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MODELING THE RESILIENCE OF URBAN MOBILITY WITH A SYSTEM DYNAMICS APPROACH

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ABSTRACT
A resilient urban mobility system should be able to absorb the effects of disturbances (threats) while preserving its essential state of functionality. Given the scarcity of studies concerning the concurrent impacts of threats to urban mobility systems, a comprehensive analysis considering essential components of transport systems and their interrelationships is necessary. Thus, this doctoral research aims to describe and analyze the dynamics involved in a resilient urban mobility system to different strands of threats (such as environmental, anthropogenic, fuel-related, and health-related threats) and quantify the system's resilience to those threats using system dynamics modeling. The method for assessing resilience comprises: characterization of cause-effect relationships; formulation and validation of qualitative models; formulation, validation, and sensitivity analysis of quantitative models; simulation of scenarios. Up to now, we have developed the characterization of cause-effect relationships, as well as the formulation and validation of qualitative models.

1. INTRODUCTION

The capacity of urban systems to resist, adapt or transform themselves in the face of threats is known as urban resilience (Leichenko, 2011). A resilient urban mobility system should be able to absorb the effects of threats while preserving its essential state of functionality (Zhao *et al.*, 2013) within and between subsystems. Although there is a wide body of literature addressing the impacts of climate change and extreme weather events on transport systems (e.g., Chopra *et al.*, 2016; Mattsson and Jenelius, 2015; Mostafavi and Inman, 2016), few are related to urban mobility systems. There is also a scarcity of studies considering the impacts of increased fuel prices, peak oil, and pandemics on urban mobility systems and addressing holistic analysis methods, such as system dynamics.

Given that urban mobility systems are dynamic in time and in space, a systematic analysis framework that integrates different stakeholders is helpful. Hence, the present study explores the components of urban mobility systems and their causal relationships considering a specific time horizon, aiming at describing, analyzing, and quantifying the resilience of urban mobility in the face of threats through system dynamics modeling. To illustrate the method, we intend to carry out two case studies: the case of São Carlos, SP, in Brazil, and the case of Vienna, in Austria. Therefore, we intend to answer the following research questions: RQ1 - What are the main components of and threats to urban mobility systems? RQ2 - What are the dynamics involved in urban mobility systems in their essential state of functionality and when exposed to threats? RQ3 - How resilient are urban mobility systems in the face of threats?

2. THEORETICAL BACKGROUND

This Section presents a concise review of the literature on urban mobility systems, resilience of urban mobility, and system dynamics modeling.

2.1. Urban mobility subsystems

There is still no consensus on the divisions and nomenclature of urban mobility systems into subsystems. Based on comprehensive studies (Meerow *et al.*, 2016; Ostadtaghizadeh *et al.*, 2015; Fernandes *et al.*, 2017, 2019), Lara and Rodrigues da Silva (2021) proposed dividing urban mobility systems into eight subsystems, namely: Institutional, Social, Economic, Material and energy flows, Infrastructure, Natural, Demand, and Transport mode.

2.2. Resilience of urban mobility: Concept and threats

Fernandes *et al.* (2017, 2019) adapted the concept of resilience proposed by Folke *et al.* (2010) to urban mobility. Considering these authors, Lara and Rodrigues da Silva (2021) defined resilience as the "system's ability to maintain the current conditions or rapidly return to the original mobility status (persistence), absorb the first damage and reduce the impacts from a disturbance by adopting different alternatives to the essential mobility conditions (adaptability), or adapt to change (transformability) across temporal and spatial scales".

Threats to urban mobility systems can cause the system to collapse and cause negative impacts on trip patterns, economy, etc. Thus, urban systems must be resilient. After an extensive search in the literature on threats that specifically affect the resilience of 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.

2.3. System dynamics modeling

System dynamics (SD) models are commonly used for policy analysis and design aimed at solving problems in complex systems (Sterman, 2002). The method relies on qualitative - Causal Loop Diagrams (CLD) - and quantitative - Stock and Flow Diagrams (SFD) - procedures to analyze the system's behavior over time. 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. On the other hand, quantitative models use stock and flow tools to describe the dynamics between system elements. Components of SFD can be added in the form of mathematical rules that can explain and predict their evolution in the short and long term (Lopes, 2010). Through this quantitative modeling phase, the analyst builds a simulation model to evaluate the system's behavior under multiple scenarios (Sterman, 2002). SD is a method widely used to characterize and analyze systems in different areas of knowledge. However, we found relatively few studies using systems dynamics to assess the resilience of urban mobility systems in the face of threats (for example, Macmillan *et al.*, 2018; Moradi and Vagnoni, 2018; Suryani *et al.*, 2020, 2019).

3. METHOD

The framework for assessing the resilience of urban mobility comprises the following steps:

i) *Characterization of cause-effect relationships:* Identification of cause and effect relationships and feedback between the primary system elements, as well as boundaries and time horizons. This step can be performed through literature survey, opinion of experts, decision-makers, and stakeholders, and search in official databases.
ii) *Formulation of qualitative models:* Investigation of the causal beliefs, creation of causal loop diagrams (CLDs), structure and feedback processes. The causal loop diagrams (CLD) shall be created under different conditions, namely: essential state of functionality, affected by a disruptive event, and still functioning due to its resilience.
iii) *Validation of qualitative models:* Careful examination of the model's consistency and realistic representation of critical aspects of the problem through consultancy to local managers, community planners, engineers, decision-makers, and other relevant stakeholders, and comparison with historical data covering the time horizon of the simulation.
iv) *Formulation of quantitative models:* Parameter estimations, setting initial conditions and checking model consistency, and creation of stock and flow diagrams (SFD).
v) *Validation of quantitative models.*
vi) *Sensitivity analysis*: Confirmation of the quantitative model's consistency by testing if the model produces appropriate results when the inputs take extreme values such as zero or infinity, for example.
vii) *Simulation of best-worst scenarios:* Synthesis of problems to evaluate the performance of quantitative models (SFD). Application of "what if?" model analysis based on the proposed strategy (Suryani *et al.*, 2019).

4. PRELIMINARY RESULTS

Up to now, the first and second steps of the framework have been completed. The third step is partially completed, and steps four to seven comprise the next research stage.

The first step was a literature review, in which we identified an expressive number of variables to characterize urban mobility subsystems and their interrelations and interconnections. Similar variables were aggregated for the CLD to describe the system behavior in a meaningful and straightforward way. The most relevant causal relationships were subsequently selected. In the second step, we created qualitative models representing urban mobility systems under different conditions, namely: essential state of functionality, affected by disruptive events, and still functioning due to its resilience. The essential state of functionality 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. Considering the system affected by threats, four strands of threats that may act concurrently were identified: environmental threats, anthropogenic threats, fuel-related threats, and health-related threats. We built a CLD for each strand of threat. Variables, links, and feedback loops important to describe a resilient system were identified in the system under threat. The CLD's for a resilient system and for the system under threat are slightly similar. However, there is an important difference between these diagrams. In the CLD under threat, the dynamics have a reactive pattern, while in the resilient CLD, a preventive pattern is observed. The third step comprises the validation of the CLDs. This step is currently in progress. Data from the Community Mobility Reports of Austria from March 16 to December 26, 2020, were used to validate the system behavior when affected by health-related threats (COVID-19 pandemic). The remaining CLDs still need to be validated.

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