells mean that there is no relationship between the two respective variables.

	v1	v2	v3	x4	x5	x6	x7	x8	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33
x1					0.3	0.4														+0.4	-0.7											
x2	0.2																0					0			0.6							
x3		-0.4			-0.4					-0.2																		-0.3	-0.1			-0.3
x4									-0.7																							
x5		0.2	-0.4																													
x6										0.4															0.3						0.2	
x7																0.4		0.6														
x8				-0.4	-0.4		-0.4																									
x10					-0.3						-0.4		-0.2					-0.4					-0.4									-0.2
x11																	0.3															
x12									-0.2					0.6																		
x13										0.3																		0.2				
x14				0.4										0.4																		
x15						0.3					0.2				0.2																	
x16						0.2				0.3																						
x17							0.2											0.5										0.4				
x18	0.3					0.3						0.4			0.3				0.2									0.3	0.3			
x19														0.3					0.2									0.6	0.2			
x20														0.6																		
x21																	0.4		0.2													
x22																	0.4					0.4										
x23	0.3																0.1												0.2			
x24	0.3																															
x25																																
x26																0.4	0.4					0.3	0.4			0.3		0.4				

	v1	v2	v3	x4	x5	x6	x7	x8	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33
x27	0.3																											0.3	0.3			
x28																																
x29															0.2																	
x30																																
x31																																
x32			-0.3																									0.4				
x33																												0.2				

Table 17: Edge Weights for Systems Diagram / Adjacency Matrix for FCM

[1]

[1] Photos are author's own