Transport resilience to weather and climate

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Urban transport resilience to weather and climate: an interdisciplinary view from Rio de Janeiro

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Abstract

Weather causes damage and disruption to public transport, especially in developing megacities where transport demand is high, trip-lengths can be long, and poor socio-economic conditions exacerbate impacts. Here, an analytical framework overviews urban transport resilience to current weather and future climate in Rio de Janeiro. It describes how heavy rainfall and high temperatures impact on rail, metro, and Bus Rapid Transit (BRT) networks, and characterises the triggers, actors and linkages that combine to create barriers or pathways to transport resilience. There are three improvements to weather and climate resilience, namely; (i) the creation of Centre of Operations Rio (Centro de Operações Rio; COR) to co-ordinate daily operations and disaster response, (ii) a series of innovations in operational integration enabled by co-locating services within COR; and, (iii) infrastructure investment prior to the Olympic Games, which increased transport provision. The results highlight the need for integration and leadership across the private transport sector and demonstrate how resilience to current weather and future climate is intrinsically linked to sustainable urban mobility and should be considered in state and municipal planning strategies for housing, public services, and commercial and industrial development. Without adaptation, climate change will exacerbate existing systemic problems identified by the framework.

Key words:
Sustainable Urban Mobility
Town & city planning
Transport planning
Climate adaptation

1. Introduction

In the future, increasing numbers of people will live in urban areas (UN, 2016a), and urban areas are expected to experience more extreme weather events associated with climate change (Rahmstorf & Coumou, 2011; Coumou & Rahmstorf, 2012; Fischer & Knutti, 2015). The resilience of urban transport systems to current weather and future climate is therefore paramount; transport allows people to access jobs, markets, education, healthcare, and other amenities, which are fundamental to modern society (UN, 2016b). Nowhere is this more important than in megacities (i.e. a city with more than 10 million people) where transport demand is high (Morichi, 2005), and in which urban sprawl has led to high and generally increasing travel times (Gakenheimer, 1999; Motte et al., 2016). The high demand for transport services in megacities means that even relatively minor or short-lived disruption to the transport systems caused by weather has the potential to impact a large number of people. Moreover, the majority of current (24 of 31) and future (34 of 41) megacities are in the developing Global South (UN, 2016a) where economic and social issues such as poverty and poor infrastructure services makes them particularly susceptible to weather events (Mirza, 2003; De Sherbinin et al., 2007; Cervero, 2013).

There are numerous studies examining the impact of extreme weather on transport systems (e.g. Koetse & Rietveld, 2009; DfT, 2014; Molarius et al., 2014; Jaroszweski et al., 2015; Ferranti et al. 2018), or the potential longer-term impact of climate change (e.g. National Research Council, 2008; Koetse & Rietveld, 2009; Jaroszweski et al., 2010; Palin et al, 2013; Leviäkangas, & Michaelides, 2014; Jaroszweski et al., 2014). There are also several studies that consider the concept of transport resilience (e.g. Mattson & Jenelius, 2015; Reggiani et al., 2015; Wang, 2015), or that measure the resilience of a particular system(s) (e.g. DfT, 2014; D'Lima & Medda, 2015). However, except Schweikert et al. (2014) and Hearn (2015) there is little research describing the impact of current weather on transport, or discussing transport resilience in the Global South. Indeed, Koetse & Rietveld's (2009) overview of the impact of climate change and weather on transport includes over 28 case studies from North America, over 13 case studies from Europe, and others from Australia, Israel and Japan; but no case studies explicitly from the Global South. Similarly, the International Transport Forum (ITF) report, *Adapting Transport to Climate Change and Extreme Weather* features few case studies from the Global South (ITF, 2016). There is also little consideration of the socio-cultural context of transport resilience. For example, urban flooding is only considered problematic for road transport in Ho Chi Minh City, Vietnam, when the level of water is deeper that a motorcycle exhaust pipe (interview, HCMC, January, 2017). Similar or lesser depths of flooding would be unacceptable in London, UK. The expectation of transport resilience therefore varies globally, and transport resilience studies must consider the local context.

Separately, and particularly in the last two decades, there has also been significant scholarly research on urban resilience (Sharifi, 2020). A review by Büyüközkan et al. (2022) classifies these into three headings; literature reviews, conceptual models, and analytical models (see references therein). There are also studies that overlap into other research areas such as sustainability (e.g. Zeng et al., 2022; Zhang and Li, 2018) and urban planning (e.g. Masnavi et al., 2018). There is also a body of research stemming from the 100 Resilient Cities Programme (RC100) launched by the Rockefeller Foundation in 2013-2019. The RC100 Programme provided finance (funding for a resilience officer) and guidance (to develop a resilience strategy, and be part of a resilient city network) to enable cities, including several in the global South, to increase their resilience (Rockefeller Foundation, 2014). Rio de Janeiro was part of the RC100 programme, and for a review of the Programme see Urban Institute (2018). Published research on specific RC100 cities includes: Athens and Rome (Galderisi et al., 2020), Rotterdam (Spaans & Waterhoot, 2017), Durban (Roberts et al., 2020), Cape Town (Croese et al., 2020), Amman (Shamout & Boarin, 2021), Jakarta (Leitner et al., 2018). It is challenging to measure the impact of the RC100 programme on city resilience (Spaans & Waterhoot, 2017) and there are some questions regarding the inclusivity of the equity of the approach (Leitner et al., 2018; Fitzgibbons & Mitchell, 2019). However, RC100 has undoubtedly changed conversations about resilience in cities across the world (Reiner and McElvaney, 2017). More recently, studies have theorised how to embed resilience in city polices, or assess the extent at which this is happening (e.g. Hernantes et al., 2019; Lomba-Fernández et al., 2019). Although urban resilience studies have a greater global reach as compared to research driven by the transport sector, by its nature these studies are holistic, with limited focus on transport, or practical information to support transport decision makers (Spaans & Waterhoot, 2017).

This study examines the impact of current weather, specifically high temperatures and heavy rainfall events, within the context of a megacity, from the perspective of those who use, operate, and make decisions on transport within Rio de Janeiro. It employs a process-oriented analytical framework from Bai et al. (2010) to consider the triggers, actors, linkages, barriers, and pathways to explore what factors (e.g. policies, processes) are being used to minimise the current impacts of weather and also plan for longer term climate change. Specifically, it asks: 1. What is the impact of current weather and future climate on transport in Rio de Janeiro? 2. What are the triggers, actors, linkages, barriers, pathways to transport resilience to current weather and future climate? 3. How is (or can) transport resilience being achieved? It argues that within global South megacities, transport resilience to current weather and future climate is intrinsically linked to sustainable urban mobility, and therefore cannot be considered in isolation. The novelty of the study is two-fold; conceptually it advances interdisciplinary research into transport resilience and sustainable urban mobility by applying a proven analytical framework (Bai et al., 2010) from the social sciences to examine a subject (specifically *transport* resilience to current weather and future climate) that is predominantly researched within engineering disciplines using quantitative approaches. Practically, it presents the first case study of transport resilience to current weather and future climate from the global South and provides a systematic and comprehensive approach to that can be applied in other cities, globally, to share challenges and best-practice solutions.

2. Theory

Traditionally, transport resilience studies: (i) discuss existing definitions of resilience such as ecological or engineering (see Reggiani et al., 2015 for a review); (ii) define a measure of resilience; and then (iii) measure the ability of a system or network against this definition (e.g. Chan & Schofer, 2019; Zhou et al., 2019; Mattsson & Jenelius, 2015; D'Lima & Medda, 2015). These studies are generally context specific, and therefore extremely useful for the urban area, network, or transport operator, but by their inherent design for the local context lack scalability, and do not permit comparisons with other networks or urban areas. This is particularly true for rail or subway networks that have long-life infrastructure that has developed over multiple decades in unique socio-economic and environmental contexts. Where similar shorter-life infrastructure such as Bus Rapid Transit has been deployed in multiple locations, inter-comparison between systems is possible (e.g. Scorcia et al., 2019; Deng et al., 2013), although these studies typically focus on operational metrics rather than transport resilience. More recent interdisciplinary work is acknowledging that transport resilience to weather and climate is a multifaceted challenge that requires consideration of interdependencies with other systems (e.g. electricity, communication) and other sources of disruption such as commuter behaviour (Cimellaro et al., 2019; Markolf et al., 2019; Murdock et al., 2018). The number of interdependencies and sources of disruption increase with urban size, and in megacities in the global South where the rate of urban growth often exceeds the rate of infrastructure provision (Turok, 2016), the resilience of a transport network is intrinsically linked to its urban surroundings.

Studies of urban resilience, because of their holistic approach tend to be top-down and applicable across different cities and regions. There are multiple studies that offer a framework for urban resilience (e.g. Ribeiro, et al., 2019; Reiner and McElvaney, 2017; Rockefeller Foundation, 2014; Jabareen, 2013) or which conceptualise the implementation of resilience (e.g. g. Hernantes et al., 2019; Lomba-Fernández et al., 2019; Iturriza et al., 2019). There are also case studies of resilient cities (e.g. Spaans & Waterhoot, 2017; Leitner et al., 2018; Galderisi et al., 2020; Roberts et al., 2020; Croese et al., 2020; Shamout & Boarin, 2021) and thoughtful consideration of what urban resilience means to whom and to what, when, where, and why? (Meerow and Newell, 2019; Meerow et al., 2016). However, these frameworks, concepts and their associated discourse can appear abstract and removed from day-to-day activities (Iturriza et al., 2019) such as stakeholder operational decisions that minimise impact of weather on transport thereby increasing its resilience.

As an RC100 participant Rio de Janeiro has initiated conversations and projects on urban resilience (Rio Resiliente, 2016). To capture what this means for urban transport resilience to weather and climate, this project draws on a proven framework originating in sustainability transition research developed by Bai (2010). This analytical framework considers the circumstances of sustainability experiments and how they evolved, by examining the triggers, actors, linkages, barriers and pathways in order to identify common patterns and pathways, ultimately to understand how to enable a sustainability transition, i.e. a long-term shift toward sustainable socio-technical systems (see further Markand et al., 2012). Applying this framework within the context of transport resilience to current weather and future climate therefore enables a systematic analysis of the triggers, actors, linkages, barriers and pathways, in order to understand how to achieve a long-term transition to weather and climate resilience across the urban area. This framework was chosen for its ability to capture the separate elements that combine to create good practice or constitute bad practice. The analytical approach allows a simple classification of multiple sources of information into a common template, and can be applied to a diverse range of quantitative datasets (e.g. interviews, reports, case studies). As the framework is both simple to use and widely applicable, it creates a common platform for describing the elements of good and bad practice that can be easily replicated in other urban areas, facilitating knowledge exchange. Conceptually, the framework allows the capture of the context specific information associated with transport resilience research, within the broader context of urban resilience, bridging the gap between research siloes. Practically, the framework captures best practice for city decision-makers, within a structure that can be applied in other cities and regions.

Building on Bai et al. (2010) the different elements of the framework are defined as:

- **Triggers** - Events or other factors such as natural disasters, public health concerns, policy changes, media exposure etc., that prompt or enable transport resilience to current weather and plan for future climate.
- **Actors -** The key stakeholders associated transport resilience to current weather impacts and planning for future climate weather impacts including politicians, transport operators, technical experts, passengers, urban residents and more.
- **Linkages** – The relationships between the actors, and how these enable resilience, and whether these are two-way, vertical (one way power), or horizontal (e.g. cross agencies).
- **Barriers** – An obstacle in the way of transport resilience to current weather and/or planning for future climate. They may be political (e.g. climate change scepticism or different priorities), financial (e.g. lack of resource for maintenance, new infrastructure, training/education), technological (e.g. inability to measure or predict weather or weather impact), environmental (e.g. coast or mountain determining infrastructure position), or cultural/social acceptance (e.g. opposition to change).
- **Pathways –** Those options that have, or have the potential to enable transport resilience to current weather and future climate over different time periods. In the shortest-term, these are mitigation measures to prevent operational disruption, or response measures, to enable resumption of service. Longer-term these are transitions to a more resilient system.

The framework is applied to analyse qualitative data obtained via detailed interviews with senior professionals and community representatives in Rio de Janeiro between 2015 and 2018. The interviews also explored the impact of weather on urban transport from the perspective of those who use, operate and/or make decisions concerning these systems. There are three research questions:

1. What is the impact of current weather and future climate on transport in Rio de Janeiro?
2. What are the triggers, actors, linkages, barriers, pathways to transport resilience to current weather and future climate?
3. How is (or can) transport resilience being achieved?

Accordingly, Section Three details the methods and provides an overview of the study area, and Section Four addresses the research questions. Section Five draws conclusions. Lastly, this holistic exploration of transport resilience uses a multi-modal operational perspective, and here transport resilience is defined as all matters related to the "*ability of the transport network to withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects*" (DfT, 2014).

3. Methods

3.1 Sampling

The study undertook three rounds of semi-structured interviews between 2015 and 2018 (Table 1). Participants were purposefully selected for their expertise by the in-country research team via their established networks, with different groups of people invited for interview as the research progressed. Understanding transport resilience to weather and climate was the overarching aim of each interview round, but the exact questions evolved as the research progressed, and data saturation (i.e. additional interviews were no longer providing new information) was reached in some areas. The initial interviews took place with transport operators and civil servants working with the municipal authority. These provided a preliminary understanding of transport resilience, from which a more detailed set of questions were derived on the impact of impact of weather, weather mitigation measures, and climate change adaptation. The second round of interviews drew information from different transport operators, civil servants working for both the municipality and the state, and academics. The final round of interviews targeted perspectives from publics missing from the first and second round of interviews, such as community representatives, politicians and a non-governmental transport organisation (NGO). All interviews were semi-structured, with the same set of questions used across each of the three sets of interviews, with linking questions to join the different rounds of interviews. Moreover, the same interviewer was present during all rounds of interviews to ensure flow and consistency (although interviews were undertaken in pairs). Interview data is anonymous in line with university ethical requirements. Some interviews contained multiple participants whom responded as a group, and their collective views are considered as one interview. The nature of the interview content varied; for example, the community representatives described the impact of weather on their communities, the operators could describe specific impacts and mitigation measures for their network, and the civil servants, politicians and NGO offered a broader perspective on transport resilience and climate change adaptation across the city. Despite the different perspectives and expertise, many of the same themes came up in multiple interviews.

The qualitative data were analysed using codes predefined by the analytical framework (impact, triggers, actors, links, barriers, pathways), and inductive codes, that were developed through the coding process itself. Note that with the exception of the word “impact”, which is widely used to discuss the effect of weather on transport, the predefined codes were not used in the semi-structured interviews, nor were the questions leading. Table 2 summarises the measures taken to ensure the validity and reliability of the qualitative analysis.

3.2 Rio de Janeiro Metropolitan Area

The Rio de Janeiro Metropolitan Area (RJMA; Fig. 1) has 13 million inhabitants in 21 municipalities (UN, 2016a). Approximately 50% of the population live in the municipality of Rio de Janeiro where the population density is highest in the North Zone along a corridor that includes rail, road and metro links to the Central Business District (CBD) in the Central Zone (PDTU, 2015; Figure 2). Within the municipality an estimated 1.5 million people live in more than 1,000 *favelas*, i.e. areas of informal land development, typically on hillsides or other land unsuitable for commercial development. This unplanned and unregulated development impacts transport resilience. Favelas can be juxtaposed to transport routes, and inadequate drainage and sanitation infrastructure can lead to waste on the lines, blocked drains, and increased risk of flooding during heavy rainfall. Sanitation is poor across the RMJA with only 40% of the population connected to a formal sewage system (SNSA, 2016). Employment opportunities for RMJA are concentrated in the Central and South zones of Rio de Janeiro, namely service sector jobs in the CBD, industrial/freight transport jobs in the northwest and port area near São Cristóvão and Ramos; and domestic and service sector jobs (e.g. Copacabana, Ipanema, and Leblon) (Motte et al., 2016).

The majority of trips are made on public transport (49% public transport, 31% active transport; 20% private vehicle), mainly by municipal and inter-municipal buses, accounting for 63% and 18% of public transport respectively (GRJ, 2016). The three largest transport systems in terms of infrastructure assets are the overland rail system (7% modal share), the metro system (7% modal share), and the new Bus Rapid Transport (BRT) system (Fig. 2). Rail is the oldest network extending 70 km from the CBD into peripheral towns and transporting 600,000 people/day*. The infrastructure is state-owned and operated by SuperVia, under contract until 2048. The metro network is also state-owned and operated by MetrôRio, under contract until 2038. It has expanded in stages since 1979 and consists of Line 1 (600 000 people/day*), Line 2 (250,000 people/day*), and Line 4 (50,000 people/day*; Figure 2). Line 4, a legacy of the Olympic Games opened in 2016 and is operated by MetrôRio on behalf of another concession, Rio Barra. BRT is a municipal-level concession operated by a consortia of 17 different operators who own and manage separate assets (e.g. buses, depots, garages). There are currently three operational lines: TransOeste 2012 (189k people/day*); TransCarioca, 2014 (150k people/day*); and TransOlímpica, 2016 (25k people/day*). These serve the West and North Zones of the Rio de Janeiro municipality. The TransBrasil line will operate in the North and Central Zone when complete (estimated 2021). Other systems include light rail (VLT; Veículo Leve sobre Trilho) a municipal-level concession with two lines operating in the Central Zone. The Teleférico do Alemão, (2011-2016) and Teleférico da Providência (2014-2016) are two new gondola systems that were constructed in the run up to the Olympic Games and served large favela complexes in the North and Central Zones (respectively; Fig. 3b). These were operated by state-level concessionaries but all services ceased in 2016 after the Olympic Games. There is also a ferry service between Niterói and Rio de Janeiro.

The concentration of employment opportunities in the central and southern zones has created a strongly pendula travel pattern in the RJMA with high demand for transport services towards the Central and Southern zones each morning, and the reverse each afternoon and early evening. Generally, those with the lowest levels of income, who are less likely to own private transport, travel the greatest distances, and spent the greatest proportion of their wages on public transport (PDTU, 2015; Pereira et al., 2015).

3.3 Weather and Climate Change in Rio de Janeiro Metropolitan Area

Summer in RJMA is generally hot and wetter, whereas winter is mild and drier. The average daily maximum temperature ranges between 25°C (Jun-Sep) and 30°C (Jan/Feb). Monthly mean rainfall varies between approximately 41 mm/month in winter months (Apr-Aug), and over 100 mm/month from November to March (Neiva et al., 2017). Heavy rainfall events are commonplace from December to April, and notable 24 hour rainfall events include January 1998 (272.8 mm), April 2006 (252.8 mm), April 2010 (288.0 mm) (CCAS, 2016), and April 2019 (310mm; BBC, 2019).

Since the 1960s, the city has become warmer; both the mean maximum temperature and the number of warm days has increased, whilst the number of cold days has decreased (Dereczynski et al., 2013). Climate modelling projects an increase in mean temperature of 1.4°C by 2070; the maximum temperature could be 4.5 °C warmer (Silva et al., 2014; note these temperature projections do not include the urban heat island effect). Detecting and projecting future changes in rainfall is limited by the availability of observational data (two stations); total annual rainfall has slightly increased, and the amount of rainfall falling during heavy rainfall events has increased at one station (Dereczynski et al., 2013), and is projected to increase in the future (Silva et al., 2014).

As a coastal city, Rio de Janeiro is extremely vulnerable to future changes in sea level, and the frequency of storm surges has increased since records began in 1850 (De Sherbinin et al., 2007; CCAS, 2016). Storm surges can cause urban flooding in lagoon areas (e.g. Lagoa) and cause drainage canals to overflow as seawater flows upstream, particularly when associated with rainfall events. Understanding the impact of global sea level rise and future changes to storm surge frequency in RJMA is problematic for oceanic observations are insufficient in terms of quality and quantity (CCAS, 2016).

4. Results & Discussion

4.1 What is the impact of current weather and future climate on transport in Rio de Janeiro?

Tables 3a, 3b and 3c summarise the impact of weather on the major transport networks, i.e. the overland train, metro and BRT as described by senior transport professionals. Table 3d compiles weather impact as experienced by other participants, such as the community representatives. Heat and heavy rainfall cause the greatest transport disruption and discomfort. Heat is a regular problem during summer and causes asset failures, namely track buckles, sag of overhead lines, and track short circuits on the overland rail network, air conditioning failure on some of the older metro fleet, and air conditioning failure on the BRT buses. High temperatures have been particularly problematic for BRT; on hot days, <20% of the fleet can be out of service with heat-related failures, primarily air-conditioning problems. On the Transoeste corridor, which is surfaced with asphalt, heat and heavy rain have combined to degrade the road surface and consequently the buses need to travel at a lower speed to prevent damage to the undercarriage caused by the uneven surfaces. For passengers, high temperatures cause thermal discomfort, particularly when using feeder buses (for BRT), municipal buses or vans, where there is no air-conditioning or shade at the bus stops. All operators have mitigation measures to deal with high temperatures (Tables 3a-c), and transport disruption is generally localised, with service resuming once the failure has been resolved.

In contrast, heavy rainfall and flooding causes widespread transport disruption that persists for longer. Several regions of the city are low-lying, or have insufficient drainage, or problems with waste management, and heavy rainfall can lead to neighbourhood-scale flooding. Railway infrastructure is overland with gaps in enclosure walls and level crossings, and floodwater can flow onto the railway line forcing the line or local station to close until the water dissipates. Even when metro and railway operations are unaffected by heavy rainfall, neighbourhood flooding (e.g. Olaria, Penha, Praça da Bandeira; Fig. 2b) can prevent passengers from accessing the station or platforms. Road transport can be suspended until floodwaters decrease (Table 3c, 3d), and disruption on the road network is exacerbated by the topography of the city that constrains travel between gaps in the massifs or tunnel sections (e.g. Túnel André Rebouças). Mitigation methods include pumping at railway and metro stations, and the diversion of the BRT (Tables 3a-c).

Climate observations and climate projections indicate that heavy rainfall events are increasing in frequency and intensity, that mean and maximum temperatures will increase, but that the impact of global sea-level rise on the city is unclear (Section 2.3 and references therein). Although not specifically related to future climatic conditions, increasing sea level has the potential to increase coastal flooding, that could exacerbate pluvial and flooding during heavy rainfall events. There is a Climate Change Adaptation Strategy for the municipality of Rio de Janeiro (CCAS, 2016) and a resilience strategy (Rio Resiliente, 2016); neither strategy explicitly addresses transport resilience to extreme weather or longer-term climate change, but it is considered in both. None of the transport operators (BRT, railway, metro) have a climate change adaptation strategy for their network, nor is climate adaptation part of current operational procedures or future planning.

4.2 What are the triggers, actors, linkages, barriers, pathways to transport resilience to current weather and future climate?

The analytical framework provides a means to capture the different elements that can combine to create good practice or constitute bad practice to aid analysis and support understanding. Each element can be presented separately, but as all elements are interlinked, sometimes the analysis is supported by presenting some elements together. For example, should this framework be applied to compare two cities, the list of actors for each city could be compared. Here, the actors are presented with their linkages, for presenting the linkages requires presenting the actors, and combining these elements improves written clarity in this context.

4.2.1 Triggers

Transport resilience to current weather and planning for future climate is triggered by political, financial and extreme weather events. As municipal mayor, Eduardo Paes (2009-2017; since 2021) oversaw a series of mega events including World Youth Day, 2014 FIFA World Cup, and 2016 Summer Olympic Games. These events leveraged significant federal finance for several transport investments including the new BRT system, the now defunct gondala systems, and associated infrastructure improvements including underground reservoirs to improve drainage and reduce neighbourhood flooding that impacts transport services (e.g. Praça da Bandeira, see Section 4.1; Figure 2b). There have been questions about the suitability of these transport investments (Ferranti et al., 2020), and the influence of the International Olympics Committee and the economic and political vested interested of key decision-makers (Kassens-Noor, 2016), as part of the broader criticism of mega-event legacies (e.g. Grix et al.,2017). Although there has, and continues to be serious concerns about these spending decisions, without these international sporting events in Rio de Janeiro there would not have been new investment in transport infrastructure with the co-benefit of improving resilience, directly, by improving drainage, and indirectly by creating new provision and therefore more travel options.

Contemporaneous to the Olympic preparations, in April 2010, Rio de Janeiro experienced heavy rainfall and severe flooding that incapacitated the city for several days, bringing the issue of resilience to the fore. In response, the municipality built the Centre of Operations Rio (COR: *Centro de Operações Rio*), a high-tech operations centre that integrates the daily operations of multiple agencies, including transport, public utilities and civil defence, and the strategic response to city-level emergencies such as extreme weather.

4.2.2 Actors and linkages

Figure 3 and Table 4 overview the actors and their linkages. There are many actors, particularly transport operators, as a consequence of the private transport sector. Broadly, global and national actors have provided the funding for infrastructure investments and initiatives to increase resilience. This includes funding from Rockefeller Foundation to increase the resilience of the city and instate a city resilience officer (Rio Resiliente, 2016), and funding from the World Bank that specified an investigation of transport resilience to weather and climate that is currently underway. Regional actors such as the State and Municipal Governments are responsible for tendering private operators to run the transport networks, and working with these operators to define their contractual requirements. Although not undertaken in the name of resilience or adaptation, these infrastructure investments can improve weather resilience; for example, a new fleet for the railway and metro has improved the standard of air-conditioning on these modes, and refurbishing the overhead lines on the railway network with auto-tensioned lines reduces the incidence of line-sag in hot weather. Other actors include academics or NGOs working undertaking research on road surfacing or climate change.

City inhabitants have a direct impact on transport resilience to weather. Firstly, neighbourhood flooding that impacts transport operations can originate from poor waste management practices, especially in areas of informal housing where public services are insufficient and people can live adjacent and under transport routes. BRT and SuperVia have public campaigns on their fleet to raise awareness of the role the public can have in reducing flood risk by adopting good waste management practices. Secondly, local residents can report incidents that impact resilience (e.g. local tree fall or flooding) and receive travel updates to plan their journey, predominately via COR, although some information may be available from social media linked to specific operators. COR also specifically contacts community leaders in the favelas for status updates and to provide information to this harder to reach group. Thirdly, transport operators report a regular change in commuter behaviour during heavy rainfall. When there is morning rainfall, the railway network experiences a 3-5% decrease in ridership as passengers prefer to use local buses to commute the whole distance rather than get wet travelling to the train station, or avoid making the journey entirely. Conversely, on rainy afternoons the railway and metro networks experience increased demand as theses service are considered more reliable than local buses whose service may be disrupted by urban flooding. Passengers may also decide to delay their journey home until after the rain has stopped.

There are multiple linkages between different actors. Many are linked to the COR, and the centre is well placed to co-ordinate transport resilience to weather and climate at multiple levels. That said, the connection between the state-level metropolitan transport agency and the municipal-level COR was unclear, and communications between these two specialist organisations would undoubtedly be beneficial. Within COR, CIMU (Centro Integrado de Mobilidade Urbana: Centre of Integrated Urban Mobility) integrates transport resilience on an operational level providing the operators with regular meteorological forecasts and weather warnings developed by meteorologists co-located in COR; the weather warnings such as heavy rain also inform other municipal operations such as waste collection and drainage maintenance in areas prone to urban flooding.

4.2.3 Barriers

Barriers are summarised by theme in Figure 4. There are several barriers linked to urban design; the concentration of jobs in the Central and South Zones, combined with the limited mass transit outside these zones, and continued development of periphery areas has created: (i) high bus-dependency, and road-based transport is less resilient that other mass transit modes; and, (ii) a strongly pendula transport pattern, which exacerbates travel disruption. Poor drainage, especially in the oldest areas of the city (e.g North and Central zones) is the major cause of flooding during heavy rainfall. Barriers related to urban design are often locked in by the physical form of the region; massifs create pinch points and low-lying coastal regions are susceptible to flooding. Governance is another prominent theme, and included concerns that limited transparency, evidence-based decision-making, and community consultation (Ferranti et al., 2020) were barriers to creating a resilient transport system. Other barriers are linked to the private transport sector, and whether it is possible for multiple operators in different spheres of governance (state/municipal), with no contractual responsibility to collaborate or adapt to climate change to unite to enable transport resilience to weather and climate. Poor integration of systems, both operationally and strategically to improve connectivity and thereby increase redundancy during extreme weather is a further barrier.

There are also financial and political barriers to enabling weather resilience measures. Rio de Janeiro state was declared bankrupt in 2016, and future public-private partnerships investments in weather resilience were considered unlikely, particularly given the significant recent infrastructure investments (Section 4.2.1). Moreover, transport investment is politicised and the long-term transport investments required for weather and climate resilience are difficult to align with short-term political visions. This is compounded in the current political climate where recent transportation investments (e.g. Line 4) and major actors such as the former State Governor of Rio de Janeiro are linked to the long-running corruption scandal, *Lava Jato* (see Valarini and Pohlmann, 2019), and there are questions about the vested political and economic interests of transport decisions made in the name of the Olympic Games (Kassens-Noor et al., 2016), and new politicians seek to distance themselves from the decisions of previous governments. Other barriers to weather resilience are technological, or linked to the culture and capacity within the transport sector to consider and undertake adaptation to climate change, and the availability of the scientific evidence base to support decision-making. None of the operators have a climate adaptation plan that are becoming more common in the global North. These typically include both engineering solutions and measures to increase the adaptive capacity of an organisation to respond to climate change, via increased training and education, that are becoming increasingly standard part of transport operations in the global North (e.g. Toplis et al., 2015; Jacobs et al., 2018; Network Rail, 2019; PIARC, 2020).

4.2.4 Pathways

Short-term resilience measures are shown in Tables 3a-c. These mitigation measures enacted by the transport operators are designed to: prepare for or prevent weather impacts (e.g. removing rubbish that could cause flooding); enable their systems to continue operating during extreme weather (e.g. reduced speeds when line sag is a problem); or return to operations as soon as possible following extreme weather (e.g. pumping of flood water, heat-related maintenance by BRT). Other short-term approaches to weather resilience include *Siga Viagem,* and *CIMU* that enable operational integration of transport modes during extreme weather (Section 4.3.1).

Interviewees proposed future pathways to increase resilience to current weather and future climate including making climate change adaptation a contractual obligation for transport operators. Both SuperVia and Rio Metro have long-term contracts until 2048 and 2038 respectively, and early climate adaptation has the potential to reduce future operational costs (Quinn et al., 2018). A long-term pathway was for the city to create new centralities of employment and use Transport Orientated Development to ensure there is effective public transport.

4.3. How is (or can) transport resilience being achieved?

4.3.1 Specific examples of actions that have improved transport resilience

The interviews revealed three recent examples of improvements to transport resilience (Table 5). Firstly, the construction of the COR created a centralised operational response to extreme weather by co-locating key public services and disaster response. "*The big gain of the COR is the direction of the efforts of the teams of the city hall, making the response time of the teams is very short. This is key to reducing the impact of disasters"* (Interviewee, Round 2). Building on this COR used WRI (World Resources Institute) funding to bring together city managers to raise awareness of climate change and build capacity in this area.

Secondly, this facility, combined with the need for contingency planning for the series of mega-events led to a series of innovations for transport resilience, including the physical and operational integration of the different transport operators in a new unit called CIMU (Centro Integrado de Mobilidade Urbana: Centre of Integrated Urban Mobility), and the development of Siga Viagem, a ticket that enables passengers to switch transport if their route or mode is no longer operational due to extreme weather. For World Youth Day, the Olympics and the FIFA World Cup, CIMU enabled integrated and effective contingency planning to transport visitors to the city. This close integration and contingency planning did not continue after the mega-events, although city-wide emergency response continues to be co-ordinated via CIMU, which is well-regarded by the transport operators. COR characterises the outward-facing modern governance style of Paes that promoted digital information and communication technologies to improve city-level management (Paschoal & Wegrich, 2017) and the centre is a case study for C40 Cities, the Urban Sustainability Exchange and others. However, with the commencement of a new mayor in January 2017 (between rounds 2 and 3 of the interviews) the primary role of COR changed from weather and climate resilience to public security. Governance of COR was moved from the Conservation Secretariat to the Public Order Secretariat, and protocols for warning the public and managing city-level response to flooding appear to have changed since interviews were undertaken. This exemplifies comments made by interviewees, prior to the changes to COR, on the fickle nature of governance and shifting political visions (Figure 4). In January 2021, Eduardo Paes was re-elected as Mayor, and whether weather and climate resilience will return as priorities as the city continues to live with the covid-19 pandemic is yet unknown.

Thirdly, there was significant investment from government and international funders in transport and other infrastructure in the run up to the Olympic Games, including VLT, BRT, the ill-fated gondola systems, and related infrastructure such as underground reservoirs. Although many of these investments were contentious (Section 4.2.2) and infrastructure such as BRT have proven poorly resilient to hot temperatures and heavy rainfall, the city does have a new transport portfolio that in part increases resilience by offering modal choices therefore increased redundancy during extreme weather.

4.3.2 Transport resilience in a Global South context

> *"Here are so many problems related to transport that it's very hard to treat climate problems alone"* (Interviewee, Round 2).

To date, transport resilience studies have typically focused on the engineering or operational solutions that enable transport operators to increase weather and climate resilience (e.g. RSSB, 2015; Jacobs et al, 2018; Ferranti et al. <in press>), and embedding climate adaptation within business as usual (e.g. Quinn et al., 2018; Toplis et al., 2015; Climate-Adapt, 2020). Most studies originate from the global North, where weather resilience and climate change adaptation are often mandated in national or international policy such as the UK's Climate Change Act (Dawson et al., 2017) or the European Union's Climate Change Adaptation strategy.

This case study from Rio de Janeiro shows that transport resilience to current weather and future climate is not simply an engineering problem for transport operators. Indeed, the technological and capacity barriers were few as compared to barriers related to governance, urban design, finance, and politics. The impact of heavy rainfall on metro, road and railway networks is a consequence of urban challenges, such as poor drainage and waste management, compounded by the juxtaposition of informal housing (favelas) close to transport routes, rather than the failure of transport assets or infrastructure. The impact of weather is exacerbated by a range of physical and socio-economic factors. The dichotomy between affordable housing and employment creates long travel times and a pendula travel pattern that exacerbates transport disruption. Transport governance is poorly integrated and there is no mandate for climate change adaptation in the transport sector. These urban challenges must be addressed to deliver transport resilience to weather and climate, but action to addresses these challenges must not be solely undertaken in the name of weather resilience or climate adaption. Instead, these barriers are part of the broader paradigm of sustainable urban mobility (SUM), which advocates efficiency in the transport system, shorter journeys via better land use planning, and modal shift, along with leadership, strong governance and long-term thinking (Banister, 2011).

These barriers are not unique to Rio de Janeiro (Turok, 2016); developing megacities are often characterised by urban mobility issues, environmental problems and fragmented governance and policies (Canitez, 2019). Accordingly, there needs to be more interdisciplinary research that considers transport resilience within the context of challenges experienced in the global South, particularly in megacities where transport services are in demand, and the disruption caused by extreme weather can be great. The analytical approach used in this study provides a useful framework to examine holistically transport resilience to weather and climate in other cities, to compare best practice examples and similar challenges, ultimately to enable transport within megacities to transition to a position of weather and climate resilience.

Moving forwards in Rio de Janeiro, a holistic and multi-level approach is required to improve transport resilience to current weather and embed planning and adaptive measures for future climate resilience. This should incorporate operator specific infrastructure improvements such as overhead line sag, track-buckling, and the air-conditioning issues associated with the BRT fleet. It must be combined with operational and strategic collaboration between the multiple transport operators to improve integration between systems to create redundancy and travel alternatives during extreme weather events, and to dissipate pinch points within the system. Transport resilience to current weather and future climate should be incorporated within strategic planning policies to address the long-term distribution of employment and homes and change the current transport pattern which concentrates the daily commute of more than a million people through flood-prone areas. Strong leadership is required to deliver these short and long-term changes and the success of COR (until 2017) demonstrates how resilience can be improved using existing resources when there is a mandate for action. The strength of CIMU shows that leadership can take place within different parts of organisational hierarchy; here the transport operators (not those who allocate their contracts) are leading the sharing of information and best practice to improve transport resilience.

4.4 Discussion of the approach and limitations

This studied adopted an existing analytical framework (Bai et al., 2010) from sustainability research to explore the multiple facets of transport resilience to weather and climate in the context of a megacity. The framework allowed a systematic and holistic analysis of qualitative data to understand the triggers, actors and linkages that combine to create barriers and pathways for transport resilience. It provides a method to describe a complex challenge faced by many megacities and the means to compare mutual challenges and best practice examples.

Qualitative research was undertaken following the principles outlined in Cleary et al (2014), namely that: participants were purposefully selected based on their professional or community standing; the responses were studied intensively, as per the smaller sample size; selection was driven by the framework; and, care was taken to recruit participants who could provide a diversity of views (e.g. politicians from opposing parties). That said, the dataset does not include the perspectives of municipal and intermunicpal bus operating companies who have the largest modal share of transport, albeit the fewest infrastructure assets for they operate on public roads maintained by the municipal authorities. The interviews were also undertaken before the coronavirus pandemic, which has significantly affected transportation in the short-term by reducing the numbers of daily commuters, and increasing the use of informal transport modes as larger transport networks (e.g. BRT) have reduced operations but employees still need to travel to work (Costa, 2020). The longer-term consequences of the impact of the pandemic on transport are unknown.

5. Conclusions and future applications

This manuscript presents a perspective of transport resilience from Rio de Janeiro derived from the expertise of senior professionals employed within the transport sector combined with the experience from community transport users. Specifically, it:

- Considered the impact of high temperatures and heavy rainfall on transport operations from the perspective of transport professionals and those who use the systems.
- Considered current climate adaptation plans and noted that transport resilience is not explicitly covered. The transport operators are not required to create a climat adaptation plan to ensure steps towards future climate resilience.
- Identified the triggers, actors, linkages, barriers, pathways to transport resilience to current weather.
- Revealed three examples of resilience improvements, namely; (i) the creation of Centre of Operations Rio (Centro de Operações Rio; COR) to co-ordinate daily operations and disaster response, (ii) a series of innovations in operational integration enabled by co-locating services within COR; and, (iii) infrastructure investment prior to the Olympic Games, which increased transport provision.

Conceptually, it demonstrates the value of an analytical framework in a new context, to provide comprehensive and systematic analysis of transport resilience. Future research will apply this framework to other megacities, to consider the similarities and differences with Rio de Janeiro, and create a series of case studies of best practice. Importantly, it highlights how transport resilience to weather and climate is intrinsically linked to SUM, and argues the need for a multi-level integrated response to these challenges. There is also scope for future research to draw more deeply on sustainability transitions, the parallels with resilience, and scope to apply Multi-Level Perspective approach (e.g. Geels, 2005; Canitez, 2019) or consider alternative approaches such as aspirational futures methodology (Rogers and Hunt, 2019). Here, far-future aspirational scenarios are used to guide urban decision-making and increase cross-sector collaboration by considering how an engineering intervention (e.g. a green infrastructure corridors) can deliver the necessary co-benefits required in order to achieve that aspirational future.

Practically, for the decision-makers in Rio de Janeiro, this detailed analysis of transport resilience to weather and climate provides an evidence base of best practice in transport resilience to extreme weather, alongside the barriers and pathways to weather resilience. It provides three examples of improvements to transport resilience to weather and climate, and demonstrates the importance of COR, in its original function, to lead and integrate transport resilience measures. This is an important observation for those preparing climate adaptation plans. The analysis highlights the importance of international investment as a trigger for resilience and the need for greater integration and collaboration across the private transport sector with multiple spheres of governance. Lastly, it emphasises how transport resilience to current weather and longer-term climate change must be considered in not only in transport strategies and policies at municipal, regional, and federal levels, but also within strategic planning decisions on the location of housing, public services (e.g. health care and education), commercial development, and industrial development, as part of sustainable urban mobility. Without adaptation, future climate impacts such as more frequent and intense rainfall events, and hotter temperatures will exacerbate the existing systemic problems identified by the framework.

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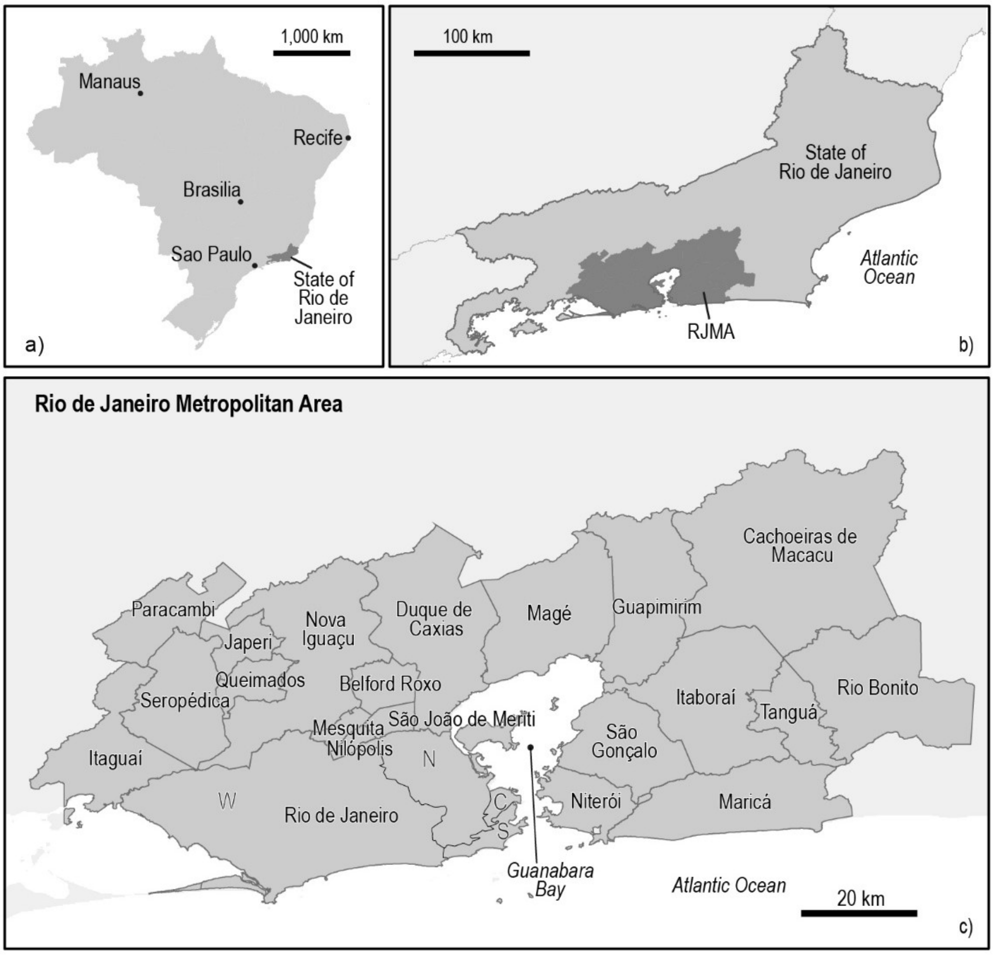
Figure 1: a) Brazil; b) Rio de Janeiro State; and c) Rio de Janeiro Metropolitan Area. Zones in Rio de Janeiro municipality are marked as: W=West Zone, N=North Zone, C=Central Zone, and S=South Zone.



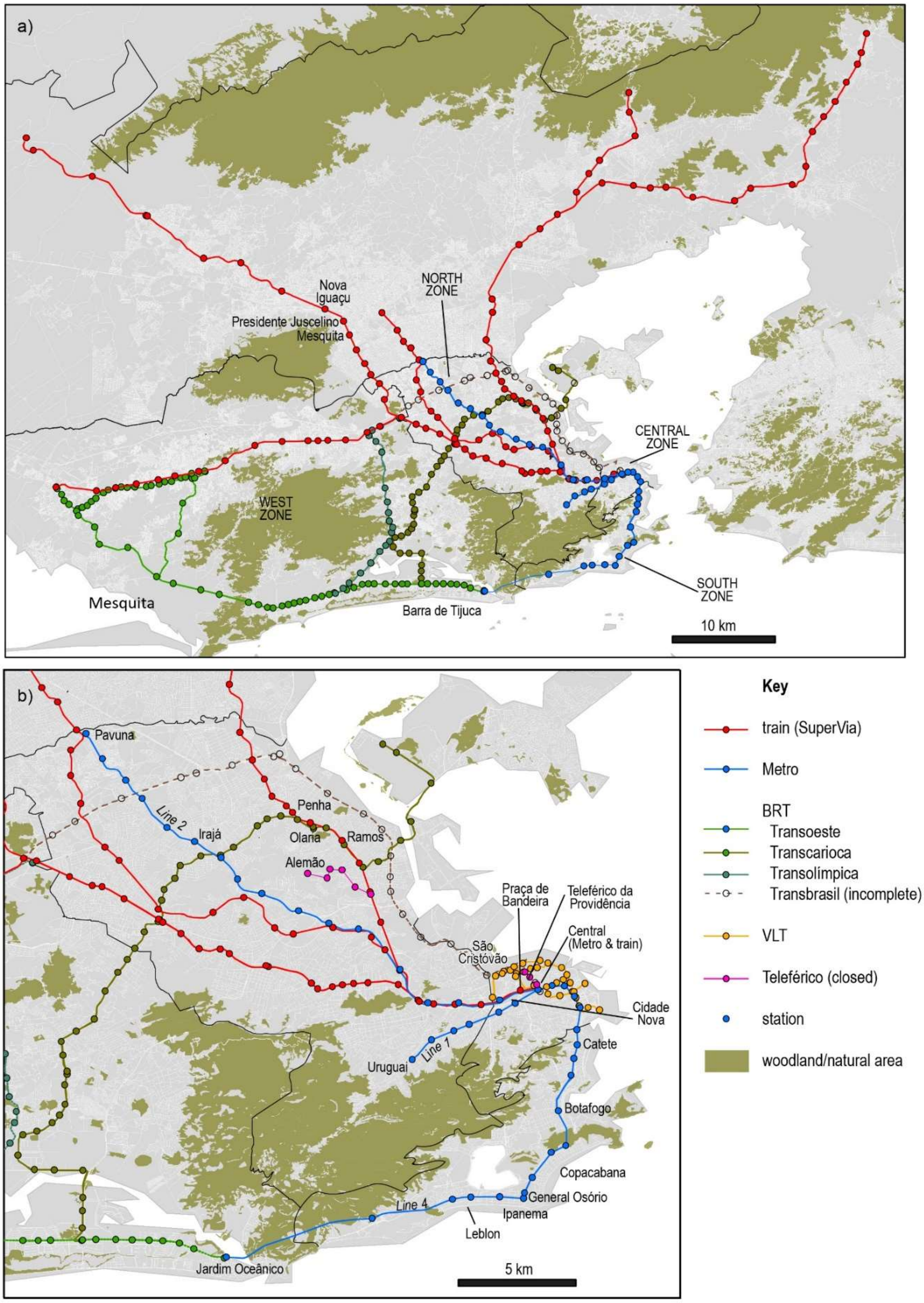


Figure 2: Public transport map for: a) Rio de Janeiro Metropolitan Area; and b) the central, north and southern zones of the municipality Rio de Janeiro. [COLOUR]

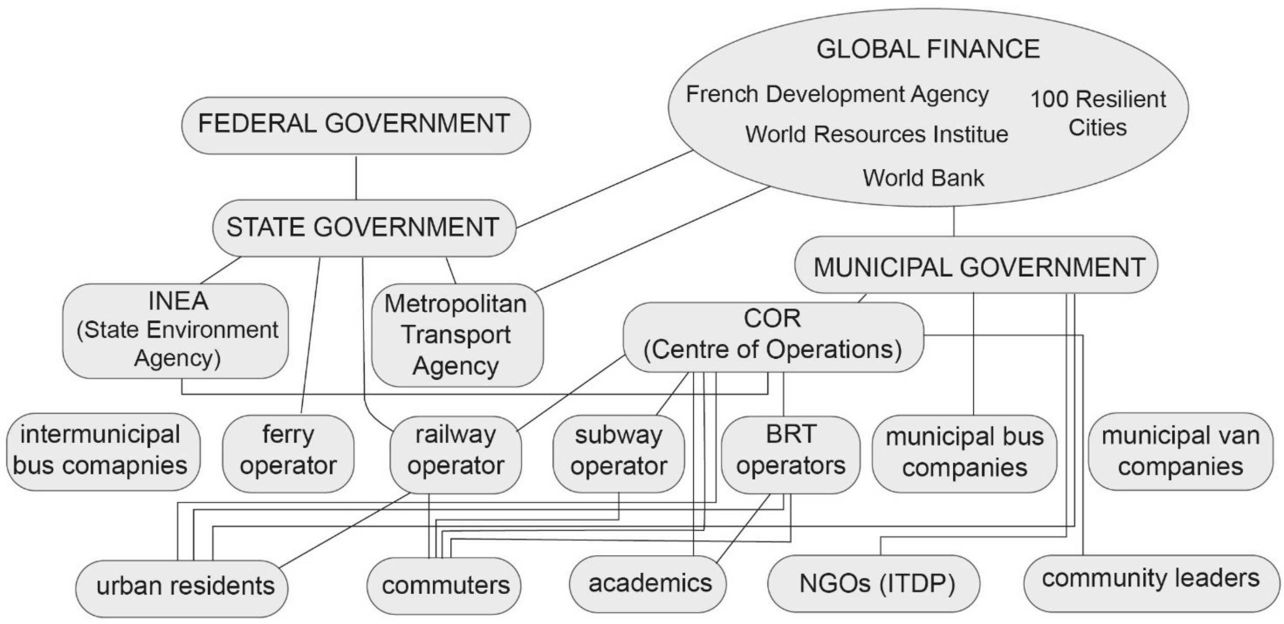


Figure 3: The linkages between the different actors connected to transport resilience to weather and climate in Rio de Janeiro

Urban Design	Governance	Political	Integration	Financial	Cultural	Natural/physical	Capacity	Technological
Dense urbanisation, many impermeable spaces on Transcarioca route	Collaboration with other operators and climate adaptation are not contractual opportunities for operators	Long-term transport investments don't align with short-term political vision required to win elections.	Investments managed in isolation, options for integration between systems (and thus redundancy) not considered	How can a climate change adaptation plan be implemented without any money?	Climate change adaptation, talking about extreme weather, not part of culture.	Geography of RJMA creates pinch points because there are only a few routes through the mountains and this reduces redundancy.	Local sea-level rise unknown; climate projections insufficient	BRT aircon system insuficient for RMJA; technology does not exist. "*Problem without solution* ".
Distribution of jobs and housing creates pendula transport that reduces system efficiency.	Limited public consulation that could have optimised transport investments	Political change, new mayor doesn't want to be associated with previous mayor's decisions	Poor integration, especially out of south and central zones, reduces redundancy options, need integrate fares and systems	State is bankrupt; little potential for funding, even public-private partnerships.	Vandalism of assets by passengers	Low-lying coastal region with marshes, prone to flooding, and future sea level rise	How can decision makers and/or politicians work with climate projections to incorporate them in decision-making?	
Social housing continues to be constructed at city edges, adding pressure to pendula transport.	Decisions on transport not made by transport experts &/or expertise ignored.	Corruption: Lava Jato; "bus mafia",	No cross-modal operational integration	BRT operational costs more than anticipated. Less money for operations and adaptation				
Asphalt roads on Transoeste not resilient to weather (BRT)	Private transport market, multiple actors, multiple scales, poor connectivity. How to unite for adaptation?							
Water network very old and is biggest cause of road closures.	COR primarily for the municipality, not wider RMJA.							
Little mass transit provision outside South/Central zones creates bus dependancy, which is less weather resilient (road flooding) than mass transit	Little transparency in decision making, e.g. bus rationalisation							

Figure 4: The barriers to transport resilience in Rio de Janeiro coded into themes (modified from Bai et al, 2010)

Table 1: Participants during the different interview rounds. The number in brackets (2) denotes the number of interviews. There were 19 interviews in total.

Interview Round	Participants
1 (2015)	Transport operator (2), civil servant (1)
2 (2017)	Transport operator (4), civil servant (2), academic (2)
3 (2018)	Community representative (5), Politician (2),Transport NGO (1),

Table 2: Strategies used to ensure the rigour of qualitative research in this project. After Noble and Smith (2015)

Concept	Measures Taken
Validity (truth value)	*Reflexivity and reflection on own perspectives* - A reflective log was maintained to document key decisions in the research development - The interview team discussed their understanding before and after each interviews - Ongoing sampling biases were acknowledged and addressed (where possible) in future interview rounds *Representativeness of findings* - Interviews were recorded and transcribed to allow repeated consideration of the text - Interviewees willingly provided their time and expertise, explaining their views or technical matters in detail so that the interviewers clearly understood their perspective - Coded text was not considered in isolation, but within the broader conversation to ensure it accurately represented the participant view - Sampling biases are considered (Section 4.4)
Reliability (consistency/ neutrality)	*Achieving Auditability* - A methodological log was created to document rationale for key decisions - The three interview rounds used differing but linked questions as the research evolved, data became saturated, participant type changed (e.g. from technical expert to community representative). In each round, the questionnaire was the same for all participants. Some questions (e.g. impact of weather) were asked in all interview rounds. - Interviewing was done in pairs, but with one researcher attending all interviews to ensure consistency. - Interviews were transcribed for coding - Coding was undertaken systematically using specialist software. Some codes were predefined, but emerging codes were applied retrospectively

Table 3a: The impact of weather on the railway network

Weather hazard	Occurrence		Potential impact	Mitigation measures (where known)
Heat	Frequently during summer (Dec-Feb)	Direct	Rail buckle Line sag Track circuit	Visual inspection at 11:00, 13:00, 15:00 on days where temperature exceeds 35°C. Teams check known vulnerabilities. Reduced speeds when line-sag is an issue.
Rainfall	At least once per winter season	Direct	Flooding of station Flooding of line Increased injury risk for passengers using walkways and viaducts that are already in poor condition	Lineside operatives remove rubbish that could exacerbate flooding. SuperVia own pumps to remove water; these are overwhelmed during heavy rainfall events. Posters/education on trains encouraging people not to litter as it causes flooding
		Indirect	Neighbourhood flooding preventing access to station Change in travel behaviour during wet weather	
Wind	At least once per winter season	Direct	Debris on line Damage to overhead cables	
Lightning	unknown	Direct	Damage to telecommunications and signalling	

Table 3b: The impact of weather on the metro system

Weather hazard	Occurrence		Potential impact	Mitigation measures (where known)
Heat	Not specified	Direct	Aircon failure on older fleet on Line 2 which is overground	Individual carriage can be closed and isolated to allow the train operations to continue until maintenance is possible
Rainfall	At least once per winter season	Direct	Flooding of station or access to station (Line 2) Flooding of line (Line 2)	MetrôRio have pumps at vulnerable stations
	At least once per winter season	Indirect	Neighbourhood flooding preventing access to station Change in travel behaviour during wet weather	Extend the opening hours to accommodate passengers who are travelling later to avoid wet weather
Wind		Direct	Debris on over ground sections of line	

Table 3c: The impact of weather on the BRT network

Weather hazard	Occurrence		Potential impact	Mitigation measures (where known)
Heat	Commonplace during summer (Dec-Feb)	Direct	Failure of air-conditioning Engine overheating Damage to asphalt corridors	Garages on standby to mend heat-related failures Concrete corridors used for newer BRT routes Garages on standby to mend heat-related failures
		Indirect	Increased maintenance caused by damage to bus undercarriage caused by uneven asphalt road surface caused by melting and rutting. Antisocial behaviour increases in hot weather	Buses travel at slower speed
Rainfall and flooding	Frequent	Direct	Flooding and poor drainage (combined with heat) has damaged the road surface	Concrete corridors used for newer BRT routes Buses travel at slower speed Higher boarding of BRT buses means these can operate in deeper flood waters
			Flooding of station or bus corridors (~ 4-6 times per year between November and March)	Flood-risk map, contingency plans to transfer buses to public roads High-resolution rain & flood forecasts from COR meteorologists
		Indirect	Increased maintenance caused by damage to bus undercarriage caused by uneven asphalt road surface	
			Neighbourhood flooding preventing access to stations	

Table 3d: Non-expert experiences of the weather impact on transport

Weather hazard	Mode	Experience
Heat	BRT	Breakdown of buses because of air-conditioning failure In periphery locations there can be a long walk without shade to reach feeder bus stops, which often have no shade
	Municipal buses, & vans	Buses uncomfortable, no air-conditioning Local bus stops often have no shelter from sun Heat exacerbates dust problems for those waiting at stops where there is no asphalt
	Active travel	Lack of shade for walking and cycling
Rainfall and flooding	Metro	Local scale blackouts lead to electricity loss at metro station (one station, block-level blackout) Cannot leave metro station due to local neighbourhood flooding
	BRT	BRT boarding is higher than other buses so can keep moving when other buses cannot Services can be rerouted during flooding. Sometimes they are cancelled.
	Municipal buses, & vans	If the service is cancelled due to weather you often have to pay the fare again to travel via a different mode No shelter when waiting for buses in the rain, and longer waits due to service disruption
	All modes	Litter and waste block drains causing neighbourhood flooding Roads and neighbourhoods can be impassable to reach or exit public transport services. Road-based transport can stop leaving passengers to wait for several hours until the flooding has drained When there is no public transport, end up walking in the rain, health concerns such as leptospirosis
Wind	Road-based transport	Tree fall can block roads

Table 4: Summary of the actors and their role in transport resilience to weather and climate, as identified from the interviews. Linkages are shown in Figure 3.

Actor	Role
World Bank, World Resources Institute, 100 Resilient Cities, French Development Agency	- Provide finance for transport investments, which often requires consideration and reporting of resilience, climate adaptation, or capacity in these areas - Facilitate networking with other municipal authorities and sharing of best-practice
Federal Government	- Decide and fund large-scale transport and infrastructure investments for RJ state
State Government	- Decide and fund transport and infrastructure investments for RJ state (Figure 1). - Award and negotiate contracts for transport operators (rail and metro)
INEA (Instituto Estadual do Ambiente)	- State environment agency responsible for producing an early warning system for landslides (often during heavy rain)
Metropolitan Transport Agency	- Provide technical advice, undertake transport planning for state e.g. PDTU (2015), provide reports for external funders (e.g. World Bank) including climate adaptation and extreme weather
Super Via	- Operate the railway (contract until 2048), including constructing new assets agreed with State, asset maintenance and response to extreme weather. Private company therefore profit is required to continue operations
Rio Metro	- Operate Lines 1&2 of the metro (contract until 2038), and operate Line 4 on behalf of the other concession, including constructing assets agreed with State (Lines 1&2), asset maintenance and extreme weather response - Private company therefore profit is required to continue operations
CCR Barcos	- Operator of ferry service between Rio de Janeiro and Niteroi.
VLT	- Operator of the light rail system, VLT Carioca (Veículo Leve sobre Trilhos)
Intermunicipal bus companies	- Over 58 bus companies running 650 lines between cities in the RJMA on public roads (GRJ, 2016). Private companies therefore profit is required to continue operations
Municipal Government	- Decide and fund transport and infrastructure investments for RJ city (Figure 2). Currently (since 2016) building the 4th BRT line, TransBrasil, due to finish in 2021 (originally 2017/18). - Award and negotiate contracts for transport operators (BRT, municipal buses) - Responsible for maintenance and investment in city infrastructure, e.g. drainage, sanitation, and services such as waste collection
COR (Centro de Operações Rio) Centre of Operations	- Co-ordinate daily operations within city that enhance resilience, e.g. drain maintenance in flood risk areas - Convene CIMU (Centro Integrado de Mobilidade Urbana: Centre of Integrated Urban Mobility), that brings together the transport operators to co-ordinate transport systems, during events or extreme weather - Co-ordinate and facilitate (via the provision of the bespoke building) emergency response to extreme weather - Provide weather forecasts and extreme weather alerts for transport operators - Provide resilience updates for urban residents via media and social media, such as severe weather alerts - Provide alerts and two-way communication with favela residents
Consórcio BRT	- Operate the Bus Rapid Transport network including feeder buses and representing a consortium of over 50 companies, including asset maintenance and response to extreme weather. - Private company therefore profit is required to continue operations
Municipal bus companies	- Approximately 48 bus companies in four consortia running 705 bus lines on public roads (GRJ, 2016). Private companies therefore profit is required to continue operations
Municipal vans	- Informal transport in municipality using public roads that fills the transport gaps left by larger networks
Academics	- Undertake research (e.g. improving asphalt durability to rain and heat) related to transport resilience
NGOs, e.g. ITDP (Institute for Transportation and Development Policy)	- Provide technical advice and reports - Engage with community groups and transport users
Urban residents	- Poor waste practices (e.g. fly tipping) can increase flood risk - Modification of city infrastructure during the construction of informal housing can increase burden on waste and sanitation infrastructure, and/or increase flood or landslide risk - Vandalism of infrastructure or assets represents a considerable cost for some operators, e.g. BRT,
Public Transport Commuters	- Users of the transport system and vital for transport operator income and operation of systems - Majority of public transport users from lower income classes, for whom the systems are vital for employment, education, access to health provision etc. - Vandalism of infrastructure or assets represents a considerable cost for some operators, e.g. BRT - Travel behaviour changes during extreme weather such as heavy rainfall or extreme heat

Table 5: Specific examples of improvements to transport resilience to weather and climate

Trigger	Actors	Linkages	Barriers	Pathways
Extreme weather, global finance	Local government, IBM, WRI	Public-private partnership	In 2017 the new mayor relocated the governance of COR from Conservation Secretariat to the Public Order Secretariat, changing the primary function from weather and climate resilience to public security.	As centre of resilience COR integrated daily operations and emergency response to reduce the disruptions caused by extreme weather
Mega events (mainly Olympics)	COR (municipal government), transport operators	Cross/inter-agency involvement	Collaboration not contractual responsibility for transport operators, so level of engagement decreased after mega-events. Function and governance of COR has changed.	The need for high-level contingency planning and co-location of multiple services led to several innovations that improved operational resilience to extreme weather and climate: - CIMU (centre of integrated urban mobility) - Siga Viagem, to permit modal switch in extreme weather - New meteorological forecasts, maps and warnings to guide operations. These can be hourly during extreme weather. - Integration of landslide alert system run by INEA - Climate Change Adaptation Plan for City (CCAS, 2016) - City Resilience report (Rio Resiliente, 2016)
Olympic Games	Local, state and federal government, international funders	International linkages, vertically integrated with little consultation	Concerns regarding investment decisions and corruption of transport investment	New infrastructure provides more travel options during extreme weather Specific infrastructure projects to increase resilience, e.g. water storage to improve drainage