Resilience of Urban Mobility Systems: Combining Urban Subsystems and Threats with a System Dynamics Approach

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Abstract. Urban systems are dynamic, complex, and often involve multiple stakeholders, resulting in responses with distinct time lags. A resilient urban mobility system should be able to neutralize the effects of disruptive events (threats) while maintaining its essential state of functionality. Given the lack of studies addressing threats to urban mobility and the concurrent impacts on the urban mobility system, a holistic analysis considering key elements of transport systems and their interactions is necessary. Thus, this study aims to describe and analyze the dynamics involved in a resilient urban mobility system using qualitative system dynamics modeling. We start by identifying the main system components, threats, interrelations, and interconnections. Then, we create causal loop diagrams (CLD) of the urban mobility system under different conditions: (i) in the essential state of functionality, (ii) affected by a disruptive event and (iii) still functioning due to its resilience. Analyzing the CLDs indicated that the dynamics involved in a resilient urban mobility system have a preventive nature as it reflects the importance of transport policies considering climate change and disaster prevention policies/measures. In addition, the results showed that public opinion and incentives to use sustainable transport play an important role in balancing the system. Therefore, the negative effects of threats on the system, such as deaths, damage to transport infrastructures, and collapse of mobility performance, can be prevented. The outcomes of this study may be used to support the process of planning and building resilient cities.

Keyword: Urban resilience · Urban mobility systems · System dynamics · Causal loop diagrams · Threats to urban systems

1 Introduction

Cities are complex and self-organized systems with nonlinear behavior and dynamic properties [1], which can be further divided or aggregated into other systems. Disruptions, disturbances, or shock events that occur in one part of the system may lead to difficulties elsewhere [2, 3] and eventually impact the whole system. Urban mobility systems are subject to frequent and continuous disruptive events (threats), which compromise not only the satisfactory functioning but also the integrity of infrastructures, resulting in multiple negative impacts [1, 4, 5].

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O. Gervasi et al. (Eds.): ICCSA 2021, LNCS 12956, pp. 93–108, 2021.
https://doi.org/10.1007/978-3-030-87010-2_7

The ability of cities or urban systems to resist, adapt or transform themselves in the face of shock and stressful events is known as urban resilience [6]. A resilient urban transport system should be able to neutralize the effects of threats while maintaining its essential state of functionality, reconciling the reduction of its ecological footprint while improving the quality of life [1]. Although some studies have addressed combined threats to all elements of urban systems [7, 8], most strategies to quantify urban resilience consider the particularities and scales of different urban subsystems separately [1, 9]. A wide range of studies has also addressed the impacts of climate change and extreme weather on transport systems [10–13], but few are related to urban mobility. There is also a lack of studies addressing the threats to urban mobility and their concurrent impacts on the system.

Given that transport systems are essentially dynamic in time and in space, a systematic analysis framework that integrates different stakeholders and/or agents is advantageous. Problems with these characteristics fit precisely into System Dynamics (SD) modeling. SD is based on Causal Loop Diagrams (CLD), whose (qualitative) representation indicates how a change in one variable affects other variables, which in turn affect the initial variable again. System components can be added in the form of mathematical rules that can explain and predict their evolution in the short and long term. SD can help to understand decision-making mechanisms in complex situations (e.g., how policy targets, strategies, incentives, or penalties in one part of the system influence other subsystems and eventually change the behavior of the whole system [14]). SD models can help to properly manage and control transport systems and provide plausible solutions to many transportation problems [2], such as threats to urban mobility and the resilience of urban mobility when faced with a threat [15–18].

In addition, an in-depth qualitative analysis of the dynamics in a system allows visualization of the system's hypothesized structure, and the proper construction of quantitative models [19]. Hence, the proposed research investigates the components of urban, transport and urban mobility systems, aiming at describing and analyzing the resilience of urban mobility in the face of its main threat (or eventually threats), through qualitative system dynamics modeling. We intend to answer the following questions: What are the main components of and threats to urban mobility systems? What are the dynamics involved in urban mobility systems in their essential state of functionality and when exposed to the main threat? How resilient are urban mobility systems in the face of the main threat (or threats)?

This section introduced the importance of modeling the resilience of urban mobility system using a conceptual analysis of system dynamics. The remainder of this paper is organized into four additional sections. Section 2 presents a brief background on urban mobility systems and resilience. In Sect. 3, we describe the qualitative system dynamics models used for characterizing the resilience of urban mobility systems. Section 4 discusses the results. Finally, the conclusions and suggestions for future works are presented in Sect. 5.

2 Theoretical Background

In this section, we present a brief literature review on urban mobility systems and resilience. We investigate the components of the systems found in the literature and

propose a standardized nomenclature and a division into subsystems. Furthermore, we introduce the concepts and threats to characterize the resilience of urban mobility systems.

2.1 Urban Mobility Systems

A system is a set of elements that are interrelated and interconnected forming a complex whole [20]. An urban system is a complex and adaptative interdependent network consisting of different subsystems [21, 22] which can be further divided or aggregated into larger and more complex systems depending on the context of the study [23], such as urban transport and urban mobility systems.

Stefaniec et al. [24] divided transport systems into three subsystems: environmental, economic, and social. Environmental is related to resources, land-use, and ecological issues, such as waste and pollution. Economic includes the movement of people and goods, economic development, and measures to avoid the economic vulnerability of society. Social corresponds to safety, human health, social interactions, and equity. Lopes et al. [25] identified three transport subsystems: transported people and goods, means or services of transportation, and network through which movements happen.

In general, the divisions and nomenclatures of the subsystems diverge in most of the studies we found. The studies conducted by [21, 26–28] are comprehensive and addressed several elements. Therefore, based on the studies presented, we propose dividing urban mobility systems into eight subsystems, as indicated in Table 1.

Table 1. Urban mobility subsystems

Subsystem	Urban mobility subsystems
Institutional	Governance and policies (local norms, customs, and laws), actors and institutions (governmental and nongovernmental)
Social	Communities, people, demographics, justice and equity, safety, human health, social interactions, social movements, right to urban mobility
Economic	Development of societies and economies, monetary capital, measures to avoid economic vulnerability of society, transport infrastructure investment
Material and energy flows	Materials produced or consumed in or by a system (energy)
Infrastructure	Infrastructures and built environment, land use and structural design, network through which movements happen, transportation infrastructure
Natural	Natural includes ecology, environment, natural resources, estimated vehicle emissions, and geographical conditions
Demand	Transported people and goods, movement of people and goods, attitude/mobility options, origin, and destinations
Transport mode	Movement of people and goods, means or services of transportation, traffic congestion, transport modes, public transportation, private transportation, attractiveness

2.2 Resilience: Concepts and Threats

The concept of resilience has increasingly been applied in urban transport studies and has drawn the attention of urban and transport planners. Urban resilience refers to the ability of an urban system - and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales - to maintain or rapidly return to desired functions [21], to absorb the first damage, to reduce the impacts from a disturbance [29], to adapt to change, and to quickly transform systems that limit current or future adaptive capacity [21, 29].

Fernandes et al. [27, 28] adapted the concept of resilience of Folke et al. [30] to urban mobility. The authors defined persistence as the potential of an individual or group to maintain existing mobility patterns, possibly affecting their socioeconomic conditions, but without compromising their quality of life. Adaptability corresponds to the potential to adopt different alternatives to the essential mobility patterns, also without compromising the quality of life. Transformability is the potential to create new conditions for adaptability and persistence in the face of future threats. In addition, Roy et al. [31] defined mobility resilience as the ability of a mobility infrastructure system (for people's trips) to manage shocks and return to a steady state in response to extreme events, such as hurricanes, earthquakes, terrorist attacks, winter storms, wildfires, floods, and others.

The concept of resilience we selected for this study is specific regarding urban mobility, but also considers the interactions and interconnections with other system components. Thus, the resilience of an urban mobility system corresponds to the ability to maintain the current conditions or rapidly return to the original mobility status (persistence), to absorb the first damage and to reduce the impacts from a disturbance by adopting different alternatives to the essential mobility conditions (adaptability); or to adapt to change (transformability) across temporal and spatial scales.

After an extensive search in the literature on threats that specifically affect the resilience of urban, transport, and urban mobility systems, we identified 37 types of threats. We then aggregated similar threats into common names that are representative of the original individual meanings. For instance, terrorism, targeted destructions, malevolent attacks, and pranks were called malicious hazards. The final list was reduced to 17 threats. Natural disasters (39.4%), climate change (15.5%), malicious hazards (9.9%), and technical failures (8.5%) were the most frequent threats, whereas peak oil (5.6%) and increased fuel price (4.2%) were the least frequent.

The investigation of threats to urban mobility systems is important to characterize the system responses before, during and after shock events, so that proper frameworks for measuring and characterizing resilience could be designed. In the studies analyzed, we observed that the methods and variables used to describe resilience vary according to the threat outlined. Therefore, we identified threats to the urban mobility system and segregated them according to the subsystem affected. The studies more frequently address increased fuel prices (33.3%), peak oil (29.6%), and disrupted fossil fuel supply (14.8%) as threats to the urban mobility system. The *Social* and *Economic* subsystems were most often associated with these threats.

3 Method

After conducting a comprehensive literature review on urban mobility systems and resilience, we identified the main subsystems, threats, and variables. Considering these subsystems, we proposed a method to describe the dynamics involved in an urban mobility system in its essential state of functionality and in the face of threat(s). Finally, we built models, using causal loop diagrams (CLD), illustrating the resilience of an urban mobility system in the face of a major threat. The method follows these steps:

1. Characterization, based on the literature review, of interrelations and interconnections between the elements of an urban mobility system: identification of cause and effect relationships (and feedbacks) [32] between the main system elements. Moreover, identifying the boundaries of the system (resilience of what) [17–19], and time horizons [17, 18].
2. Qualitative modeling describing the system in the essential state of functionality: investigation of the causal beliefs [15], creation of CLD, structure and feedback processes [33, 34].
3. Qualitative modeling of the system when affected by one or more disruptive events: creation of CLD, structure and feedback processes in the face of threat(s).
4. Qualitative modeling of the system facing one or more disruptive events but still functioning due to its resilience: creation of CLD, structure and feedback processes describing persistence, adaptability, and transformability of an urban mobility system in the face of threat(s).

CLD models comprise a graphic tool used for better understanding the cause and effect relationships between the components of a system [20]. Cause and effect relationships are graphically represented by an arrow and a sign (positive or negative). When components or variables are directly proportional, that is, when the growth in one variable (cause) produces an increase in another variable (effect), it is stated that the causal relationship between the variables is positive. In contrast, when the variables are inversely proportional, that is, when the growth in one variable (cause) produces a decrease in another variable (effect), the causal relationship between the variables is negative.

Causal relationships help the development of positive (or reinforcing) feedback loops, negative (or balancing) feedback loops, and archetypes. Reinforcing loops lead to an exponential growth of the system, while balancing loops lead to stabilization. Archetypes comprise common system structures that produce characteristic behavior patterns [35]. More specifically, archetypes are composed of specific combinations of reinforcing and balancing loops [14].

Qualitative models provide an in-depth understanding of the dynamics involved in a system, allowing a global view of the entire functioning of the system. This is particularly important to identify the impacts of decision-making processes that might run counterintuitively, worsening functionalities, or intensifying the malfunction of the system. Models are validated through careful examination of their internal consistency and their realistic representation of critical aspects of the problem [14, 15, 20]. To do this, case studies to establish realistic databases are needed. In this study, we focus on identifying cause and effect relationships that have already been validated by researchers

from several areas of knowledge. Model validation and quantitative system dynamics modeling using case studies will be the focus of future investigations.

4 Results and Discussions

The first step of the method corresponds to identifying interrelations and interconnections between system elements. We identified 118 variables used to characterize urban mobility subsystems and their associations. However, to include only variables in the CLD that are relevant to describe the system behavior, we aggregated similar variables and selected the most relevant to characterize the causal relationships, as presented in Table 2.

Table 2. Variables for characterizing subsystems

Subsystem	Variables
Institutional	Land-use policies, Private motorized transport policies, Priorities of policymakers to transport policies, Active and public transport policies, Technological strengths [1, 13, 16, 36], Disaster prevention policies/measures, Segregated housing or relocation programs
Social	Deaths, Employment, Health issues, Safety, Urban segregation, Vulnerable social groups [12, 16, 32, 33, 36–43]
Economic	Economy, Trip costs [1, 12, 16, 39, 40, 43, 44]
Material and energy flows	Fuel consumption [3, 16, 36, 43]
Infrastructure	Compact urban form and structure, Transport infrastructure investments, Green infrastructures, Impervious area, Transport infrastructure recovery [1, 16, 17, 36, 39, 40, 45], Transport infrastructure maintenance, Infrastructure conservation status
Natural	Climate change, Flooding, GHG emissions [1, 33, 39, 42, 44, 45], Environmental issues
Demand	Private motorized travel demand, Population, Active and public travel demand, Public awareness and willingness to change [17, 36, 37, 40, 43–45]
Transport mode	Efficiency of vehicles, Mobility performance, Transport mode attractiveness, Travel time, Traffic congestion, Travel distance, Technological strengths [3, 12, 13, 16, 17, 36, 37, 42–45]

Based on the variables selected, we built qualitative models to represent an urban mobility system under different conditions: (i) in the essential state of functionality, (ii) affected by a disruptive event and (iii) still functioning due to its resilience. The essential state corresponds to common system structures that represent the system's behavior during a typical day, that is, the essential state is an archetype of the urban mobility system. The CLD, in this case, resulted in fourteen feedback loops, in which

ten are reinforcing (R1 to R10) and four are balancing (B1 to B4) loops, as depicted in Fig. 1. A schematic representation of reinforcing feedback loops (R), in which the most frequent variables are underlined, correspond to:

(R1) PRIVATE MOTORIZED TRANSPORT POLICIES $\xrightarrow{-}$ TRIP COSTS $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ PRIVATE MOTORIZED TRANSPORT DEMAND [$\xrightarrow{-}$ ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL POLICIES $\xrightarrow{-}$] $\xrightarrow{+}$ PRIVATE MOTORIZED TRANSPORT POLICIES

(R2) PRIVATE MOTORIZED TRANSPORT POLICIES $\xrightarrow{+}$ TRANSPORT INFRASTRUCTURE INVESTMENTS $\xrightarrow{+}$ MOBILITY PERFORMANCE $\xrightarrow{-}$ TRAVEL TIME $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ PRIVATE MOTORIZED TRANSPORT DEMAND [$\xrightarrow{-}$ ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL POLICIES $\xrightarrow{-}$] $\xrightarrow{+}$ PRIVATE MOTORIZED TRANSPORT POLICIES

(R3) ACTIVE AND PUBLIC TRANSPORT POLICIES $\xrightarrow{-}$ TRIP COSTS $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{+}$ ACTIVE AND PUBLIC TRANSPORT POLICIES

(R4) ACTIVE AND PUBLIC TRANSPORT POLICIES $\xrightarrow{+}$ TRANSPORT INFRASTRUCTURE INVESTMENTS $\xrightarrow{+}$ MOBILITY PERFORMANCE $\xrightarrow{-}$ TRAVEL TIME [$\xrightarrow{+}$ TRIP COSTS] $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{+}$ ACTIVE AND PUBLIC TRANSPORT POLICIES

(R5) ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{-}$ PRIVATE MOTORIZED TRAVEL DEMAND [$\xrightarrow{+}$ TRAFFIC CONGESTION] $\xrightarrow{-}$ MOBILITY PERFORMANCE $\xrightarrow{-}$ TRAVEL TIME [$\xrightarrow{+}$ TRIP COSTS] $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL DEMAND

(R6) ACTIVE AND PUBLIC TRAVEL DEMAND $\xrightarrow{-}$ FUEL CONSUMPTION $\xrightarrow{+}$ TRIP COSTS $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ ACTIVE AND PUBLIC TRAVEL DEMAND

(R7) ACTIVE AND PUBLIC TRANSPORT DEMAND $\xrightarrow{-}$ PRIVATE MOTORIZED TRANSPORT DEMAND $\xrightarrow{-}$ ACTIVE AND PUBLIC TRANSPORT DEMAND

(R8) ECONOMY $\xrightarrow{+}$ PRIORITIES OF POLICYMAKERS TO TRANSPORT POLICIES $\xrightarrow{+}$ ACTIVE AND PUBLIC TRANSPORT POLICIES $\xrightarrow{+}$ TRANSPORT INFRASTRUCTURE INVESTMENTS $\xrightarrow{+}$ MOBILITY PERFORMANCE [$\xrightarrow{-}$ TRAFFIC CONGESTION $\xrightarrow{-}$] $\xrightarrow{+}$ ECONOMY

(R8') ECONOMY $\xrightarrow{+}$ PRIORITIES OF POLICYMAKERS TO TRANSPORT POLICIES $\xrightarrow{+}$ PRIVATE MOTORIZED TRANSPORT POLICIES $\xrightarrow{+}$ TRANSPORT INFRASTRUCTURE INVESTMENTS $\xrightarrow{+}$ MOBILITY PERFORMANCE [$\xrightarrow{-}$ TRAFFIC CONGESTION $\xrightarrow{-}$] $\xrightarrow{+}$ ECONOMY

(R9) MOBILITY PERFORMANCE $\xrightarrow{-}$ TRAFFIC CONGESTION $\xrightarrow{-}$ MOBILITY PERFORMANCE

(R10) FUEL CONSUMPTION $\xrightarrow{+}$ GHG EMISSIONS $\xrightarrow{-}$ POPULATION $\xrightarrow{+}$ VULNERABLE SOCIAL GROUPS $\xrightarrow{-}$ PRIVATE MOTORIZED TRAVEL DEMAND $\xrightarrow{+}$ FUEL CONSUMPTION

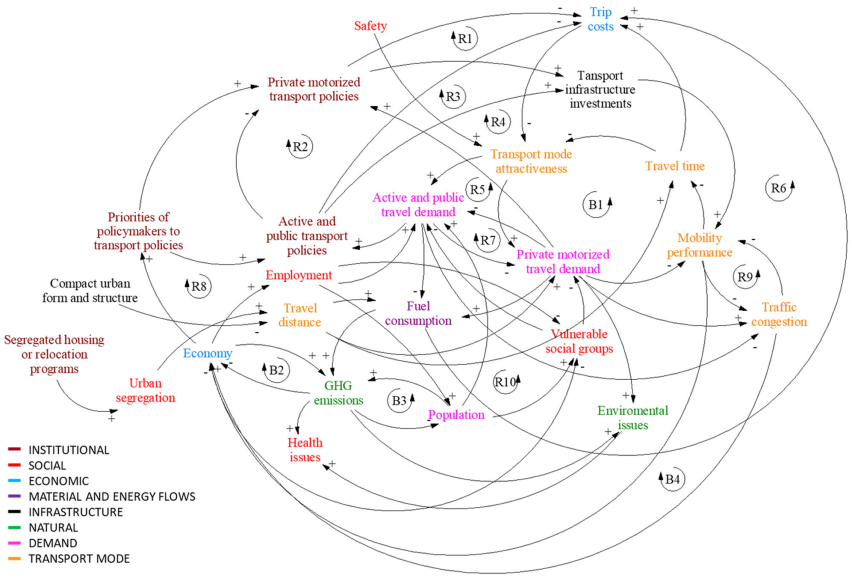

Fig. 1. Causal loop diagram for urban mobility system in its essential state of functionality

The separate loops can be interpreted as follows. In reinforcing loop R1, for example, an increase in policies aimed at private motorized transport decreases costs incurred by private motorized trips, which increases the transport mode attractiveness, increasing private motorized transport demand (which decreases active and public travel demand, reducing policies on active and public transport, which increases policies on private motorized transport), which in turn increases policies related to private motorized transport. As the interpretation of the other loops follows a similar logic, we will not explain them in detail, except for loop R8.

Reinforcing loop R8 indicates that an increase in the economy leads to more priorities of policymakers towards active and public transport policies, which increases investments in active and public transport infrastructures. An increase in transport infrastructure investments leads to more mobility performance (which decreases traffic congestion), which in turn increases the economy. Reinforcing loop R8' is equal to R8, but instead of the variable active and public travel policies, it refers to the variable private motorized transport policies.

A schematic representation of the balancing feedback loops (B) from Fig. 1, in which the most frequent variables are underlined, correspond to:

(B1) PRIVATE MOTORIZED TRAVEL DEMAND [$\xrightarrow{+}$ TRAFFIC CONGESTION] $\xrightarrow{-}$ MOBILITY PERFORMANCE $\xrightarrow{-}$ TRAVEL TIME [$\xrightarrow{+}$ TRIP COSTS] $\xrightarrow{-}$ TRANSPORT MODE ATTRACTIVENESS $\xrightarrow{+}$ PRIVATE MOTORIZED TRAVEL DEMAND

(B2) ECONOMY $\xrightarrow{+}$ GH EMISSIONS $\xrightarrow{-}$ ECONOMY

(B3) POPULATION $\xrightarrow{+}$ GH EMISSIONS $\xrightarrow{-}$ POPULATION

(B4) ECONOMY $\xrightarrow{+}$ EMPLOYMENT $\xrightarrow{-}$ VULNERABLE SOCIAL GROUPS $\xrightarrow{-}$ PRIVATE MOTORIZED TRAVEL DEMAND $\xrightarrow{-}$ MOBILITY PERFORMANCE [$\xrightarrow{-}$ TRAFFIC CONGESTION $\xrightarrow{-}$] $\xrightarrow{+}$ ECONOMY

In general, *Social*, *Transport mode* and *Institutional* subsystems have a greater influence over the CLD regarding the essential state of functionality, as they represent 58.3% of the variables. The CLD is general and does not consider the dynamics over time, that is, there are links and loops that can occur at different times, producing different impacts on the general system. For instance, the variable mobility performance is affected by several variables that tend to stabilize (balancing loop B1) or generate an exponential growth over it (reinforcing loop R9).

Additionally, Fig. 1 illustrates that the priorities of the public authorities for directing policies aimed at active, public, or private motorized transport are related to economic interests. Thus, although there are dynamics that pressure the implementation of public policies favoring a particular travel mode, these policies only occur if there is a convergence of the priorities of policymakers with economic interests. In addition, loop R10 indicates that a decrease in vulnerable social groups (e.g., low-income population) leads to an increase in fuel consumption. This is because there is an increase in the population traveling by private motorized vehicles, which means an increase in private motorized travel demand. However, loop R10 has no other balancing loops acting to stabilize it, thus an exponential growth in fuel consumption is observed.

Therefore, urban mobility in its essential state of functionality is driven by economic interests, whereby mobility performance and travel demand have dynamics with exponential growth, as well as stabilizing dynamics that can lead to balanced feedback loops. Furthermore, measures must be taken to stabilize fuel consumption as the functioning of the system exponentially aggravates environmental issues and is exposed to fuel restrictions.

We observed in the literature review that natural disasters and climate change are more often indicated as threats to urban systems, while increased fuel prices and peak oil are more frequently indicated as threats to urban mobility. Hence, a gap in studies addressing climate change impacts on urban mobility was noted. For this reason, we also built a CLD representing the system behavior when threatened by natural disasters and climate change. The diagram resulted in eleven feedback loops, in which five are reinforcing (Rt1 to Rt5) and six are balancing (Bt1 to Bt6) loops (Fig. 2). The interpretation of reinforcing and balancing feedback loops in Fig. 2 follows the same logic explained for the causal loop diagram regarding the system in its essential state of functionality.

In general, when the system is under threat, new variables, links, and loops are created and rearranged in response. The system response depends on the intensity of the shock and the intrinsic characteristics of the system, for instance, the existence

of disaster prevention policies. Our model considers a variety of these possibilities, resulting in an increase in the participation of the number of variables that comprise the *Infrastructure* and *Institutional* subsystems (from 8.3% to 16.7% and from 16.7% to 19.4%, respectively), in relation to the essential state. *Institutional*, *Transport mode*, *Social*, and *Infrastructure* subsystems have a greater influence over the CLD as they represent 72.2% of the variables.

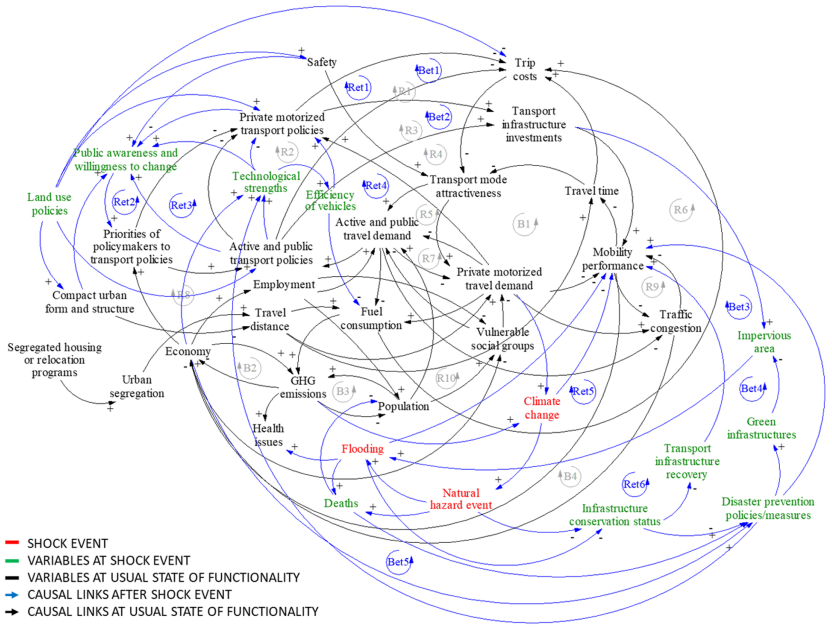

Fig. 2. Causal loop diagram for urban mobility system under environmental threats

Additionally, Fig. 2 indicates that the priorities of policymakers for directing transport policies are not only a consequence of economic interests, but also of public opinion (Rt3). Reinforcing feedback loop Rt3 pressures policymakers towards sustainable travel modes, stabilizing loops with private motorized travel policies. On the other hand, there are dynamics that reinforce or balance climate change, as can be observed in loops Rt5, Rt6 and Bt5. Mobility performance affects economy (Rt5) and private motorized travel demand (Rt6), causing an exponential increase in climate change. In loop Bt5, disaster prevention policies/measures affect fatalities, flooding, and infrastructure conservation status, stabilizing fuel consumption, GHG emissions, and, consequently, climate change. Loops Bt1 and Bt2 balance private motorized policies through technological strengths, such as innovation, smart city strategies, intelligent transportation systems (ITS), electric vehicles, alternative fuels, and energy efficiency (fuels and vehicles). In contrast, loop Rt6 is counterintuitive, as measures for the recovery of private motorized infrastructures may, in fact, increase private motorized demand, aggravating climate change.

Therefore, an urban mobility system threatened by climate change is driven by interests of the economy and public opinion, especially with regard to encouraging the

use of sustainable transport. Furthermore, technological strengths, energy efficiency of vehicles and disaster prevention play an important role in stabilizing fuel consumption, mobility performance, private motorized demand, and climate change. These findings are important to support and guide decision-making processes in low-carbon policies and smart cities paradigms, for instance.

Finally, in the last part of our analysis, we built a CLD for the resilience of urban mobility system based on the analysis of several attributes proposed by Fernandes et al. [28] and Folke et al. [30]: persistence, adaptability, and transformability. The CLD representing a resilient urban mobility system resulted in eleven feedback loops, in which five are reinforcing (Rr1 to Rr5) and six are balancing (Br1 to Br6) loops. The interpretation of reinforcing and balancing feedback loops in Fig. 3 follows the same logic explained for the causal loop diagram regarding the system in its essential state of functionality.

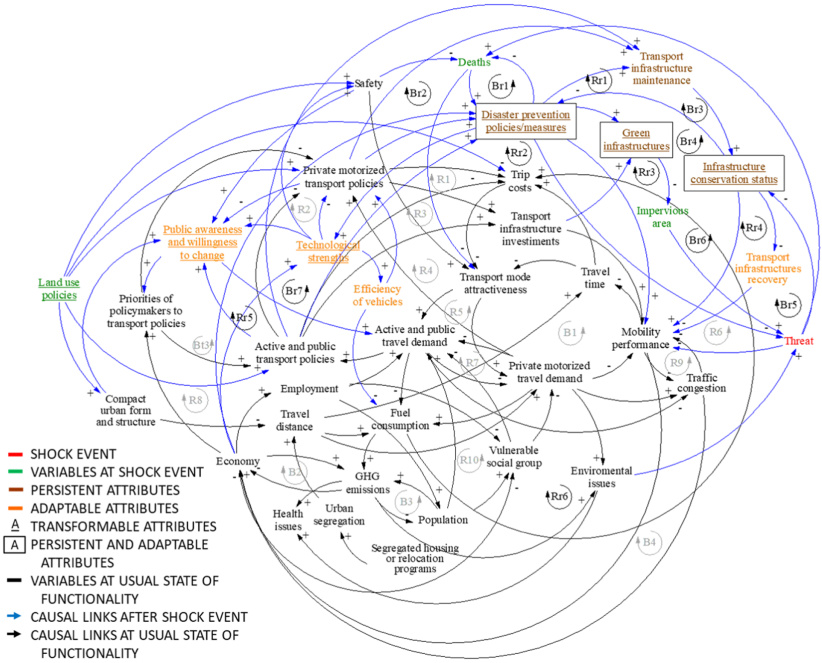

Fig. 3. Causal loop diagram corresponding to a resilient urban mobility system

In general, a resilient urban mobility system should have attributes that allow the system to maintain its current conditions (persistence), to absorb the first damage and reduce impacts (adaptability), or to adapt to change, and to quickly transform subsystems (transformability) after a shock event. Analyzing the system under threat (Fig. 2) made it possible to identify variables, links, and feedback loops that are important to describe a resilient system. Thus, the CLD from Fig. 3 showed that the *Institutional*, *Infrastructure*, *Transport mode*, and *Social* subsystems have a greater influence over the diagram, as they represent 75.0% of the variables.

Additionally, Fig. 3 indicates that the CLD for a resilient system is slightly similar to the CLD for the system under threat, however, there is an important difference between the two diagrams. In the CLD under threat, the dynamics have a reactive pattern, while in the resilient CLD they have a preventive pattern, as can be seen in feedback loops Rr1 to Rr5, in which transport policies provide for the planning of disaster prevention policies/measures. In addition, loop Rr6 strengthens the dynamics aimed at controlling fuel consumption and climate change, strengthening the economy and disaster prevention policies/measures. On the other hand, loops Br1 to Br7 tend to stabilize threats and the effects of threats to the system, such as deaths, infrastructure conservation status, and fuel consumption. Besides that, it can be observed that public opinion plays an important role in balancing the system, as well as encouraging the use of sustainable transport.

5 Conclusions

Urban mobility systems are dynamic, complex, and often involve multiple stakeholders or agents, resulting in responses with distinct time lags [46]. Previous studies used strategies to quantify the resilience of urban mobility considering the particularities of system's components separately (e.g., [36, 47, 48]). There is also a lack of studies addressing threats to urban mobility and the concurrent impacts on the urban mobility system. Thus, a holistic analysis considering key elements of transport systems and their interactions over space and time is necessary. Moreover, qualitative models provide an in-depth understanding of the dynamics involved in a system, allowing a global view of the entire functioning of the system.

This study indicated that the urban mobility system can be divided into eight subsystems: *Institutional*, *Social*, *Economic*, *Material and energy flows*, *Infrastructure*, *Natural*, *Demand* and *Transport mode*. The main threats to urban mobility are related to climate change, increased fuel prices, and peak oil. We selected climate change as the main threat to carry out the next steps. Analyzing the CLD regarding the urban mobility system in its essential state of functionality indicated that economic interests play an important role in directing transport policies. In addition, measures to stabilize the dynamics involved in fuel consumption must be taken, as it is related to an aggravation of environmental issues and exposes the system to fuel restrictions. The CLD of the system threatened by climate change and natural disasters showed that technological strengths, energy efficiency of vehicles and disaster prevention play an important role in stabilizing fuel consumption, mobility performance, private motorized demand, and, consequently, climate change. Furthermore, the system is driven by interests of the economy and public opinion, especially with regard to encouraging the use of sustainable transport.

The CLD of the resilience of the urban mobility system is similar to the CLD of the system under threat. However, the dynamics of the system under threat have a reactive pattern, while in a resilient system they have a preventive pattern. This can be seen through the dynamics concerning transport policies that provide for the planning of disaster prevention policies/measures and strengthening of the dynamics aimed at controlling fuel consumption and climate change. Thus, the economy and disaster prevention policies/measures are reinforced, preventing the negative effects of threats to the system (deaths, infrastructure conservation status, and mobility performance). Besides

that, public opinion and incentives to use sustainable transport play an important role in balancing the system.

The study characterized the dynamics involved in urban mobility system in its essential state of functionality, under natural hazards and under resilient functioning. Considering this, the study helps to develop holistic quantitative models to determine the resilience of urban mobility using a system dynamics approach. Thus, besides answering the questions formulated in the introductory section, this study proposes a new division of subsystems and addresses a threat to urban mobility that has been scarcely explored in the literature using holistic qualitative models. The model shows that the elements of the urban system are strongly connected, generating effects in different parts of the system.

Thus, when analyzing urban mobility considering the threat of climate change, we are faced with other threats already mentioned in the literature (e.g., flooding, natural disasters, GHG emissions, population growth, vehicle demand, etc.). However, most of the studies we found analyze only one effect at a time, not considering the dynamics that lead to its appearance, or its interconnections with other subsystems, that is, cause and effect relations are not always considered.

The proposed method can support the development of integrated urban and transport management, in which the consequences of policies and actions carried out in one part of the system can be identified and have effects on other predicted parts. In addition, the study can be adapted to different urban systems and even other situations that have systemic characteristics, such as smart cities and Industry 4.0. Thus, the outcomes of this study may be used to support the process of planning and building resilient cities.

This study provides an in-depth understanding of the dynamics involved in the urban mobility system through qualitative models (CLD). However, the models do not allow a local analysis and do not consider the dynamics over time. For future work, we suggest extending this study for quantitative models based on stock and flow diagrams. To do this, it would be necessary to validate the model through case studies, for example. In addition, other threats could be explored, such as increased fuel prices, and peak oil. Consequently, an integrated analysis considering several threats, as well as the resilience of urban mobility systems under concomitant threats could be carried out.

Acknowledgment. . This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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