FEDERAL UNIVERSITY OF CEARÁ

TECHNOLOGY CENTER

DEPARTMENT OF TRANSPORT ENGINEERING

TRANSPORT ENGINEERING GRADUATE PROGRAM

DOCTORATE IN TRANSPORT ENGINEERING

NELSON DE OLIVEIRA QUESADO FILHO

A METHOD FOR FORMULATING AND ASSESSING PUBLIC TRANSPORT INTERVENTIONS BASED ON EQUITY PRINCIPLES

FORTALEZA

2025

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Thesis presented to the Transport Engineering Graduate Program, Technology Center, Federal University of Ceará, as partial requirement to obtain doctor degree in Transport Engineering. Research Field: Operation and Planning of Transport Systems.

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Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

Q35m Quesado Filho, Nelson de Oliveira.
A Method for formulating and assessing public transport interventions based on equity principles / Nelson de Oliveira Quesado Filho. – 2025.
137 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, Centro de Tecnologia, Programa de Pós-Graduação em Engenharia de Transportes, Fortaleza, 2025.
Orientação: Prof. Dr. Francisco Moraes de Oliveira Neto.

1. Ex-ante. 2. Accessibility Planning. 3. Equity. 4. Resilience. 5. Optimization. I. Título.
CDD 388

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Approved in: March 13, 2025

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ACKNOWLEDGEMENTS

This section is intentionally written in Portuguese.

Ao meu orientador, professor Moraes, pelas incansáveis provocações que constantemente me desafiaram e engrandeceram esta tese.

À banca examinadora, formada pelos professores Felipe, Gildemir, André e Rosário, esta última em especial pela valiosa supervisão durante o período do doutorado sanduíche em Lisboa.

Ao Programa de Pós-graduação em Engenharia de Transportes e à Universidade Federal do Ceará (UFC), pela infraestrutura disponibilizada e pelo incrível material humano, que tornou essa jornada muito mais saborosa.

Aos professores Manoel - sem dúvida o melhor professor do mundo -, Flávio e Bruno que, com seu impressionante talento para a docência, marcaram minha trajetória.

À Viviane, minha maior entusiasta, que além de estar sempre ao meu lado, me presenteou com a Clarice, expressão máxima do nosso amor. Aos meus sogros, Dr. Arthur e D. Marília, torcida cativa da primeira fileira, que sempre estiveram próximos, vibrando com cada uma das nossas conquistas.

Ao Filipe, meu melhor amigo, pela disponibilidade a todo e qualquer momento; aos queridos amigos Murta e Duduv, que não permitiram que a distância nos afastasse; e ao grande amigo Pablo, pelo lembrete do pragmatismo necessário para se alcançar os sonhos.

À turma do CBN, meus amigos-irmãos, cujos momentos compartilhados foram fundamentais para aliviar o peso dos desafios acadêmicos e renovar as energias com risadas, cumplicidade e apoio mútuo.

Aos amigos do OPA-TP e do PETRAN, em especial Davi, Gaio, Yag, Cris, Gabi, Gustavo, Rubia, P. Bruno, Beliza, Juliana, Kaio e Webert, pelos debates acadêmicos acalorados e enriquecedores, que muito agregaram à minha formação técnica.

À Unichristus, onde aprendi o verdadeiro sentido de ser professor, e pude compartilhar os desafios do ensino superior com os queridos Franco (o maioral), Paula, Adriano, Claudia, Marisa, Tatiane e Elayne.

Por fim, à minha irmã Flávia, presença firme e constante, com quem sempre posso contar, faça chuva ou faça sol.

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

RESUMO

O planejamento do transporte prioriza a eficiência em detrimento da equidade, reforçando as disparidades na acessibilidade. Avaliações convencionais *ex-ante* não levam em conta as necessidades das populações vulneráveis. Esta tese de doutorado desenvolve um método para formular intervenções de transporte público com base em princípios de equidade, integrando planejamento estratégico, otimização orientada por equidade e resiliência na avaliação *ex-ante*. A primeira contribuição é uma abordagem de planejamento estruturado que vincula diretamente o diagnóstico do problema à formulação da intervenção, garantindo que os projetos propostos sejam baseados em restrições de acessibilidade. A segunda é um modelo de otimização orientado por equidade que prioriza melhorias de acessibilidade para as populações mais desfavorecidas, mudando o planejamento de transporte de uma perspectiva utilitária para uma baseada em princípios de justiça. A terceira contribuição aplica a resiliência nas avaliações *ex-ante*, permitindo que os planejadores avaliem como os ganhos de acessibilidade se mantêm sob interrupções, garantindo a estabilidade de longo prazo. Essas contribuições se traduzem em três estruturas: uma metodologia de planejamento para lidar com as desigualdades de acessibilidade, uma ferramenta de otimização para intervenção equitativa no transporte e um método de avaliação com base na resiliência. A aplicação da estrutura proposta no estudo de caso demonstrou eficácia na orientação de investimentos em transporte público equitativos. Os resultados mostraram que as intervenções formuladas usando uma abordagem orientada para o problema reduziram as lacunas de acessibilidade, principalmente para as populações vulneráveis. O modelo de otimização orientado priorizou com sucesso as melhorias que minimizaram o número de indivíduos abaixo dos limites críticos de acessibilidade. A análise de resiliência revelou que pode haver um bom desempenho no cenário esperado, mas um comportamento distinto quando confrontado com interrupções. Apesar de seus pontos fortes, a pesquisa é limitada por pressupor condições estáticas de uso do solo e demanda de viagens. Pesquisas futuras devem incorporar modelagem comportamental para levar em conta as respostas do lado da demanda, integrar interações de uso do solo para explorar mudanças de acessibilidade de longo prazo e desenvolver mais técnicas de otimização multiobjetivo baseadas em resiliência.

Palavras-chave: transporte público; acessibilidade; equidade; e*x-ante* avaliação; otimização.

ABSTRACT

Urban transport planning has traditionally prioritized efficiency over social equity, often reinforcing accessibility disparities. Conventional *ex-ante* evaluations, based on cost-benefit analysis, fail to account for the needs of vulnerable populations. This thesis develops a method for formulating public transport interventions based on equity principles, integrating strategic planning, equity-driven optimization, and resilience in *ex-ante* evaluation. The first contribution is a structured planning approach that directly links problem diagnosis to intervention formulation, ensuring that proposed projects are based on actual accessibility constraints rather than arbitrary assumptions. The second is an equity-driven optimization model that prioritizes accessibility improvements for the most disadvantaged populations, shifting transport planning from a purely utilitarian perspective to one based on social justice principles. The third contribution introduces resilience into *ex-ante* evaluations, allowing planners to assess how accessibility gains hold up under disruptions, ensuring long-term stability in equitable transport access. These contributions translate into three practical frameworks: a planning methodology for addressing accessibility inequities, an optimization tool for equitable transport intervention design, and a resilience informed evaluation method for stress-testing projects before implementation. The application of the proposed framework in the case study demonstrated its effectiveness in guiding equitable and resilient public transport investments. Results showed that interventions formulated using a problem-oriented approach significantly reduced accessibility gaps, particularly for vulnerable populations. The equity-driven optimization model successfully prioritized transit improvements that minimized the number of individuals below critical accessibility thresholds while maintaining operational feasibility. Additionally, resilience analysis revealed that might have a good performance on the expected scenario, but a distinct behavior when confronted by disruptions. These findings confirm that integrating diagnostic-based planning, capability-driven optimization, and resilience evaluation into transport decision-making leads to more just and sustainable urban mobility outcomes. Despite its strengths, the research is limited by assuming static land-use and travel demand conditions. Future research should incorporate behavioral modeling to account for demand-side responses, integrate land-use interactions to explore long-term accessibility changes, and further develop resilience-based multi-objective optimization techniques.

Keywords: transit; accessibility; equity; *ex-ante* evaluation; optimization.

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LIST OF ABBREVIATIONS AND ACRONYMS

PASFOR	*Plano de Acessibilidade Sustentável de Fortaleza e sua Área de Influência* (Plan for Sustainable Accessibility of Fortaleza and its Influence Area)
CBA	Cost-Benefit Analysis
MCDA	Multicriteria Decision Analysis
LVB	Land Value Benefits
ALUTI	Activity, Land Use and Transport Interactions
GDP	Gross Domestic Product
HDI	Human Development Index
ICT	Information and Communication Technology
BU	*Bilhete Único* (Single Pass)
ROW	Right-of-Way
BRT	Bus Rapid Transit
LRT	Light Rail Transit
TOD	Transit-Oriented Development
RB	Regular Bus
TB	Trolleybus
SCR	Streetcar
RTRT	Rubber-tired Rail Transit
RRT	Rail Rapid Transit
RGR	Regional Rail
GTFS	General Transit Feed Specification
CSV	Comma-Separated Values
GA	Genetic Algorithm

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1 INTRODUCTION

This chapter's purpose is to establish the context in which this doctoral research is inserted (section1.1), to highlight the research gaps and questions that are addressed (section1.2), to detail the research objectives (section1.3), to justify the research effort (section1.4), to describe the methodological overview and the thesis outline (section 1.5), and to present the case study (section1.6).

1.1 Background

The prevailing state of practice on *ex-ante* assessment of transport systems interventions relies on Cost-Benefit Analysis (CBA), which confronts the implementation costs of the intervention with its monetized benefits; these benefits are generally associated with travel time reductions and ridership increase. Despite its advantages related to economic efficiency and communicativeness, CBA methods have been largely criticized for their arbitrary monetization of benefits. Travel time, for instance, is not a market-negotiated good: it is not traded and has no market value. Nevertheless, different people in different contexts may value their time very differently (Donais *et al.*, 2019).

Furthermore, since up to 90% of the benefits considered in Cost-Benefit Analysis are travel gains (ITF, 2022), sustainable intervention alternatives that promote minor time travel reductions - bicycle or public transport policies, for example - might be disregarded in favor of projects that could spur greater commute distances, like new highways. Also, non-users may value transportation services, which benefits could not be detected on a willingness-to-pay approach (Wee; Geurs, 2011; Donais *et al.*, 2019).

To cope with those limitations, new assessment methods arise, such as Multicriteria Decision Analysis (MCDA) and Land Value Benefits (LVB). The former combines non-monetized benefits with monetized ones, through weighting factors defined by a variety of stakeholders with - at most of the time - conflicting opinions. This method facilitates the inclusion of subjective aspects, but do not eliminate the weight arbitrariness problem inherent to the process, creating a "black box" effect (Donais *et al.*, 2019; Wang; Levinson, 2022).

The latter, Land Value Benefits method, suggests that the benefit incurred from a transport system intervention is reflected on the increase in the willingness to pay for land use, *i.e.* the change in the ease to access activities is monetarily equal to the change in land value where the intervention is being implemented. Although land use is traded and its prices can be objectively assessed, it is not always possible to determine in which extend the gains are due transport projects (Wang; Levinson, 2022). Other *ex-ante* assessment methods are also applied - namely Cost-Effectiveness Analysis, Techno-Economic Analysis, and Activity-Based Costing - but less often (Donais *et al.*, 2019).

Regardless of the minutiae of these methods, their criteria assumes an utilitarian approach, which accepts any given allocation of utility among individuals, as long as it moves towards the maximum expected aggregated welfare possible. In other words, maximizing utility is indifferent to its distribution, and may accept to reduce vulnerable groups' benefits if it promotes an overall greater amount of benefits. In addition, utility commonly accrue from individuals' willingness to pay, biasing the disposition of benefits to more privileged groups or activities, such as more lucrative businesses (Pereira *et al.*, 2016).

In that sense, current transport project assessment methods may not be fair, once it values individuals' time based on its income and it does not consider the befits distribution within nor over distinguished groups. Therefore, they have been criticized for reinforcing socio-spatial problems: travel constraints can reduce activity participation, which can lead to increased social inequalities for vulnerable individuals (Wee, 2011; Pereira *et al.*, 2016).

Although the concept of fairness in the transport research context is rather new, it is claimed that, from a moral perspective, accessibility – the easiness one can reach opportunities – should be addressed as the main benefit accounted regarding transport system intervention impact (Vecchio; Martens, 2021; Geurs; Wee, 2004; Luz; Portugal, 2021; Pot *et al.*, 2024). That is because it is necessary for individuals to have a minimum level of access to key activities, so their basic needs are met. Hence, transport system interventions assessment must evaluate how they reduce accessibility distribution distortions among social groups, in opposition to verify the maximum utility surplus (Pereira *et al.*, 2016).

The urban transport planning shift towards fair accessibility distribution has substantial implications in relation to what should be considered a problematic situation and how to propose and evaluate transit solutions (Garcia, 2016). Some research effort has already been applied in this direction (Karner *et al.*, 2024; Amorim; Silva, 2024; Alogdianakis; Dimitriou, 2024), but a detailed and well defined framework for formulating and assessing public transport interventions that explicitly embodies this new paradigm is still absent in the literature.

1.2 Gaps and Research Questions

Despite recent advances in understanding and diagnosing urban accessibility, the high complexity of the phenomenon makes it challenging to adequately formulate projects. This challenge is particularly pertinent because incorrect intervention propositions lead to inappropriate policies choice in which accessibility problems are not addressed (ITF, 2022). A problem oriented planning may be the way to handle those questions (Garcia, 2016).

Notwithstanding, predominant *ex-ante* evaluation methods are disconnected from a strategic urban mobility planning, once they are not applied within integrated analysis, assessment, and feedback activities (Freire, 2019; Freiberg, 2022). It is argued that solely through systematic problems diagnosis, strategic and tactical alternative choice, and impact evaluation feedback it is possible to properly assess urban mobility networks (Garcia, 2016). That is because accessibility distribution inequities are problematic only if they are not fair, *i.e.* when vulnerable individuals are socially excluded by insufficient accessibility levels, which presupposes a diagnosis investigation before assessing possible solutions (Wee; Geurs, 2011; Lucas *et al.*, 2015; Pereira *et al.*, 2016).

Strategic diagnostic analysis - as an prior problem understanding step that aids *ex-ante* assessments - tackle the issues underlined so far. It should characterize not only privileged and vulnerable groups, but also the accessibility distribution between and within them, and the causal relations that affect this distribution. Those are essential information to perform a proper *ex-ante* evaluation, *i.e.* to formulate and assess solutions that could effectively attend to urban accessibility problems (Garcia, 2016).

However, despite being present in several urban mobility planning methods (Meyer; Miller, 2001; May *et al.*, 2005; Magalhães; Yamashita, 2009; Garcia, 2016), the project formulation stage is vaguely described and no explicit connection is made between the diagnosed accessibility restrictions and the transit project attributes. Most of the effort in current literature is driven onto appraising transportation project alternatives that are announced, under development or developed. Recent works on accessibility evaluations (Garcia, 2016; Pereira, 2019; Freire, 2019; Freiberg, 2022; Deweese *et al.*, 2022; Amorim; Silva, 2024; Vecchio *et al.*, 2020) don’t go through a conceptual phase nor discuss the merit of proposed interventions.

Appropriate interventions cannot be selected if the right projects are not formulated and proposed: given the endeavor mobilizing transport projects, once started they are likely to be implemented, even unsuitable ones (ITF, 2022). That is because as soon as funds are committed, the scope for making changes is limited, and, considering the wide range of possible measures (from carbon taxation and land-use policies to infrastructure development), conceptual solution, *i.e.* project formulation, plays a main role on strategic planning (Donais *et al.*, 2019).

In that sense, Sousa (2019) suggests a prescriptive approach based on a strategic diagnosis. In its study, it is argued that transport project impacts should be estimated on future state of affairs, regarding what was found about the urban systems causal relationship. The problem evolution scenario can be used as a comparative baseline, or a reference "do-nothing" alternative. The author also highlights the importance of considering multidisciplinary (land use - transport - activity) project propositions that relay on problem understanding analysis.

Therefore, **there is a methodological gap regarding the formulation of public transport interventions supported by a diagnostic analysis**.

The inclusion of fairness in the formulation and assessment of urban public transport projects raises numerous questions about which benefits should be considered and which distribution patterns are equitable (Willberg *et al.*, 2023; Geurs; Wee, 2004; Wee; Mouter, 2021). These questions underline the importance of considering justice concepts in the context of transportation. According to Pereira *et al.* (2016), stakeholders can benefit from an ethical perspective that is supported by the justice theories of Rawls' Egalitarianism and the Capabilities Approach, two of the most important justice theories in political philosophy.

These ethical perspective offer relevant advantages in the context of transport systems: they are a universal approach to justice, aligned with individual rights and liberty protection, accommodating issues about the ability to reach opportunities and the plurality of society, attending the conditions of sufficientarianism and egalitarianism, admitting the vulnerability of certain groups and the respect for the rights of all. These principles recognize that inequity must hold individuals accountable for their choices and, at the same time, accept that such choices are a product of their context, being flexible enough to be applied in different dimensions of goods, rights, and benefits (Sen, 2011; Martens, 2012; Lucas *et al.*, 2015).

Aforesaid justice theories point the capability of achieving basic needs and opportunities - considering that individuals' choices are determined by their personal constraints - as the main resource to be distributed in a transportation intervention (Wee; Geurs, 2011; Amorim; Silva, 2024). In that sense, the definition of accessibility is intrinsically linked to the opportunities available for individuals to attain, considering their restrictions, desires, and necessities.

Accessibility refers to an individual's combined capability and should, therefore, be the criterion for policies formulation and assessment. Accessibility distribution evaluation ought consider that all individuals must dispose a minimum level of access to basic activities, that vulnerable groups must experience reduced inequalities in accessibility distribution, and that interventions must improve overall average accessibility levels while promoting accessibility distribution equity. A transport policy is fair if it employs investments in such a way as to prioritize vulnerable groups, mitigating morally questionable disadvantages and distortions in the ability of individuals to achieve opportunities (Loh; Kim, 2020; Deweese *et al.*, 2022; Amorim; Silva, 2024; Ferreira, 2023).

Applying these Rawlsian principles early in project formulation can yield more equitable outcomes. Studies suggest that when planners identify who benefits and who is burdened in advance, they can redesign projects to spread benefits more evenly (Amorim; Silva, 2024). Also, emphasis on maximizing total benefits often means distributional impacts are often ignored in project selection (Wee; Mouter, 2021).

Recent studies emphasizes a persistent gap between theoretical equity principles and their actual incorporation into the formulation of urban transit interventions (Karner *et al.*, 2024; Pot *et al.*, 2024). While research on accessibility and fairness has flourished (Lucas, 2012; Vecchio; Martens, 2021; Wee; Mouter, 2021), equity analyses, when performed, typically occur ex-post (Vecchio *et al.*, 2020), evaluating whether projects inadvertently exacerbated disparities. Consequently, low-access populations may remain underprioritized, even though guaranteeing "sufficient" accessibility for all is recognized as fundamental (Pereira *et al.*, 2016; Amorim; Silva, 2024).

While progress has been made in considering social distribution in transport accessibility, research often fails to distinguish between those in real need and those already well-served. Many studies focus on reducing variance (Ferguson *et al.*, 2012; Zhang *et al.*, 2016) or minimizing gaps (Caggiani *et al.*, 2017), but these do not always address actual challenges faced by disadvantaged communities (Niehaus *et al.*, 2016).

A diagnostic process is crucial for identifying those in need (Sousa, 2019), yet many studies lack this step or focus only on evaluating existing projects (Deweese *et al.*, 2022; Amorim; Silva, 2024). Despite discussions on equity in transport planning (Behbahani *et al.*, 2019; Pavia *et al.*, 2023; Amorim; Silva, 2024; Wang *et al.*, 2024), no study has combined Rawls' Egalitarianism and Sen's Capability Approach into a framework for public transport interventions. Additionally, attempts to integrate equity-based metrics into transit design have shown that early attention to vulnerable communities can reshape routes, fares, and complementary services (Loh; Kim, 2020; Behbahani *et al.*, 2019; Michailidis *et al.*, 2023a).

Thus, **there is a methodological gap regarding the formulation of public transport interventions in the light of promoting equitable accessibility distributions**.

Ex-ante evaluations for transit projects have evolved, incorporating various sustainability and accessibility criteria (Freire, 2019; Garcia, 2016; Wee; Mouter, 2021). However, they still fail to address the extent in which transportation systems can withstand from disruptions, minimizing economic, environmental, and social impacts (Bešinovic', 2020; Wan *et al.*, 2017; Zhou *et al.*, 2019).

One way to mitigate these unintended effects is considering the resilience of a transport project to uncertainties. Resilience in transportation planning refers to a system's ability to absorb disturbances and maintain its core functions under various shocks, such as economic crisis or climate change (Proper, 2011; Liu *et al.*, 2025).

Historically, transport resilience has been discussed in post-disaster recovery contexts, but its integration into *ex-ante* evaluations remains limited Bešinovic´ (2020). In accessibility planning, resilience is increasingly recognized as a crucial factor for ensuring equitable and sustainable urban mobility.

Given the large investments, public transport must be long-term resilient to land use changes or it risks becoming ineffective (ITF, 2022; Cavalcante, 2023). Kurth *et al.* (2020) demonstrated that even minor disruptions could trigger severe GDP declines and increased transport costs, especially in high-demand urban areas. Cats e Jenelius (2016) found that a 75% reduction in metro capacity in Stockholm led to a 22% increase in travel times and economic losses of $177,000 per hour.

Neglecting resilience in ex-ante assessments can worsen social inequalities, particularly in regions with historically delayed or incomplete transportation projects. Studies on São Paulo's metro expansion indicate that partial implementations often increase inequalities, disproportionately affecting vulnerable populations (Freiberg, 2022).

Ex-ante resilience assessments contribute to sustainable infrastructure development by balancing vulnerability, recovery, mitigation, and preparedness. Traditional transport planning often prioritizes efficiency and cost minimization, but future resilience research must focus on trade-offs between regular operations and disruption response strategies (Bešinovic´, 2020).

Finally, **there is a methodological gap on incorporating the resilience dimension of accessibility planning paradigm into the *ex-ante* assessment of transit interventions**.

The gaps discussed in this section culminate in the following research questions.

- How to formulate public transport interventions from an *a priori* diagnosis of the mobility network, establishing a problem-oriented approach?
- How to formulate public transport interventions in the light of promoting equitable accessibility distributions?
- How to incorporate the resilience dimension of accessibility planning paradigm into *ex-ante* assessment of transit interventions?

1.3 Objectives

Accordingly, this thesis' objective is **to propose and validate a method for formulating public transport interventions based on equity principles**. In this sense, the main objective can be decomposed into the following specific objectives:

a) To propose and validate a framework to systematically formulate public transport interventions, based on previous diagnosis analysis.
b) To propose and validate a framework to objectively formulate public transport interventions based on equity principles.
c) To propose and validate a framework to evaluate the resilience of proposed interventions based on equity principles.

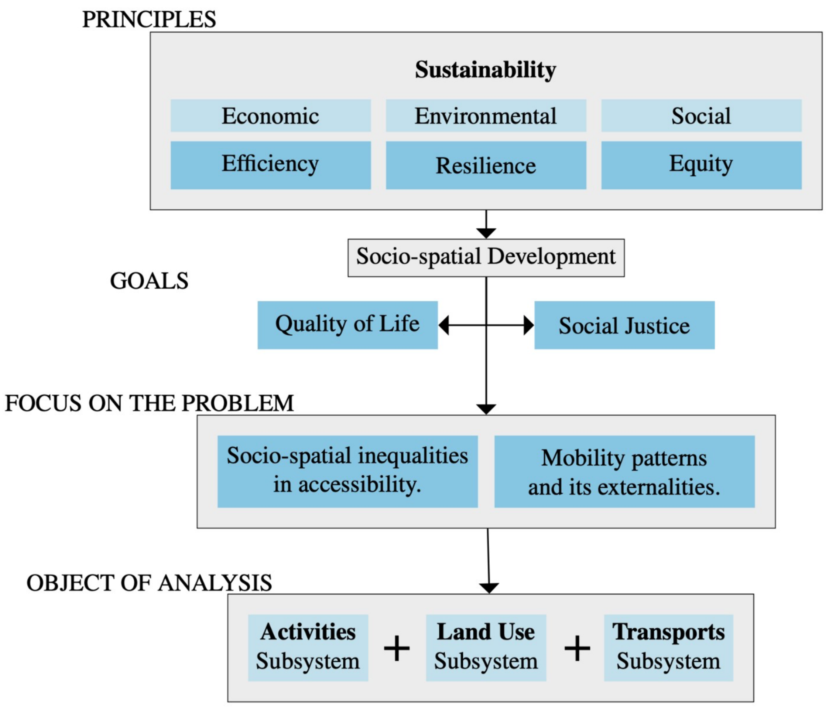
The thesis' products may contribute to improve urban mobility policies, to reduce inequalities in access to key activities, and to pave the way for more sustainable urban mobility systems, and efficient and effective solutions to social problems.

1.4 Relevance

The current paradigm for planning urban sustainable accessibility, as shown on

Figure 1 (Representation of the accessibility planning paradigm), defines and delineates (i) the relations between the elements of analysis, which are the transport system, the land use system and the activity system; (ii) the focus of planning, which is social-spatial inequalities in accessibility and mobility patterns; (iii) the underlying sustainability principles, which are economic efficiency, environmental resilience and social equity; and (iv) the planning goal, which is socio-spatial development through social justice and quality of life (Cavalcante, 2023).

Figure 1 – Representation of the accessibility planning paradigm



Source: Translated from Cavalcante (2023).

This paradigm is noted as the most adequate way to face a multi-system environment (Activity, Land Use and Transport Interactions[1]) that affects restrictions on people's capacity to reach activities (Sousa, 2019).

The public transport system, for its shared nature, plays a central role in the current accessibility planning paradigm. From the guiding principles perspective, public transport projects - like regular bus, subway systems or shared bicycles, for example - are more efficient, as they are more cost-effective and scalable; more resilient, as the environmental impacts are more controllable and generated in a lower user-rate; and more fair, as it generally serves vulnerable groups (peripheral and poorest individuals, for instance).

1 For more information, refer to Lopes *et al.* (2019).

Among the elements of transport system, the public transport component is the one in which transport planners and public administration usually can actuate in order to provide short-term accessibility gains and may be a major tool on promoting spatial development. In this sense, the planning goal, *i.e.* social justice and quality of life, rely on a proper analysis and choice of mobility projects, especially with respect to aspects of public transport.

Nonetheless, in the past decades, some countries, both in the global North and South, have suffered from declining public transport demand, perpetuating a well-known public transport vicious cycle. Revenue reduction diminishes the system's economic efficiency, often putting pressure on fare adjustment. The tariff increment, in turn, is most likely to induce public transport ridership decrease once more. This cycle is aggravated when the increase in the cost of public transport is steeper than the increase in the cost of private transport, a reality in several countries (Carvalho; Pereira, 2011; Gandelman *et al.*, 2019; Lisboa, 2020b; Swianiewicz; Brzóska, 2020; NTU, 2021; Pereira *et al.*, 2021a).

In the case of the city of Fortaleza, a recent causal inference investigation found that public transport interventions have failed to grow public transport participation in the transport modal split. Improvements in both the public and private transport system did not affect their demand, while the use of transit is heavily impacted by the mobility of other modes (Pinto *et al.*, 2021). In addition, Belo (2023) points out that the difference between investments in private and public transport might be responsible for accessibility inequalities.

Given the large number of people who depend on public transport and the high values invested in its infrastructure, the investigation of methods to propose transit investments is fundamental for the implementation of efficient and effective solutions to urban accessibility problems.

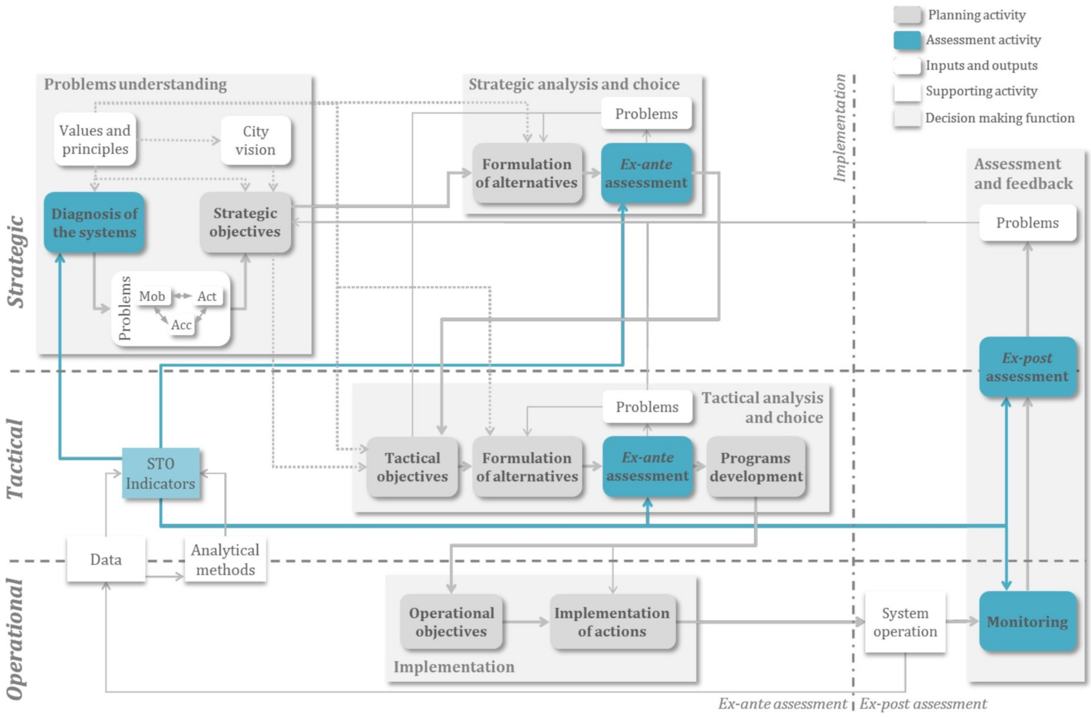
1.5 Methodological Overview and Thesis Outline

Garcia (2016) provides a comprehensive and critical analysis of the paradigm shifts in urban mobility planning and the gaps in traditional methodological procedures for planning and decision making, by reviewing the paradigm shifts in the urban mobility and accessibility field and highlighting the need for a more comprehensive approach to assessment in accessibility planning. It identifies the limitations of traditional methodological procedures and emphasize the importance of assessment tasks in addressing these limitations.

Furthermore, it proposes a problem-oriented methodological procedure for urban mobility planning, which recognizes the urban mobility network as a central element and emphasizes the role of assessment activities. It outlines the different phases of the propose methodology, including the definition of objectives and indicators, the diagnosis of problems, the strategic analysis and choice, the tactical analysis and choice, the monitoring of the system, and the *ex-post* evaluation and feedback process.

The proposed methodology (Figure 2 - Urban Mobility Planning Process) emphasizes the importance of different assessment levels, the formulation and choice of solutions, and the monitoring and evaluation of implemented actions. It also underscores the need for stakeholder consultation and the consideration of values and principles such as efficiency, equity, and resilience throughout the planning process.

Figure 2 – Urban Mobility Planning Process



Source: Garcia (2016).

As mentioned, this urban mobility planning outline involves three levels, which are strategic, tactical, and operational. The strategic level is responsible for defining the vision, diagnosis, problems, principles, values, objectives, and goals of the planning process, as well as analyzing and choosing strategic alternatives. This level is characterized by an integrated analysis of the system (Garcia, 2016).

The tactical level is responsible for developing solutions to the problems posed by strategic level decisions, including guidelines, tactics, and programs. The operational level is in charge of executing the actions established at the strategic and tactical levels and providing information for the process's monitoring and evaluation. Although the methodology is presented as a sequence of steps, it is considered an ongoing process without a mandatory chronological order of steps, and identification of problems may occur at any of the levels (Garcia, 2016).

The analysis and choice step - core element of the research gaps identified in this thesis - is presented at two of these three levels: strategic and tactical. Strategic analysis and choice primarily concentrate on macro-level interventions and overarching objectives related to the urban mobility network. This phase has a strong political emphasis and considers accessibility values framed by guiding principles such as efficiency, equity, and resilience (Garcia, 2016). Garcia (2016) suggests two (2) steps in strategic analysis and choice of alternatives. Initially, the formulation of strategic alternatives develops solutions guided by strategic objectives, and are simplified ways of overcoming problems, representing macro interventions on the urban mobility network that are considered desirable from the perspectives of the guiding principles.

The second step - *ex-ante* assessment - involves a prospective evaluation of proposed alternatives to determine their potential impact and consistency with overarching principles, thus providing a basis for refining or discarding options before final decisions are made. This evaluation serves as a feedback moment that allows the identification of new problems and the interaction with stakeholders (Garcia, 2016).

Tactical analysis and choice focus on detailed solutions that address specific issues within the urban mobility network. This phase is more technically oriented and refers to the proposal of alternatives developed to address the objectives defined at the strategic level. It consists of specifying more detailed objectives, formulating tactical alternatives, and assessing them (Garcia, 2016).

The tactical analysis and choice involves the development of alternative solutions that are feasible, effective, and aligned with the strategic objectives and values of the urban mobility planning process. It also ensures that the solutions are rigorously evaluated to identify the most effective alternatives for addressing the accessibility problems in question (Garcia, 2016).

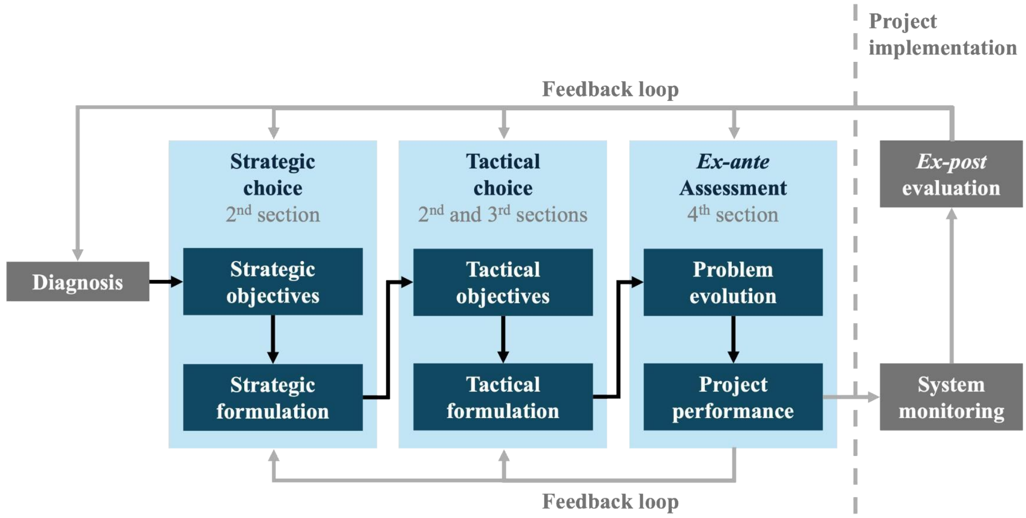
Furthermore, Garcia (2016) suggests four (4) steps in tactical analysis and choice of alternatives. Initially, the definition of tactical objectives specifies detailed goals that are constrained by the characteristics of the alternative solutions indicated at the strategic level. These objectives serve as guidelines for the development of tactical alternatives and help restrict the scope of solutions to what is considered financially and technically viable. Subsequently, the formulation of tactical alternatives develops solutions guided by tactical objectives. It includes the proposition of actions to solve the diagnosed problems, in the context of limited resources, capacity, control, and power pressure.

Afterward, *ex-ante* assessment involves the appraisal of alternatives to identify those that best solve accessibility problems. It consists of quantifying the expected benefits of solutions by applying models, considering the same set of indicators used in the diagnosis, and qualifying them through all stakeholders. This evaluation also serves as a feedback moment that allows the identification of new problems and the interaction with stakeholders.

Lastly, program development consists of a set of articulated actions focused on a defined tactical objective. These programs encompass the proposed actions, the roles of each actor/institution involved, the allocation of financial resources, and the means of dissemination and public debate. This step ensures that the proposed solutions are implemented effectively and efficiently, in alignment with strategic objectives and principles.

Based on the method presented by Garcia (2016), this thesis proposes a methodological approach that focuses on the research gaps stated in *section 1.2 Gaps and Research Questions*, which are the formulation of transit intervention at the strategical and tactical choice stage, the objective representation of transit intervention distributional impacts at the tactical choice stage, and the evaluation of transit projects resilience at the *ex-ante* assessment stage. The 3 stage methodological overview is shown in Figure 3 (Methodological Overview and Thesis Outline).

Figure 3 – Methodological Overview and Thesis Outline



Source: Garcia (2016).

The first stage, strategic choice, focuses on the first research gap, as it intends to answer the first question of this work: *How to formulate strategic solutions for transit projects from an* a priori *diagnosis of the mobility network, establishing a problem-oriented approach?* It starts with the specification of the strategic objectives in the form of the description of which constraints identified in the diagnosis stage will be addressed in the strategic formulation. It must be the product of an integrated analysis of the system, and be bounded by the characteristics of the diagnosed problems and feasible public transport solutions.

Then, strategic formulation specifies the dimensions of the transit system that are related to the restrictions stated in the strategic objectives. They focus on generic, simplified, and integrated solutions, and have a strong participative emphasis that considers accessibility values framed by guiding principles such as efficiency, equity, and resilience.

The strong problem-oriented approach is denoted by the diagnosis dependence of the method. The stage is associated with the first specific objective and is a detailed methodological proposition on how to formulate public transport projects, based on previous diagnosis analysis.

The second stage, tactical choice, focuses on the first and second research gap, as it intends to answer both the first - already stated - and second question: *How to objectively represent the impacts of a transit project under an equity-oriented approach?*. It culminates with the specification of the tactical objectives in the form of a mathematical formulation of the accessibility distribution problems that respects equity principles. It must be aligned with strategic formulation stage, and also be bounded by the characteristics of diagnosed problems and feasible public transport solutions.

Then, tactical formulation specifies the public transport system(s) that minimizes the accessibility distribution problem stated in the tactical objectives. This stage focus on specific and measurable solutions, and have a strong technical emphasis on identifying those solutions that have the greatest effect on reducing distortions in distribution of accessibility.

The strong equity-oriented approach is denoted by the discussion on the representation of transit project impacts from a justice perspective, and on its effects from the diagnosis perspective. The stage is associated with the first and the second specific objective and is a detailed methodological proposition on how to objectively represent the impact of public transport projects based on equity principles.

The third stage, *ex-ante* evaluation, focuses on the third research gap, as it intends to answer the third question: *How to incorporate the resilience dimension of accessibility planning into transit intervention assessment?* It starts with the incorporation of the uncertainty of the problem evolution in the form of different scenarios to be assessed. It must be aligned with tactical formulation stage, and also be bounded by the characteristics of diagnosed problems and chosen transit solutions.

Then, the solutions' performance on social equity - fair and inclusive access to opportunities - and economic efficiency - optimal allocation of resources - is analyzed under multiple scenarios. This stage focus on the perspective of the accessibility planning paradigm of environmental resilience - capacity to withstand to environmental changes (Cavalcante, 2023).

As depicted in Figure 3 (Methodological Overview and Thesis Outline), each chapter will explore one research question, *i.e.* one stage of the formulation of urban public transport projects, represented by the specific research objectives. The methodological proposition is validated at each chapter, and its contribution is evidenced by its application to the case study.

1.6 Case Study

Governments have the responsibility of ensuring that minimum levels of primary goods are provided to all individuals. However, the concept of a socially appropriate minimum goes beyond basic physiological needs. The way society understands the nature and role of accessibility shapes what a fair transport policy is. Therefore, the definition of accessibility problems depends on the establishment of certain expectations, which vary according to a comprehensive collective set of principles (Sen, 2011; Garcia, 2016).

Although a core set of central capabilities, such as public participation, **access to opportunities**, and good health, may hold universal definitions, as proposed by Nussbaum (2013), the standard of a specific set of capabilities, its reference values, and which individuals are in disadvantage situations depend on the vision of each community and its available resources. This is because the conception of what constitutes a decent life and basic needs, as well as the political process to achieve social justice, can differ between societies (Sen, 2011).

Considering the context-dependence inherent to urban planning (Soares, 2022), this work uses a case study to validate the methodological propositions in a global-south developing city, Fortaleza (Brazil).

In scientific research methodology, a case study is a strategy for investigation of a specific, real-world example (the "case") to gain broader insights. Yin (2009) defines case study research as an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between the phenomenon and its context are not clearly evident.

In other words, case studies allow researchers to examine complex interactions of factors as they occur naturally, which is particularly useful in fields like transport planning where context (geography, demographics, policies) critically influences outcomes (Rhee, 2004). The case study thus serves as a proof of concept for the proposed framework, demonstrating its application in a complex environment and providing evidence on its strengths and limitations.

1.6.1 Fortaleza

Fortaleza, founded in 1726, is a 312 km^2 Brazilian city, the fourth most populated state capital (2.3 millions inhabitants) and the closest one to Europe, 5.608 km distant to Lisbon. Fortaleza yielded, in 2021, the 11^{th} higher Gross Domestic Product (GDP) among all 5570 Brazilian cities (US$ 921.75 *per capita)*, is currently the second most visited national touristic destination and holds the higher population density (8.655 hab./km^2), performing a high Human Development Index (HDI) of 0.754 (PNUD, 2013; IBGE, 2022).

Fortaleza is a developing city, known for its disorderly growth. It has the majority of job positions in the central area and most of the lower-income workers living far from its center, in the west outskirts of the city. Fortaleza's travel modal split is 38% for public transport, 35% for private transport, and 27% for other means, with a motorization rate of 0,43 vehicle/inhabitant (Fortaleza, 2019; Sousa, 2019).

Its urban public mobility system is composed by a 4.000 km long road infrastructure and 1.1 million registered vehicles, of which 313 thousands are motorcycles; a 132 km long bus system, structured in 1.941 vehicles, 317 lines, 7 integration terminals, 46 exclusive bus lanes and 4 Bus Rapid Transit lines, serving 1 million users on a regular day; a bicycle sharing system, structured in 950 bicycles, 92 stations and more than 400 km of bike lanes; a 56,8 km long urban railway system, structured in 2 subway lines, 1 light rail vehicle line and 39 stations, serving 42 thousand users on a regular day; a taxicab network structured in approximately 4 thousands cars and 2 thousands motorcycle; and private companies that operate ride-sharing services (Fortaleza, 2019).

Fortaleza's urban mobility system is supported by Information and Communication Technology (ICT). Real-time information system allow users to check bus waiting times and schedule table on mobile applications. Electronic smart card system, *Bilhete Único* (Single Pass) (BU), for fare control, besides generating a high volume of data, allow temporal integration, in which users can ride any number of buses in a 2-hour period, paying only one ticket. A team of real-time traffic monitoring, along more than 200 surveillance cameras, adjusts the traffic signal timings to adapt to current traffic conditions. And the use of global positioning system aids fleet management by the service provider (Fortaleza, 2019).

In contrast, there are several known urban mobility problems in Fortaleza. Overcrowding on public transport and congested streets are reported on a daily basis, contributing to a gradual replacement of public transport by private modes, specially for the low-income individuals. Despite declining, over 14 thousands traffic crashes are registered per year, resulting in approximately 200 deaths and 13,8 thousand injured.

The absence of continuous monitoring of gas emissions hampers environmental researches, yet models estimate critical levels of air contamination. Lastly, although being considered out of the scope of the urban accessibility planning, high rates of violent crime drive users away from public transit, as is the case of the implementation of the NINA[2] project within the public transport ICT mobile application (Fortaleza, 2019; Sousa, 2019; Fortaleza, 2020; Pinto *et al.*, 2021).

2 A harassment reporting channel. For more information, please refer to <https://portal.ninamob.com/>.

1.6.2 Accessibility Problems in Fortaleza

Fortaleza's rapid growth and socio-spatial dynamics have led to pronounced disparities in access to opportunities, disproportionately affecting its most vulnerable residents. As it is further discussed in the following sections, there are several accessibility problems in Fortaleza.

Studies (Sousa, 2019; Pinto *et al.*, 2021, Siqueira *et al., 2022*) shows that job opportunities are mainly located in central areas, making accessibility difficult for low-income residents in distant neighborhoods. Low-density peripheral zones lack nearby employment and services, resulting in longer travel distances for disadvantaged groups. Consequently, the areas with the worst accessibility levels are predominantly those inhabited by low-income populations, reflecting a persistent spatial inequity.

Fortaleza's public transport network, in turn, struggles with overcrowding and congestion. Bus services often operate at full capacity during peak hours, and road congestion in key corridors slows down traffic. This overcrowding and delay not only reduce comfort and reliability, but also drive a gradual shift of travelers toward private modes. Alarmingly, even low-income individuals – who are most dependent on transit – have been increasingly turning to private options such as motorcycles for daily travel.

Additionally, the duration of travels in Fortaleza is a major barrier for many. The city's bus system uses a trunk-and-feeder design with central terminals, which often requires multiple transfers for peripheral commuters to reach central destinations. These transfers, coupled with long distances, result in excessive travel times.

Research (Belo, 2023) indicates that long commute durations disproportionately impact low-income individuals and women, limiting their access to jobs and education. Women (particularly those with household and caregiving responsibilities) are also affected by time restrictions, as they often chain multiple activities in a single journey and thus suffer more from any increase in travel time (Pinto *et al.*, 2021).

1.6.3 Rationale for Choosing Fortaleza

Fortaleza was selected as the case study for this research because its conditions encompass the equity concerns that the proposed method is designed to address. As a large city in the Global South, Fortaleza combines characteristics common to many developing urban areas – rapid population growth, spatial socio-economic disparities, strained transit systems, and limited resources – which makes it an informative and relatable example.

The accessibility issues outlined above provide a compelling real-world testbed for the thesis. In Fortaleza, one can observe in stark relief how mismatches between transport supply and urban demand lead to social exclusion. The presence of well-documented vulnerable groups (*e.g.* the sizable low-income population dependent on public transport) means that an equity-focused intervention framework can be meaningfully applied and evaluated.

1.6.4 Methodological Implications

By developing and testing the intervention framework in Fortaleza, the research aims to produce insights and methods that are transferable to other contexts facing analogous challenges. According to Yin's (2009) logic of case study, if the proposed equity-driven methodology can yield improvements in Fortaleza, those findings can analytically generalize to inform theory and practice elsewhere.

The expectation is not that the exact interventions would be applied to another city, but rather that the principles and process (consolidating accessibility diagnosis, engaging equity criteria in project design, etc.) will be applicable and beneficial in cities with comparable issues. Thus, Fortaleza serves as a proving ground to demonstrate that an equity-based approach to public transport planning can work in practice and to highlight the conditions for its application.

2 STRATEGIC AND TACTICAL CHOICE OF PUBLIC TRANSPORT INTERVENTIONS

Abstract

Public transport interventions are often formulated without a clear connection to diagnosed accessibility constraints, leading to inefficient investments and inequitable outcomes. This section proposes a structured framework for formulating public transport interventions based on an evidence-driven diagnosis. It emphasizes a problem-oriented approach, linking transit solutions to accessibility restrictions. The methodology is applied to Fortaleza, identifying constraints, setting objectives, and developing transit interventions that directly address these issues. The framework is further used to analyze PASFOR, revealing gaps in identifying time restrictions in the public transport system, and setting land use interventions. The results show that accessibility planning can benefit from a structured problem-oriented approach for transit modeling, as it helps to avoid the misidentification of restrictions, objectives, and interventions, ensuring more effective and equitable transport solutions.

2.1 Introduction

Incorrect decisions regarding transport expenditure can lead to inefficient outcomes due to wrong selection of policies. A problem-oriented approach based on a comprehensive analysis and choice of urban public transport projects may be the answer to this issue. However, the most common evaluation techniques are not connected to a strategic urban mobility planning, as they are not used in integrated analysis, assessment, and feedback processes (Garcia, 2016). Once urban accessibility distribution inequities are problematic only when vulnerable individuals are economically and socially excluded by insufficient accessibility levels (Wee; Geurs, 2011), a diagnosis investigation must be performed before assessing solutions (Sousa, 2019).

Current research in urban mobility planning argues that problem understanding should be succeeded by the design of conceptual models of the actual mobility network and improved scenarios. The latter should prioritize optimal solutions, performing high efficiency at low cost. Then, the proposed interventions are compared to future state of affairs (Garcia, 2016; Soares, 2022).

Nonetheless, appropriate interventions cannot be selected if the right projects are not formulated and proposed: given the endeavor mobilizing transport projects, once started they are likely to be implemented, even unsuitable ones. This is because as soon as funds are committed, the scope for making changes is limited, and, considering the wide range of possible intervention alternatives (from carbon taxation and land use policies to infrastructure development), intervention formulation, plays a main role on planning urban mobility networks (Donais *et al.*, 2019; ITF, 2022).

However, recent works on *ex-ante* evaluations (Garcia, 2016; Pereira, 2019; Freire, 2019; Freiberg, 2022; Deweese *et al.*, 2022; Amorim; Silva, 2024; Vecchio *et al.*, 2020) don't go through a conceptual phase nor discuss the merit of proposed interventions. Its efforts are driven onto appraising transportation projects that are announced, under development or developed.

Also, transport and urban mobility plans tend to adopt standardized, technocratic solutions that prioritize infrastructure expansion and operational efficiency while failing to address the complexities of socio-spatial inequalities (Cavalcante, 2023).

A change in perspective with respect to the ideas presented so far had no bearing on the strategies used for urban planning, which insist on solution-oriented approaches instead of problem-oriented approaches (Soares, 2022).

From the discussion above, the research question addressed in this chapter is *How to formulate public transport interventions from an a priori diagnosis of the mobility network, establishing a problem-oriented approach?* This is relevant because the urban mobility system might be seen as an important socioeconomic promoter. Also, the predisposition to choose given solution, resulting from methodological flaws, may significantly influence the selection of transit investment (ITF, 2022; Soares, 2022). Therefore, **there is a methodological gap regarding the formulation of public transport interventions supported by a diagnostic analysis**.

To provide an answer to this research question, the objective of this chapter is **to propose and validate a framework to systematically formulate public transport interventions, based on previous diagnosis analysis**. This work advances on previous research by breaking down the transition from the diagnostic stage to the intervention formulation stage, and systematically describing the steps to propose well-informed, problem oriented, and efficient public transit investments.

2.2 A Framework for Public Transport Planning

Cities and transportation have evolved together over time. Early cities were small and walking-centric, limited by walking travel time and resource availability. New modes of transportation, such as rail and the widespread adoption of automobiles, gradually expanded city sizes beyond walking distance. Consequently, modern challenges of congestion, pollution and car-crashes require the prioritization of sustainable transportation systems, such as transit, as they contribute to the economic growth and livability of cities, as seen in Munich, Paris, Stockholm, and Toronto (Ferraz; Torres, 2004; Vuchic, 2007)[3].

Public transport - or transit - is a public transportation service, available on fixed routes and predetermined schedules, open to any user willing to pay a fare. Known examples of transit are street transit, such as bus, trolley bus, and streetcar; semi-rapid transit, such as bus rapid transit and light rail transit; and rapid transit, such as rubber-tired rapid transit, monorails, and metro (Vuchic, 2007).

Public transport systems are usually in high to medium density zone, with concentrated origin and destination points, operate during peak and daily hours, and cater to work, school, business, social, and other needs. Compared to private transportation, they are a more reliable and often affordable alternative. In that sense, understanding the characteristics of transit solutions is crucial for designing efficient and effective public transportation systems that meet the needs of urban populations (Vuchic, 2007).

2.2.1 Mobility Networks

Mobility networks constitute urban models that integrate transportation infrastructure, land-use planning, and the spatial distribution of urban activities. These networks support accessibility, connectivity, and equitable mobility in urban environments (Macário, 2005; Garcia, 2016). Public transport although a critical element of these networks, alone cannot comprehensively address urban mobility requirements or ensure equitable access, as it primarily benefits populations with fewer mobility alternatives (Macário, 2005; Garcia, 2016).

A Mobility Network is a dynamic spatial structure comprising interconnected

39 The relevance of public transport in the paradigm of accessibility planning is discussed in *section 1.4 Relevance*.

nodes and links, where nodes represent distinct geographic locations such as residential areas, workplaces, service centers, or transport hubs, and links indicate the flows of people or goods between these locations (Macário, 2005). Cao *et al.* (2021) emphasize the heterogeneity in individual travel patterns and the importance of recognizing multiple layers within mobility networks, each influenced by specific spatial, temporal, and behavioral characteristics. Thus, public transport systems must operate as parts of these multilayered networks, connecting with private vehicles, pedestrian infrastructure, cycling routes, and intermodal facilities to address diverse mobility demands.

Macário (2005) argues for a comprehensive approach to urban mobility management, highlighting that isolated interventions are often ineffective unless embedded within a coordinated strategy. It is argued that the effectiveness of mobility networks relies significantly on managing interactions among transport modes, land-use patterns, and environmental conditions. These interactions are fundamental in shaping travel behaviors and influencing overall network efficiency and sustainability (Liu *et al.*, 2022).

Furthermore, Hamedmoghadam *et al.* (2019) reveals underlying mobility patterns by categorizing complex movements into simplified flow types. Such an analytical framework allows for the identification of critical areas within cities, helping to understand and manage urban mobility more effectively. These hotspots typically include central business districts, significant residential areas, or major transport interchanges, necessitating targeted and integrated transport solutions to address their unique mobility dynamics.

Implementing successful mobility networks requires robust institutional frameworks, strategic planning, detailed diagnostic analyses, and continuous evaluation mechanisms (Macário, 2005). Macário's methodology underscores sustainability and equity as central criteria at all decision-making levels, promoting collaborative stakeholder engagement and quality management principles to enhance overall system performance.

In that sense, urban mobility networks must integrate various transportation modes supported by informed policies, structured strategic planning, and ongoing performance assessments. Adopting an integrated and comprehensive methodology (Cao *et al.*, 2021; Liu *et al.*, 2022; Hamedmoghadam *et al.*, 2019) on mobility networks is essential for creating responsive, equitable, and sustainable mobility networks capable of adapting to dynamic urban conditions and meeting evolving mobility demands.

2.2.2 Accessibility Restrictions

Transport planning that focus on physical mobility alone can overlook personal and contextual factors - such as age, disability, or socioeconomic constraints - that influence how well transport actually enables one's participation in work, education, healthcare, and social life (Lucas, 2012; Lowe *et al.*, 2023). From the Capability Approach perspective - one of the main justice theories on equity -, what fundamentally matters for transport planning is whether people can genuinely reach the opportunities and perform activities they value (Sen, 2011; Vecchio; Martens, 2021).

By centering on accessibility, policies are closer to address whether individuals can convert those transport options into real "freedoms". Ensuring sufficient accessibility for everyone becomes a direct way to expand people's capabilities, creating more equitable conditions for pursuing a fulfilling life (Amorim; Silva, 2024; Silva *et al.*, 2017; Martens; Ciommo, 2017).

Soares (2022) provide a comprehensive overview of key components involved in modeling and measuring accessibility by different authors. The work by Dalvi e Martin (1976) identify 3 accessibility components: (i) people's preferences, focusing on understanding the preferences and behavior of individuals when making travel choices, *e.g.*, trip purposes; (ii) existing opportunities, referring to the availability of activities at different locations within the urban area, *e.g.*, distribution of amenities that influence travel patterns; and (iii) intensity of transport service, regarding the quality and quantity of transportation services available to individuals travel between origins and destinations, *e.g.*, travel time, frequency, reliability, and comfort.

Handy e Niemeier (1997), in turn, identify 4 accessibility components: (i) magnitude and type of spatial separation, focusing int the physical distance between origins and destinations, influencing travel patterns and accessibility; (ii) representation of origins and destinations, referring to how origins and destinations are represented in the accessibility analysis; (iii) magnitude of travel impedances, *i.e.*, factors that may discourage trips, *e.g*, congestion or travel costs; and (iv) magnitude of attractiveness, regarding the desirability of destinations, influencing travel behavior and accessibility patterns.

Lastly, Geurs e Wee (2004) identify 4 accessibility components: (i) land-use component, focusing on the spatial distribution of opportunities (*e.g.*, jobs and services); (ii) transportation component, referring to the disutility individuals face in traveling between origins and destinations using specific transport modes; (iii) temporal component - that can be seen as part of the individual component -, reflecting the temporal constraints individuals face, such as the availability of opportunities at different times of the day and the time available for engaging in activities; and (iv) individual component, regarding the diverse needs, abilities, and desires individuals dispose, including factors such as age, income, education, physical condition, travel preferences, and budget constraints.

All three approaches emphasize the importance of understanding travel behavior, preferences, and choices in assessing accessibility. They recognize that individual preferences, trip purposes, and decision-making processes play a significant role in shaping travel patterns and accessibility outcomes. They also acknowledge the dependence between land use and transportation systems, and highlight the need to assess how the spatial distribution of activities and the quality of transportation services impact individuals' ability to reach destinations efficiently.

Low accessibility levels arise when any of the underlying components — land use, transport system, or individual factors - become restrictive (Garcia,2016; Vecchio; Martens, 2021). Inadequacies in land use distribution, such as urban sprawl, often create accessibility gaps for peripheral neighborhoods, especially when residents depend on limited transit services (Martens; Ciommo, 2017; Pereira *et al.*, 2016). Transport system inefficiencies — like low service frequency or unreliable schedules—can further constrain access to jobs, schools, and healthcare for those lacking private cars (Karner *et al.*, 2024).

Meanwhile, individual characteristics (*e.g.* gender, disability, or limited income) shape how people experience and convert transport opportunities into real mobility (Lucas, 2012; Lowe *et al.*, 2023). Time constraints - such as childcare responsibilities - disproportionately impact women who must carry multiple tasks and thereby face greater barriers to reaching essential destinations (Pot *et al.*, 2024).

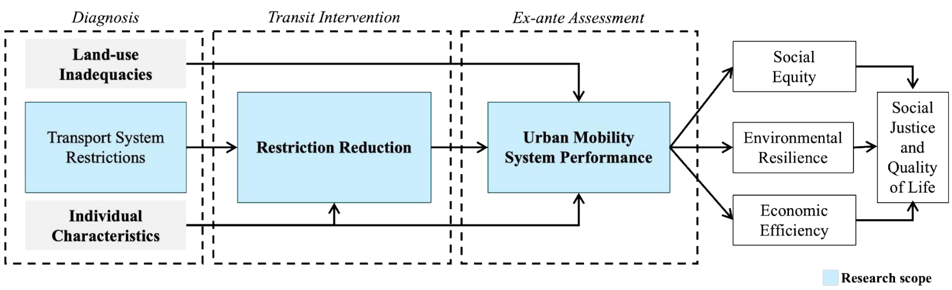
Accessibility restrictions can cause a cascade of interconnected problems (Church *et al.*, 2000; Lucas, 2012; Lowe *et al.*, 2023). Individuals with limited access to opportunities tend to engage in fewer activities, which restricts their contribution to society and personal satisfaction (karner *et al.*, 2024; Vecchio; Martens, 2021). In turn, lack of access hinders economic productivity, potentially creating under-performing communities (Lucas, 2012). Regarding environmental impacts, restrictions on accessibility by public transport, for instance, can increase dependence on private vehicles, resulting in economic inefficiencies, and higher pollutant emissions (Willberg *et al.*, 2023).

If, to reduce accessibility problems, at least one of the accessibility restrictions must be addressed (Lucas, 2012; Vecchio; Martens, 2021), designing an effective transport intervention requires identifying which specific constraint - be it financial, spatial, or otherwise - most critically limits people's access (Pereira *et al.*, 2016; Pot *et al.*, 2024). A diagnosis is thus essential for determining where mitigation efforts should focus, ensuring that interventions match the contextual needs and genuinely improve accessibility (Garcia, 2016; Karner *et al.*, 2024; Lowe *et al.*, 2023; Sousa, 2019).

Additionally, the accessibility planning paradigm (Figure 1 - Representation of the accessibility planning paradigm) is founded on the sustainability principles of economic efficiency, social equity, and environmental resilience. According to Cavalcante (2023), economic efficiency ensures that transport investments maximize benefits while minimizing costs; social equity prioritizes interventions that benefit vulnerable populations; and environmental resilience emphasizes the need for transport solutions that endure to external changes.

In that sense, transport interventions should be assessed based on how well they align with these principles, promoting social-spatial development, while address inequalities in accessibility and mobility problems (Garcia, 2016). The discussion above is summarized in Figure 4 (Accessibility restrictions and transport planning).

Figure 4 – Accessibility restrictions and transport planning

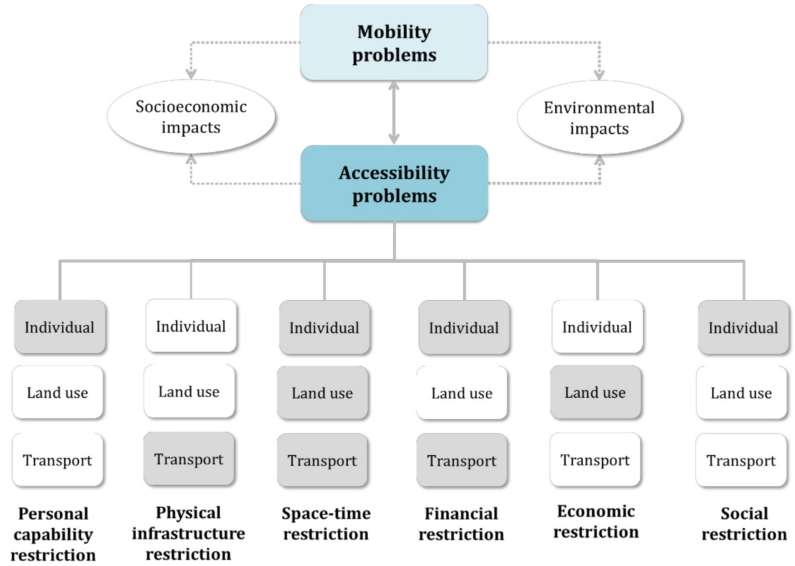


Source: Adapted from Garcia (2016).

2.2.3 Transport System Restrictions

Garcia (2016) proposes an association of the accessibility components with the study on accessibility and social exclusion by Church *et al.* (2000), where seven restrictions that limit accessibility for socially excluded individuals are described: personal capability, physical infrastructure, space, time, financial, economic, and social (Figure 5 - Causal relationships by accessibility restrictions categories).

Figure 5 – Causal relationships by accessibility restrictions categories.



Source: Garcia (2016).

Personal capability is related to the individual component and refers to physical and motor limitations that can hinder individuals' access to the transport system and their environment. Children, elders, and disabled people are among those, making their accessibility level inherently compromised. Physical infrastructure restrictions are related to the barriers imposed by the transport system itself. Deficiencies in infrastructure, such as inadequate sidewalks or dangerous intersections, restrict access, disproportionately impacting those with limited personal capacity.

Spatial and time addresses the limitations imposed by the spatial and temporal distribution of activities and services. For example, people may lack access to essential services due to distance or limited operating hours. It encompasses factors related to individual, land use, and transport components.

On the individual level, it considers limitations imposed by time availability for trips, such as the limited time constraints faced by caregivers, like lone mothers. At the land use level, it concerns the location of activities of interest, such as schools far from students or hospitals far from the elderly, which can impact accessibility. From the transport perspective, characteristics like public transport coverage or parking availability can influence both spatial and temporal accessibility.

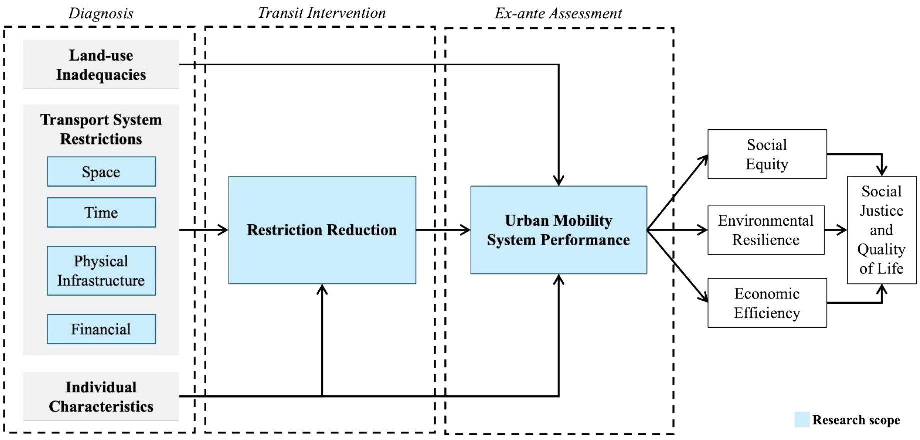
Financial restrictions limit individuals' ability to access transportation services or afford necessary travel costs, and relate to both individual and transport components. Personal income plays a crucial role in determining an individual's ability to afford travel costs. Additionally, high transport costs, whether through public transport fares or parking fees, can unduly limit low-income individuals' accessibility, forcing them to make fewer trips or choose cheaper modes. Economic limitations relate to the land use component and its ability to attract and generate opportunities. It considers the spatial distribution and characteristics of opportunities at destinations (*e.g.*, offices, shops, schools, hospitals) and the associated demand from origin locations (*e.g.*, residences). This includes competition for activities due to limited capacity. Imbalanced economic development can lead to situations where certain areas lack essential services or employment opportunities.

Social restrictions are related to individual components, referring to how sociodemographic characteristics like age, gender, and occupation influence accessibility. Identifying disadvantage groups based on these characteristics allows one to assess their specific accessibility challenges. For example, due to factors like location or financial constraints, disadvantaged groups (elders, low-income individuals, children) may experience substantially lower accessibility compared to their counterparts. Social restrictions might also be associated with other accessibility components and further influence the distribution of accessibility among social groups. For instance, lower-income groups may face job accessibility restrictions compared to high-income groups due to financial or locational reasons.

Converging with Garcia (2016), Lucas *et al.* (2016) define transport poverty as the inability to meet the daily needs of essential activities due to transportation-related factors. They also points that an individual is considered to be in "transportation poverty" if one of the following conditions applies: (1) there is no transportation option suitable for their physical conditions and capabilities, *i.e.* a physical infrastructure restriction; (2) the existing transportation options do not reach the necessary destinations to their essential activities, *i.e.* a space restriction; (3) expenditure on transportation reduces the family's residual income below the poverty line, *i.e.* a financial restriction; or (4) excessive time spent traveling, *i.e.* a time restriction. Lucas *et al.* (2016) also highlights that crime related fear can also impose transport poverty. However, this type of restriction lay outside the scope of transportation engineering as discussed in this thesis.

Out of this discussion, it is possible to point out four restrictions that are associated with the transport component of accessibility: physical infrastructure restrictions, space restrictions, time restrictions, and financial restrictions; as shown on Figure 6 (Transport system restrictions and transport planning).

Figure 6 – Transport system restrictions and transport planning



Source: Adapted from Garcia (2016).

2.2.4 Transport System Planning

In the process of urban mobility planning, interventions are formulated in two key stages: strategic choice, and tactical choice, each with distinct focus (GARCIA, 2016). The strategic choice phase is an integrated macro-level planning, where broad policy objectives and long-term solutions are defined, based on the restrictions that causes accessibility problems. At this stage, different alternative solutions are conceptualized, considering their alignment with city-wide goals and principles. The strategic level prioritizes the integration of land use and transportation systems, while considering regulatory frameworks and political pressure ITF (2021).

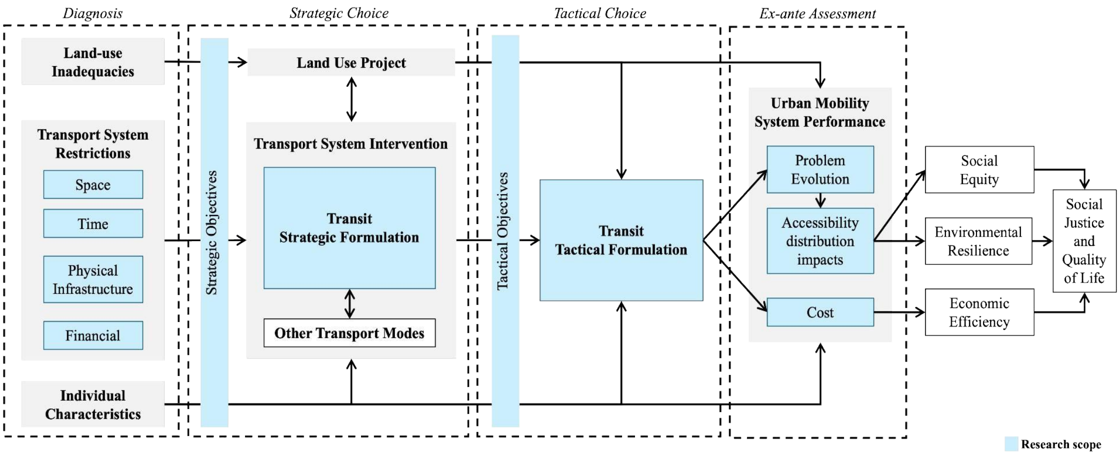
Expanding public transport, however, requires careful consideration, as it may contribute to urban sprawl; the presence of transportation infrastructure such as railways and bus terminals impacts the density and patterns of urban development around stops and terminals (Ferraz; Torres, 2004; Lima *et al.*, 2019; ITF, 2021). Therefore, improving commuting speed or transit infrastructure changes should be considered only after exploring options to minimize distances, recognizing commuting as a spatial interaction demand (Sousa, 2019).

The tactical choice phase refines the strategic alternatives into actionable interventions. In the tactical objectives stage, specific transport goals that align with strategic formulation are translated into objective guidelines. This involves specifying technical and operational aspects of transport solutions, such as an objective function for the problem, and its decision variables and restrictions. Next, tactical formulation focus on optimizing the system performance under resource constraints while ensuring that interventions align with the broader objectives established at the strategic level (Garcia, 2016).

The *ex-ante* assessment phase evaluates the potential outcomes of the proposed interventions before their implementation. This assessment must considers future land-use changes, socioeconomic dynamics, and transportation network modifications to estimate the evolution of accessibility problems (Sousa, 2019).

Ex-ante assessments employ scenario modeling to incorporate uncertainty, compare alternatives, and identify the most resilient solutions. These concepts emphasize the responsibility of ensuring that future generations do not experience lower accessibility levels than a minimum, or previous generations (Sousa, 2019). Addressing these concerns requires planning for future growth and changing demographics, ensuring accessible and sustainable cities (Garcia, 2016). The discussion above is summarized in Figure 7 - Transport system planning frame-work.

Figure 7 – Transport system planning framework.



Source: Adapted from Garcia (2016).

2.2.5 Public Transport Specifications

Public Transport modes are classified by three main characteristics: Right-of-Way (ROW), technology, and type of service. The boundaries between categories can be blurred, and hybrid systems combining elements from different categories exist, while some specialized modes - *e.g.*, ferryboats, aerial tramways, and some automated guided transit systems - are exceptions and do not fit exactly into any of these categories (Vuchic, 2007). These characteristics are described as follows.

There are 3 ROW categories: A, B and C. The C category, generically known as street transit, consists of public transport routes on shared surface-streets together with mixed traffic. Vehicles maneuver around cars and other vehicles, leading to lower speeds and reliability, as well as safety concerns. Although they are highly adaptable to changing needs, present flexible routing, and have lower infrastructure costs, they have low capacity. Examples are regular buses, trolleybuses, and streetcars (trams) (Vuchic, 2007).

The B ROW category, generically known as semi-rapid transit, consists of public transport routes on shared streets with partially separated traffic, often using dedicated lanes, busways, or light rail tracks with some at-grade intersections. Although they have higher capacity, reliability, speed, and safety, they are less flexible, still susceptible to delays at intersections, present potential conflicts with other modes, and have higher infrastructure costs than street transit. Examples are Bus Rapid Transit (BRT), and Light Rail Transit (LRT) (Vuchic, 2007).

The A ROW category, generically known as rapid transit, consists of public transport routes on exclusive, fully controlled traffic, without grade crossings. Although they perform the highest capacity, speed, reliability, and safety, they also have very high costs, infrastructure needs, inflexible routing due to fixed tracks, and may not be viable in all urban areas. Examples are metro, high-speed rail and rubber-tired monorail (Vuchic, 2007).

Technology categories refer to vehicle and track features like support (rubber tire vs. rail), guidance (steering vs. flanged wheels), propulsion (engine type), and control (manual vs. automatic). Guided and rail technologies, in opposition to steering, offer larger vehicles, higher capacity and lower operating cost, but less flexibility and higher investment. Automation, in opposition to manual technologies, increases service frequency and efficiency, but also requires high investment and introduces technical complexity (Vuchic, 2007).

Steering modes offer flexibility but face congestion challenges, while guided modes deliver predictable movements but require dedicated infrastructure. Internal combustion engines offer widespread availability but raise concerns about emissions and noise pollution, while electric propulsion fosters sustainability but necessitates infrastructure adaptations. Manual control systems depends on driver expertise, while automatic control enhances efficiency and precision but requires advanced technological investments (Vuchic, 2007).

Additionally, the type of service may be classified by route type (short-haul, city, and regional), stopping schedule (local, and express) and operation time (regular, peak-hour, and special). Well-planned routes contribute positively to higher frequency and capacity in urban transportation (Vuchic, 2007).

The combination of these characteristics influences operational, financial, political, and social factors that determines the fare rules. Fare decisions involve negotiations between operators, municipal governments, and users, balancing affordability with the financial sustainability of the system. Government subsidies reduce dependence on fare revenue, and analyzing price elasticity helps predict the impact of fare changes on passenger volumes (Ceder, 2007; Vuchic, 2005).

Modeling different fare strategies balances revenue and economic viability. Fixed fares, graduated fares, or dynamic fares that vary by peak hours aim to optimize system occupancy and reduce overcrowding. Lower fares for socially vulnerable groups and tariff integration models - such as single tickets or transfer discounts - can also be considered (Ceder, 2007).

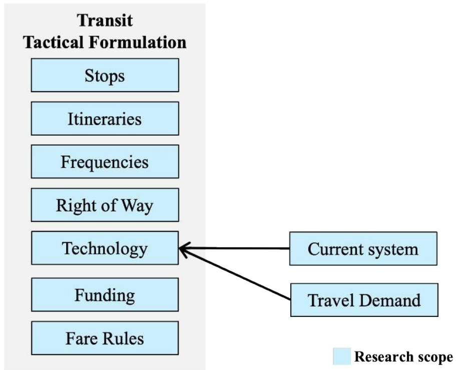
Travel demand - shaped by how many people need to travel and the distances involved - directly determines the required capacity and thus the choice of technology. Implementation and operating costs and schedule, in turn, depend on financial capacity and urgency. Existing public transport infrastructure may also predispose decision-makers toward certain solutions.

Finally, The overall vision of the city can bypass more traditional selection factors, such as time-travel reduction, and prioritizes environmental concerns, for example. In that sense, high-density communities may affects the choice of its transit modes in favor of Transit-Oriented Development (TOD)[4] (Vuchic, 2007; ITDP, 2017).

4 Transit-Oriented Development builds walkable, mixed-use communities around high-quality public transportation. Key features include denser housing, diverse land uses, pedestrian-friendly design, and easy access to stations. This approach reduces the dependence on cars, boosts local economies, and creates vibrant and healthier cities (ITDP, 2017).

The discussion above is summarized in Figure 8 - Public transport specifications.

Figure 8 – Public transport specifications



Source: Prepared by the author from Vuchic (2005).

2.2.6 Transport System Restrictions and Public Transport Specifications

The characteristics and determinant factors described shape various public transport solutions, mainly classified by their dependence on infrastructure: street-based modes and track-based modes. Street-based modes are - from lower to higher performance - Paratransit, Regular Bus (RB), Trolleybus (TB), Streetcar (SCR), and Bus Rapid Transit (BRT). Track-based modes are - from lower to higher performance - Light Rail Transit (LRT), Rubber-tired Rail Transit (RTRT), Rail Rapid Transit (RRT), and Regional Rail (RGR) (Vuchic, 2007).

Paratransit is characterized by small, flexible vehicles operating with steered guidance on standard street (ROW - C) infrastructure, propelled by internal combustion engines, typically with manual control. RB uses standard buses operating with steered guidance on street (ROW C) - infrastructure, propelled primarily by internal combustion engines, although hybrid and electric options are used, mostly with manual control. TBs are electric buses operating with steered guidance on standard street (ROW - C) infrastructure, powered by overhead wires, and manually controlled. SCRs are tram-like vehicles bound to dedicated tracks embedded within street (C) infrastructure, with rail-guided movements that offers predictability, typically electric propelled with manual control. BRT is characterized by high-capacity buses operating on street (ROW - B) infrastructure with dedicated lanes and traffic signal priority. It uses steered guidance, while propulsion includes combustion or electric, often with manual control (Vuchic, 2007).

Light Rail Transit are tram-like vehicles that go on dedicated lanes (ROW - B), with electric propulsion, guided movements, and applications for both manual and automatic control systems. RTRTs are similar to LRT in function and infrastructure dependence (ROW -

B), using tram-like vehicles with rubber tires on dedicated tracks. Electric propulsion and automatic control are standard features. RRT uses high-speed trains that operate exclusively on dedicated tracks (ROW - A), often entirely underground. Electric propulsion and automatic control ensure efficiency and precision. Lastly, RGR is a train system that connects cities or suburbs via dedicated tracks (ROW - A). Propulsion options encompass both electric and combustion configurations, while control systems vary between manual and automatic, depending on the characteristics of the network (Vuchic, 2007).

Separating Right-of-Way positively affects transit speed, reliability, cost, and safety. Higher levels of ROW separation together with advanced technology can offer performance comparable to that of private cars. Additional rail technology allows for automatic control, improving safety. However, street-based modes are readily deployable within existing street networks, while track-based modes require more upfront investment in dedicated infrastructure. In general, Right-of-Way, support, control mechanisms, and guidance systems contribute positively to achieving higher speeds, reliability, and safety. However, they can also limit the overall flexibility of the urban transportation system (Vuchic, 2007).

There are still other traffic solutions that are related to transit performance. Designating entire areas for public transportation vehicles only, or prioritizing transit at traffic lights - by proximity, by allocating green light times based on the number of passengers and not vehicles, or by coordinating consecutive traffic lights based on transit speed - can increase transit capacity, especially in the case of trunk lines operated with larger vehicles (Ferraz; Torres, 2004).

In corridors where a large number of routes operates, stop locations can be equipped with multiple parking bays for simultaneous boarding, leveled platforms, and off-board ticketing, reducing dwell time, *i.e.* enhancing capacity. This is a common feature in the case of tram-like modes. In the case of buses, it has been adopted in the corridors of trunk lines operated with larger articulated or bi-articulated vehicles, and BRTs (Ferraz; Torres, 2004).

Another strategy to increase the capacity of transit is bunching operation, usual in rail modes. In street-based modes, this practice has been used in corridors with bays arranged linearly at the stops, thus preventing independent entries and exits. In the case of a single line operating in the corridor, it is easier to implement it. The number of vehicles bunched normally varies from two to four, although the municipality of São Paulo (Brazil) has operated up to eight bunching buses (Ferraz; Torres, 2004).

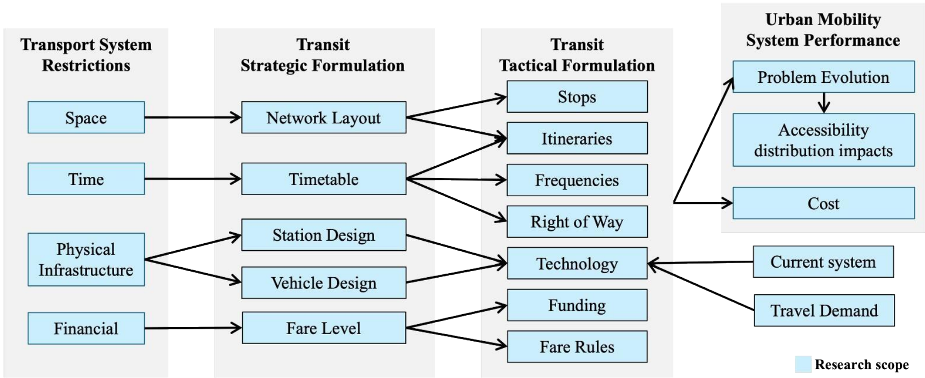
Yet, the design and layout of stops and stations can also have an impact for people with disabilities, the elderly, and children. The presence of steps and stairs without ramps, handrails or lifts, narrow doorways and passageways, and uneven surfaces are barriers for people with reduced mobility. The lack of accessible signage, audible announcements, and real-time information can be difficult for people with visual or hearing impairments or for those who need to plan their trips carefully (Church *et al.*, 2000; Ferraz; Torres, 2004; Vuchic, 2005).

Finally, transit fares are a basic element of the operation of the transit system, affecting both ridership and revenue: low (high) fares attract more (less) riders, but generate less (more) income (up to a point). Setting fares for a given transit system requires careful consideration of objectives (*e.g.*, attraction, revenue, and accessibility), requirements (*e.g.*, elasticity, and equity), and constraints (*e.g.*, collection method and operating cost) (Vuchic, 2005).

Taking into account the problem-based approach and the accessibility planning paradigm, fare is considered a relevant transit attribute in public transport projects. In that sense, public funding can often help maintain low-to-moderate fares and achieve broader urban accessibility goals.

This thesis argues that network layout, timetable, station and vehicle design, and fare level are the fundamental decision variables in the formulation of public transport projects. This is because they summarize all essential transit specifications while respond to each restrictions imposed by the transport system, as illustrated in Figure 9 (Public transport specifications and solutions).

Figure 9 – Public transport specifications and solutions



Source: Prepared by the author from Vuchic (2007), Garcia (2016).

Each of these specifications plays a role in mitigating accessibility constraints. Network layout inadequacies, such as coverage gaps, contribute to space restrictions by limiting connectivity. Inefficient timetables, such as unsynchronised operations, exacerbates time restrictions, reducing access to opportunities. Deficiencies in station or vehicle design impose physical barriers, particularly affecting individuals with reduced mobility. Fare structures and pricing policies act as financial restrictions, impacting low-income populations.

In practical terms, it is not feasible to take into account all interactions between accessibility problems and transit solutions when dealing with real-life transportation problems. Typically, the approach is to focus on the most significant elements for modeling and assessment, while treat the rest as external to the process, considering only their interactions with the system being analyzed (Cascetta, 2009).

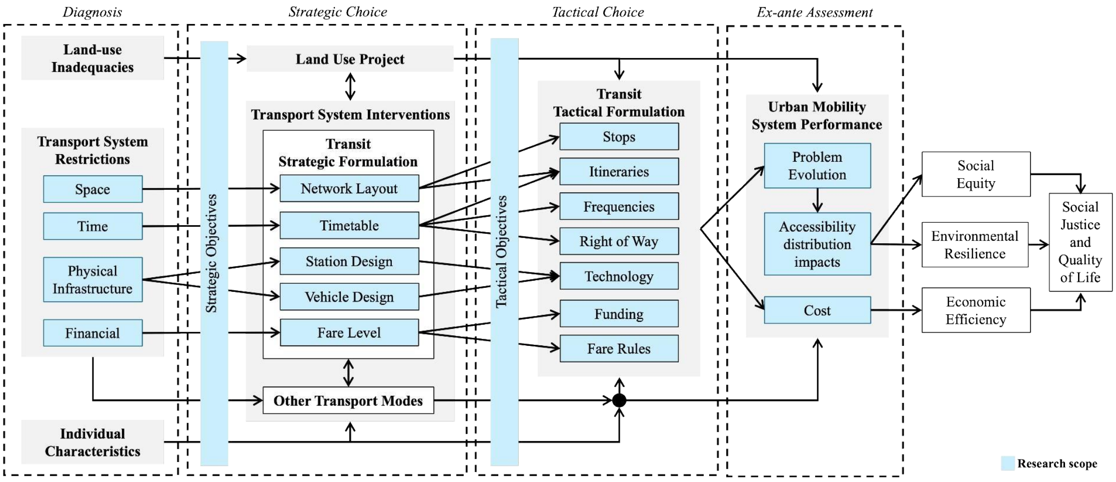
2.2.7 Public Transport Intervention Formulating Framework

The framework for formulating public transport projects emerges from the integration of the accessibility component restrictions (Figure 7 - Transport system planning framework), and transit specifications (Figure 9 - Public transport specifications and solutions). It links restrictions on the transport system component of accessibility to transit components. These restrictions - spatial, temporal, physical infrastructure, and financial - define the challenges that must be addressed to improve accessibility. And the transit elements determine the effectiveness of public transport interventions, ensuring that solutions systematically address accessibility barriers.

By combining these perspectives, Figure 10 (Public Transport Intervention

Formulating Framework) proposes a Public Transport Intervention Formulation Framework that accounts for all stages of transit formulation - from diagnosis consolidation to *ex-ante* evaluation. This framework incorporates accessibility planning principles, ensuring that interventions are not only technically sound but also aligned with equity, efficiency and resilience concepts.

Figure 10 – Public Transport Intervention Formulating Framework



Source: Prepared by the author from Garcia (2016), Vuchic (2005), Vuchic (2007).

This framework helps address the methodological gap in public transport project formulation by integrating diagnostic analysis and transit intervention formulation with a systematic problem-based approach. By directly associating transit solutions to diagnosed restrictions, it aligns transport planning with the principles of the accessibility planning paradigm, ensuring a structured, evidence-based decision-making process.

2.2.8 Methodological Advances

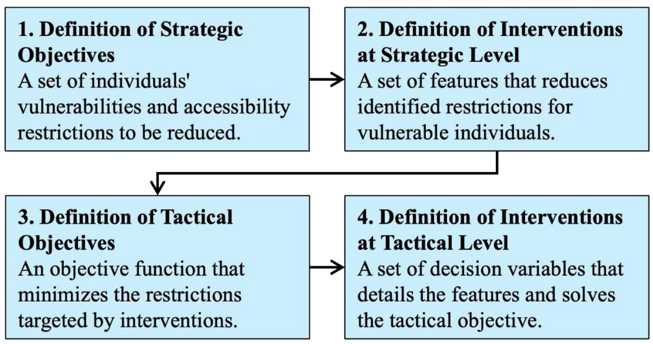
As discussed, the public transport intervention formulating framework proposed in this thesis advances beyond the strategic accessibility assessment methodology in the present literature. Although developed approaches focuses on theoretical principles of sustainability and equity, they do not specify clear criteria or systematic steps for determining public transport interventions.

To address these gaps, this thesis introduces a clear and detailed Public Transport Intervention Formulating Framework, illustrated in Figure 10. This new framework establishes explicit criteria and standardized methods to categorize and prioritize public transport interventions. By doing so, it enables urban planners and decision-makers to conduct objective, transparent, and replicable evaluations prior to implementing interventions. This structured method directly improves the decision-making process by offering practical tools to evaluate and compare projects clearly and consistently. Through specific evaluation parameters, planners can better understand and compare the benefits, impacts, and trade-offs of different intervention options.

2.3 A Method for Formulating Public Transport Interventions

The proposed method for formulating public transport projects is depicted on Figure 11 (Method for formulating public transport interventions), and consists of the 4 (four) stages of transport system planning. Each of these stages is further described.

Figure 11 – Method for formulating public transport interventions



Source: Prepared by the author.

The first step, built on previous diagnosis analysis, involves identifying the main goals in terms of reducing individuals' accessibility restrictions. By analyzing land-use constraints, transport system restrictions, and characteristics of the target population from accessibility diagnosis studies, planners define what vulnerabilities need to be addressed. These strategic objectives can be represented by a set of vulnerabilities and accessibility restrictions to be reduced.

Next, from the strategic objectives, the second step involves identifying the elements that are associated with the accessibility restrictions. Examples include the network layout, stations design, and fare levels. These interventions should respond directly to the previously identified vulnerabilities, providing the elements that will guide subsequent planning decisions. These interventions can be represented by a set of features that reduce the identified restrictions.

The third step involves the formulation of an objective function that translates the strategic objectives into more concrete, measurable targets. This might involve minimizing travel time, or environmental impacts, and it often seeks to address specific accessibility constraints, such as financial or spatial. Defining tactical objectives creates a clear framework for detailing and adjusting interventions to ensure they remain aligned with the broader policy goals. These objectives can be represented by an objective function that minimizes the accessibility restrictions targeted by interventions formulated at the strategic level.

Finally, the specific decision variables that implement the interventions are detailed. These can include determining bus stop locations, adjusting service frequencies, or setting priority lanes. The goal is to articulate how each tactical intervention contributes to meeting the established objectives while remaining feasible. Ensuring coherence across interventions during this stage is critical to guarantee the final system effectively reduces the targeted vulnerabilities and delivers improved accessibility. These interventions can be represented by a set of decision variables that details the features identified in step 2, and solves the tactical objectives.

This methodology is supported by the Figure 10 (Public Transport Intervention Formulating Framework). By focusing on problem-oriented solutions, the interventions are customized to effectively mitigate the challenges faced by users in the public transportation system.

To validate the proposed methodological framework, this research applies the method to a case study conducted in the city of Fortaleza, Brazil. The selection of Fortaleza as the study area provides a relevant urban context characterized by pronounced socio-spatial disparities and diverse accessibility challenges.

The validation process involves applying the structured methodological approach to Fortaleza’s existing public transportation system, analyzing the accessibility constraints identified through empirical diagnoses. Subsequently, the framework's proposed solutions are compared against actual public transportation intervention propositions outlined in Fortaleza’s Plan for Sustainable Accessibility (PASFOR). This comparison aims to assess the alignment between the identified accessibility constraints and the interventions proposed by PASFOR, highlighting differences and similarities in addressing equity and accessibility issues.

The choice of the Plano de Acessibilidade Sustentável de Fortaleza (PASFOR) as a comparative reference was made due to its regional importance, recent development, and detailed approach. Also, PASFOR targets the city of Fortaleza', the same geographical area addressed in this thesis. This alignment makes PASFOR highly relevant as a comparative benchmark, providing data suitable for critical evaluation. Moreover, PASFOR shares similar strategic objectives with this thesis, namely enhancing equity and sustainability in urban mobility, further strengthening its suitability for methodological comparisons.

PASFOR's stated scope includes detailed diagnostics, intervention proposals, and evaluation mechanisms, particularly addressing transport sustainability and accessibility concerns. Its extensive documentation offers a basis for comparative analysis, making it possible to identify the methodological gaps and operational limitations that this thesis aims to address. Using PASFOR as a reference thus contributes to validating the methodological innovations proposed, emphasizing practical applicability and relevance in real-world contexts.

Comparing the outcomes of the proposed framework with the PASFOR plan also allows validation by examining whether the framework accurately identifies critical accessibility issues and proposes appropriate solutions consistent with established public policy. This comparison helps determine the framework's robustness in terms of practical effectiveness, coherence, and its ability to inform decision-making processes within urban mobility planning, thus reinforcing its utility for planners and policymakers.

2.4 Formulating Public Transport Intervention for Fortaleza

Fortaleza is a Brazilian coastal capital city of 2.7 million residents (in a 312 km² area), ranking fifth among the nation's state capitals and located 5,608 km from Lisbon. Its economy is the ninth largest among Brazil's 5,570 cities, generating a GDP of US$6,298.07 per capita (2019). With the country's highest population density (8,655 inhabitants/km²) and a Human Development Index of 0.754, Fortaleza also stands as the second most visited tourist destination nationwide (PNUD, 2013; IBGE, 2022)

Fortaleza's mobility system features a 4,000 km road network with 1.1 million vehicles, including 313,000 motorcycles; a bus network of 317 routes, 1,941 vehicles, seven integration terminals, 46 exclusive bus lanes, and four BRT corridors serving roughly one million daily passengers; a bike-sharing system with 950 bikes, 92 stations, and over 500 km of dedicated lanes; an urban rail network of 56.8 km (two subway lines, one LRT line, 39 stations) serving 42,000 daily users; about 4,000 taxis plus 2,000 motorcycle-taxis; and ridesharing services (Fortaleza, 2019; Sousa, 2019).

Information and communication technologies support real-time data on bus arrivals, an electronic fare card system, and a traffic surveillance system that adapts signal timing for evolving traffic conditions. Nonetheless, Fortaleza faces chronic issues such as overcrowded buses, frequent congestion (leading to a gradual shift of low-income passengers to private modes), and high traffic crash rates of 14,000+ incidents annually (with around 200 fatalities). Additionally, concerns about personal safety reduces access to public transport (Fortaleza, 2020; Sousa, 2019; Pinto *et al.*, 2021).

2.4.1 Diagnosis of Accessibility Problems in Fortaleza

Recent research on Fortaleza's accessibility problems (Sousa, 2019; Pinto *et al.*, 2021; Pinto *et al.*, 2022; Belo, 2023; Siqueira *et al.*, 2022) identifies several groups of vulnerable individuals suffering from restrictions on accessibility components.

The public transport system imposes temporal restrictions that disproportionately affect low-income populations and women, particularly those residing in peripheral areas. It also imposes financial constraints to low-income individuals. In the land-use system, spatial restrictions result from spatial mismatch, long travel distances, and a low mix of land uses, all of which reduces accessibility. Other spatial restrictions are associated to active modes, such as the absence of adequate sidewalks, bicycle lanes and multimodal stations.

Additionally, the investment disparities between road infrastructure (favoring private vehicles) and public transportation infrastructure create accessibility gaps, reinforcing social segregation (Siqueira *et al.*, 2022), contributing to persistent socio-spatial inequalities in accessibility.

Individual characteristic such as age, physical capability, gender and income influence mobility options, with the elderly, the disabled, women and low-income individuals encountering greater transportation barriers. The restrictions are described as follows.

Time restrictions on the public transport system:

Fortaleza's public transport system operates on a trunk-and-feeder design, where peripheral areas are connected to the central region through transit terminals. This network layout necessitates multiple transfers, sometimes increasing total travel time (Belo, 2023; Siqueira *et al.*, 2022)

Also, (Sousa, 2019) found that transportation constraints related to connectivity, coverage, terminal distribution, frequency, and reliability - in particular during off-peak (Belo, 2023) - impact travel times for low-income groups.

Additionally, low-income individuals use public transport more frequently, and gender-based mobility patterns indicate that women, particularly those responsible for household tasks, have more constrained travel schedules (Pinto *et al.*, 2021).

Financial restrictions on the public transport system:

Pinto *et al.* (2021) shows that public transport usage is significantly impacted by the accessibility and affordability of other modes, with financial restrictions being an important barrier. High fare levels for low income individuals that rely on transit (Belo, 2023), and the increased appeal of individual motorized transport, driven by rising minimum wages and vehicle production subsidies, facilitated car and motorbike ownership, particularly among lower-income individuals (Pinto *et al.*, 2021).

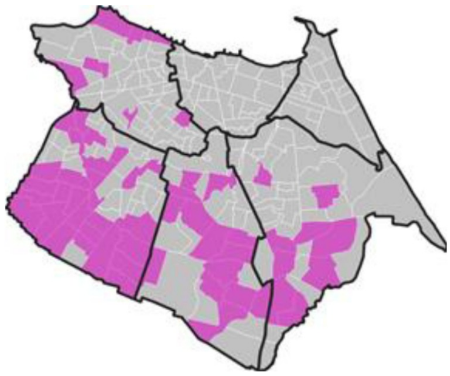
Additionally, the emergence of ride-hailing services, offering greater flexibility and customization, likely contributed to the decline in public transport ridership (Barajas; Brown, 2021; Henao; Marshall, 2017; Rayle *et al.*, 2016; Sabogal-Cardona *et al.*, 2021). In some contexts, particularly in developing countries, app-based motorcycle services have become competitive with buses due to fare prices and travel time.

Restrictions on the land use system:

Rising housing costs in central areas force lower-income populations to relocate to the periphery, where job opportunities are scarce, resulting in spatial mismatch (Lima *et al.*, 2019). Low-density peripheral areas lack economic opportunities, forcing longer commutes for low-income residents (Belo, 2023). Slow adaptation of new employment centers and mixed land use fails to counterbalance economic activity centralization, further disadvantaging low-income workers in peripheral zones (Siqueira *et al.*, 2022).

This asymmetrical distribution of land uses creates disparities in accessibility levels between peripheral and central regions, regardless of socioeconomic group, as shown in Figure 12 - Zones with critical accessibility problems/Fortaleza (Sousa, 2019). This author assess that regions with the worst accessibility levels have predominantly low-income populations. The problem is also characterized by a systematic subjection of the low-income group to lower accessibility levels, regardless of its location (Belo, 2023; Siqueira *et al.*, 2022; Sousa, 2019).

Figure 12 – Zones with critical accessibility problems (Fortaleza).
Critical zones in pink.



Source: Sousa (2019).

Restriction on transport system (other modes):

Research found that Limited integration between modes - specially cycling - are restrictions for accessing transit in Fortaleza (Belo, 2023; Siqueira *et al.*, 2022). The authors also highlight insufficient pedestrian infrastructure as sidewalks, crossings, and micro-accessibility features disproportionately affect the elderly and people with disabilities who rely on public transport.

2.4.2 Objectives at Strategic Level for Fortaleza

The diagnosis indicates that public transport in Fortaleza is constrained by several factors: excessive travel times due to the trunk-and-feeder system, requiring multiple transfers; high fares limiting accessibility for low-income populations, despite existing fare integration mechanisms; spatial mismatches between low-income residential areas and employment hubs; inadequate pedestrian infrastructure affecting the mobility of disabled individuals and the elderly; and space restrictions limiting multi-modal transfers for low-income individuals.

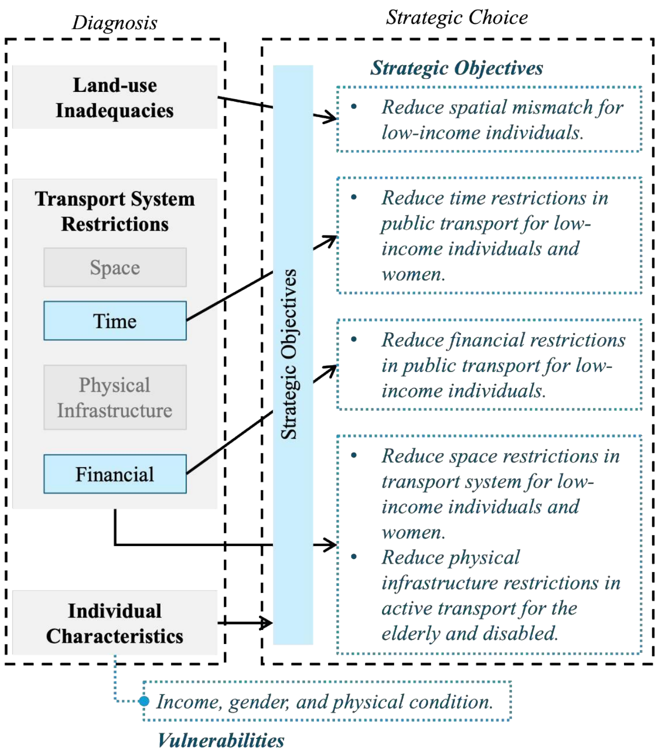
To address these challenges, each identified restriction is directly linked to a strategic objective, ensuring that proposed interventions effectively target the problems.

- **Reduce time restrictions in public transport for low-income individuals and women:** Research indicates that long travel durations disproportionately impact these groups, compromising access to work and education. Belo (2023) identified that low-income individuals residing in peripheral areas face longer travel times due to insufficient public transport services. Similarly, Pinto *et al.* (2021) concluded that women, particularly those responsible for childcare, are more affected by long commutes, which limits their participation in the labor market.

- **Reduce financial restrictions in public transport for low-income individuals:** The high cost of public transportation represents an important barrier to accessing opportunities. Sousa (2019) found that fare affordability is a major constraint for low-income individuals, leading to travel limitation. Additionally, Siqueira *et al.* (2022) emphasized that financial burdens on transport disproportionately impact households in informal employment, reducing their mobility.
- **Reduce spatial mismatch for low-income individuals:** The spatial segregation of housing and employment exacerbates inequalities in access to job opportunities. Pinto *et al.* (2022) demonstrated that job opportunities in Fortaleza are concentrated in central areas, making accessibility difficult for low-income residents in peripheral neighborhoods. Meanwhile, Belo (2023) highlighted that transport policies do not sufficiently mitigate this mismatch, further reinforcing employment accessibility disparities in the long-term perspective.
- **Reduce space restrictions in the transport system for low-income individuals and women:** Pinto *et al.* (2022) observed that transport network does not adequately address the needs of low-income or women, who often make more complex trips involving multiple stops and modes. The key challenge in this context is the difficulty of multimodal transfers, where inadequate infrastructure and service integration increase travel times and discomfort, particularly for those who rely on multiple transport modes (Siqueira *et al.*, 2022).
- **Reduce physical infrastructure restrictions in active transport for the elderly and disabled:** The inadequacy of infrastructure for walking and cycling negatively impacts the mobility of these groups. Sousa (2019) found that inadequate pedestrian infrastructure disproportionately affects elderly individuals, increasing their dependence on motorized transport. Furthermore, Belo (2023) pointed out that accessibility barriers in cycling infrastructure prevent disabled individuals from utilizing active transport modes effectively.

These strategic objectives, derived from a problem-based diagnostic framework, facilitates a structured, evidence-based decision-making process that prioritizes the needs of vulnerable populations. The strategic objectives are depicted in Figure 13 (Strategic objectives for Fortaleza).

Figure 13 – Strategic objectives for Fortaleza



Source: Prepared by the author.

2.4.3 Formulating Transit Interventions at Strategic Level for Fortaleza

The strategic objectives correspond to guidelines that support the development of the strategic alternatives, by restricting the scope of the solutions to what is considered an accessibility restriction, *i.e.* a **problem-oriented** approach. The strategic interventions are described as follows.

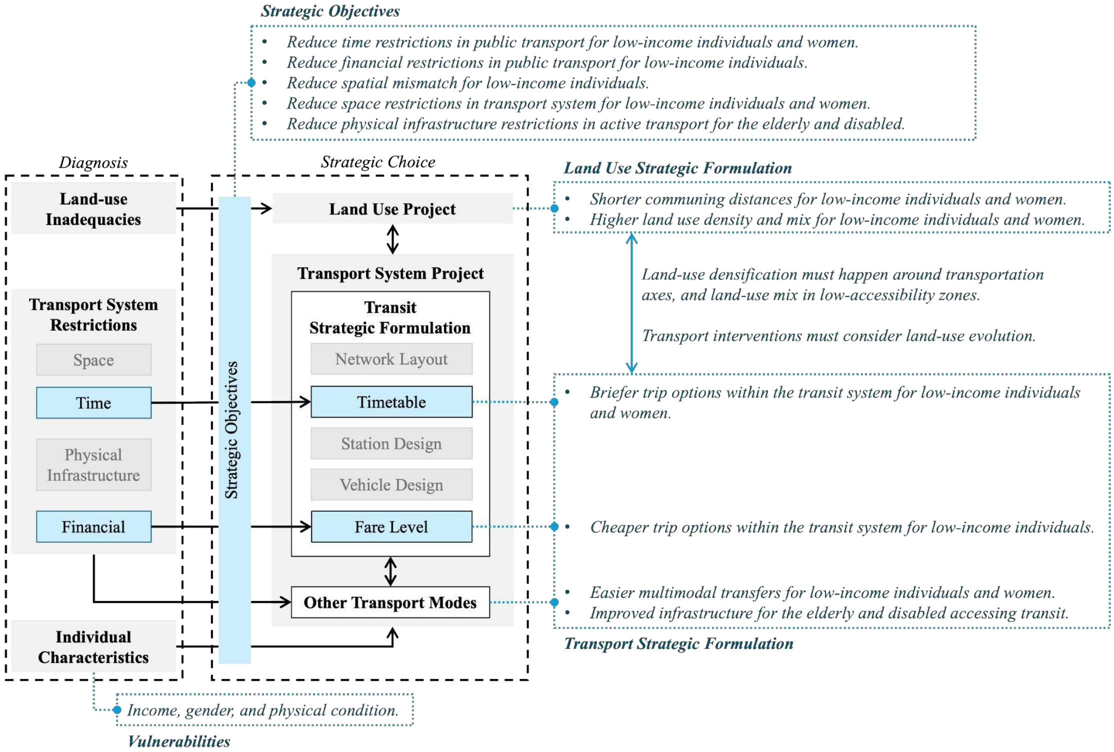
- **Briefer trip options within the transit system for low-income individuals and women:** Tackling the timetable component of public transportation, this strategy seeks to optimize service schedules and routes to minimize waiting times and improve efficiency, reducing temporal restrictions within the system (Ceder, 2007). Improved headway synchronization and demand-responsive transit can significantly enhance service reliability (Vuchic, 2005).
- **Cheaper trip options within the transit system for low-income individuals:** Focused on the fare level component, this intervention proposes policies such as fare reductions, subsidies, and integrated ticketing to make transit more affordable for low-income

individuals, addressing financial barriers (Vuchic, 2005). Studies suggest that progressive fare structures and targeted subsidies improve ridership among low-income populations (Ceder, 2007).

- **Easier multimodal transfers for low-income individuals and women:** Enhancing transport integration by improving infrastructure for easier multimodal transitions, this intervention aims to reduce the complexity and inconvenience of transfers between different modes of public transport (Vuchic, 2005). Research highlights that well-planned transfer hubs and real-time information systems improve user experience and network efficiency (Ceder, 2007).
- **Improved infrastructure for the elderly and disabled accessing transit:** Dedicated to active transport and public transit micro-accessibility, this intervention emphasizes the development of pedestrian-friendly infrastructure, universal design principles, and improvements at transit stops to support the mobility of elderly and disabled individuals (Vuchic, 2007). Investments in barrier-free infrastructure and inclusive transit planning lead to greater accessibility and independence for these groups (Ceder, 2007).
- **Shorter commuting distances for low-income individuals and women:** Addressing the spatial mismatch in land use, this intervention aims to reduce the distance between residential areas and employment opportunities for vulnerable groups, improving accessibility and reducing travel time (Cascetta, 2009). Studies indicate that employment decentralization and transit-oriented development can mitigate spatial barriers (Ceder, 2007).
- **Higher land use density and mix for low-income individuals and women:** Also targeting spatial mismatch, this intervention focuses on promoting mixed land-use developments and increasing density in underserved areas to facilitate better access to jobs, services, and essential activities within shorter travel distances (Cascetta, 2009). Research supports that higher density leads to more efficient transit networks and improved accessibility (Ceder, 2007).

The strategic formulation outlined above aligns with broader urban planning strategies to address the identified challenges effectively. Transportation solutions and land use must work collaboratively to reduce these inequalities (Sousa, 2019). Furthermore, it is essential to plan these measures simultaneously; land-use densification should be prioritized around transportation corridors, and mixed land use should be encouraged in low-accessibility areas. Transport interventions, in turn, must account for land-use changes. The definition of strategic objectives and strategic formulations are detailed in Figure 14 (Strategic interventions for Fortaleza).

Figure 14 – Strategic interventions for Fortaleza.



Source: Prepared by the author.

2.4.4 Objectives and Transit Interventions at Tactical Level for Fortaleza

Tactical choice in urban transportation planning involves defining specific, implementable actions that translate strategic objectives into practical outcomes. The tactical approach ensures that strategic goals are implemented in response to evolving land use patterns and the changing needs of populations.

Low-income individuals and women in Fortaleza face challenges related to trip duration and cost. The first is aggravated by the spatial mismatch between residential locations and employment opportunities. Many of these communities are concentrated in peripheral zones with limited access to high-capacity transit corridors, forcing them to rely on inefficient, time-consuming routes.

Land use changes in Fortaleza have intensified this accessibility gap, as economic activities continue to centralize in key urban areas, requiring longer and more complex commutes for vulnerable populations. Thus, the first tactical objective is outlined: Minimize the duration of trips for low-income individuals and women, considering the land use evolution. The first tactical formulations are derived as follows:

- **Implementation of express services:** Develop express routes connecting low-accessibility zones, particularly in peripheral areas with high concentrations of low-income individuals and women, to employment centers. These services will minimize the need for transfers and reduce travel times by providing direct trips to major destinations. The express service must operate during peak hours with limited stops and optimized scheduling to ensure efficiency.
- **Increase in frequency of high-headway routes:** Optimize the frequency of services on critical routes to ensure that waiting times are minimized. Increasing frequency will provide a more reliable transit experience and reduce travel time.
- **Adjustment of trips' departure time:** Synchronize departures on key transit routes to improve integration between feeder and trunk lines. This measure is especially relevant for routes that serve multiple employment centers, ensuring that transit users experience smooth connections without excessive waiting at transfer points.
- **Prioritization of public transport:** Implement dedicated lanes for buses and Bus Rapid Transit (BRT) systems along Fortaleza's most congested corridors. This measure is crucial for improving bus speed and reliability, reducing transit delays caused by mixed traffic. By providing buses with exclusive right-of-way, overall system efficiency and attractivenes will increase, particularly for women and low-income individuals who rely on public transport. Additionally, traffic signal priority measures and station infrastructure improvements should be introduced in areas with a high volume of transit trips to ensure faster and more reliable service.

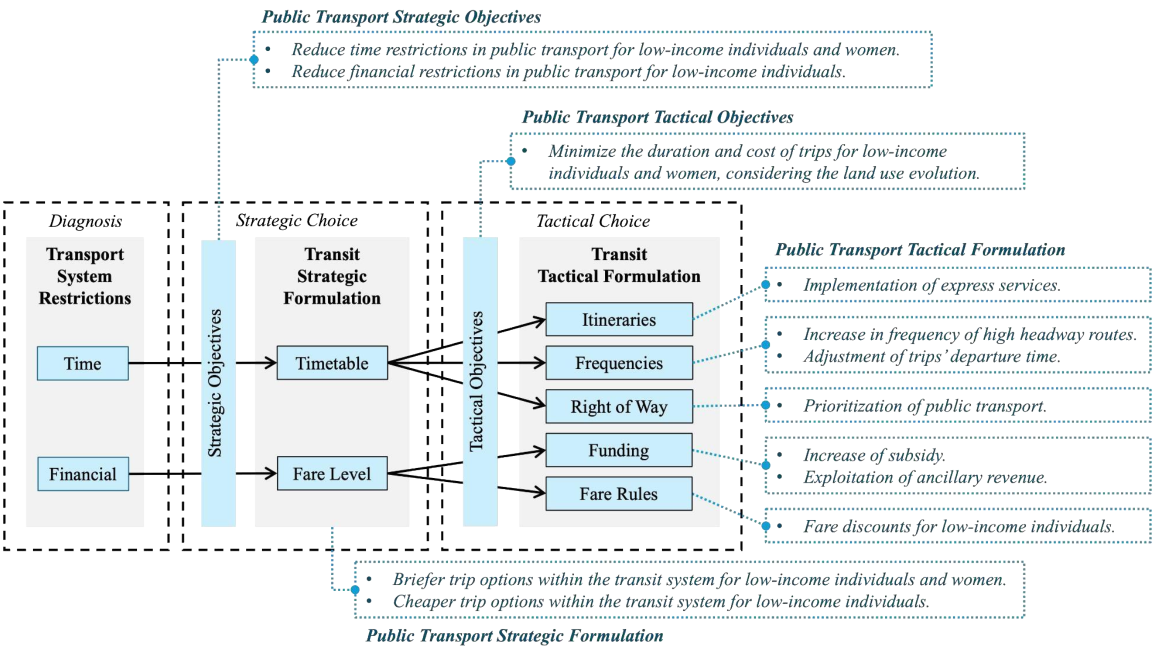
As pointed, low-income individuals in Fortaleza also face financial constraints when accessing public transportation, limiting their ability to reach employment centers, healthcare services, and educational institutions. The high cost of fares disproportionately affects vulnerable populations, creating a barrier to access.

Land use developments have further intensified these challenges, as newly developed job hubs remain further from low-income neighborhoods. Additionally, the lack of targeted subsidies intensifies the financial component on low-income communities, particularly women, who are more reliant on public transport for daily activities. Thus the second tactical objective is outlined: Minimize the cost of trips for low-income individuals and women, considering the land use evolution.

– **Increase in subsidy:** Strengthen the municipal budget allocation for public transport to ensure affordability. Fortaleza's transit funding model must include higher subsidies to mitigate fare burdens on low-income users. This approach will prevent fare increases while ensuring sustainable operations and service improvements.
– **Exploitation of ancillary revenue:** Expand funding sources beyond fare collection by incorporating advertising, leasing commercial spaces in transit hubs, and forming partnerships with private entities. Additional opportunities include offering naming rights for stations, monetizing transit data analytics, and integrating mobility-related services within public transport facilities to generate extra revenue streams.
– **Implementation of fare discounts for low-income individuals and women:** Introduce targeted fare discount programs for low-income users and women, ensuring access to affordable transit. Discounts can be applied through income-based fare structures, or government social programs. This measure directly addresses financial barriers to public transport use and supports vulnerable populations.

The definition of tactical objectives and the formulation of tactical strategies are outlined in Figure 15 (Tactical objectives and formulation for Fortaleza).

Figure 15 – Tactical objectives and formulation for Fortaleza



Source: Prepared by the author.

2.5 Public Transport Interventions in The PASFOR Plan

The *Plano de Acessibilidade Sustentável de Fortaleza e sua Área de Influência* (Plan for Sustainable Accessibility of Fortaleza and its Influence Area) (PASFOR) is a comprehensive urban planning initiative commissioned by the Municipal Infrastructure Secretariat of Fortaleza. Its primary objective is to develop a sustainable multimodal transportation network that prioritizes non-motorized modes of transport and high-capacity motorized modes, aiming to improve the well-being and quality of life of city residents (PASFOR, 2019a; PASFOR, 2019b)

PASFOR covers the city of Fortaleza and neighboring municipalities within the metropolitan transportation system, aiming to meet the accessibility and transportation needs of the region, considering environmental sustainability, social equity, and economic viability. It represents a strategic effort to address the complex challenges of urban mobility and accessibility in Fortaleza and surrounding areas, focusing on sustainable and inclusive transportation solutions (PASFOR, 2019a).

PASFOR aligns with regulatory and institutional guidelines, adhering to Brazil's National Urban Mobility Policy (Law 12.587/2012), local development plans such as Fortaleza 2040, and international frameworks, including the United Nations Sustainable Development Goals (SDGs).

A participatory approach and stakeholder engagement are essential components of PASFOR. The plan includes public consultations, workshops, and interaction with various actors such as government agencies, transportation operators, and civil society. Sectoral hearings are also conducted to address the concerns of different population groups, ensuring that urban mobility is planned inclusively and democratically (PASFOR, 2019a).

To ensure the effectiveness of the proposed measures, PASFOR establishes a set of performance indicator that allows for the evaluation of improvements in the efficiency and coverage of public transportation, equitable access to transportation services, and the quality and safety of infrastructure for pedestrians and cyclists (PASFOR, 2019a).

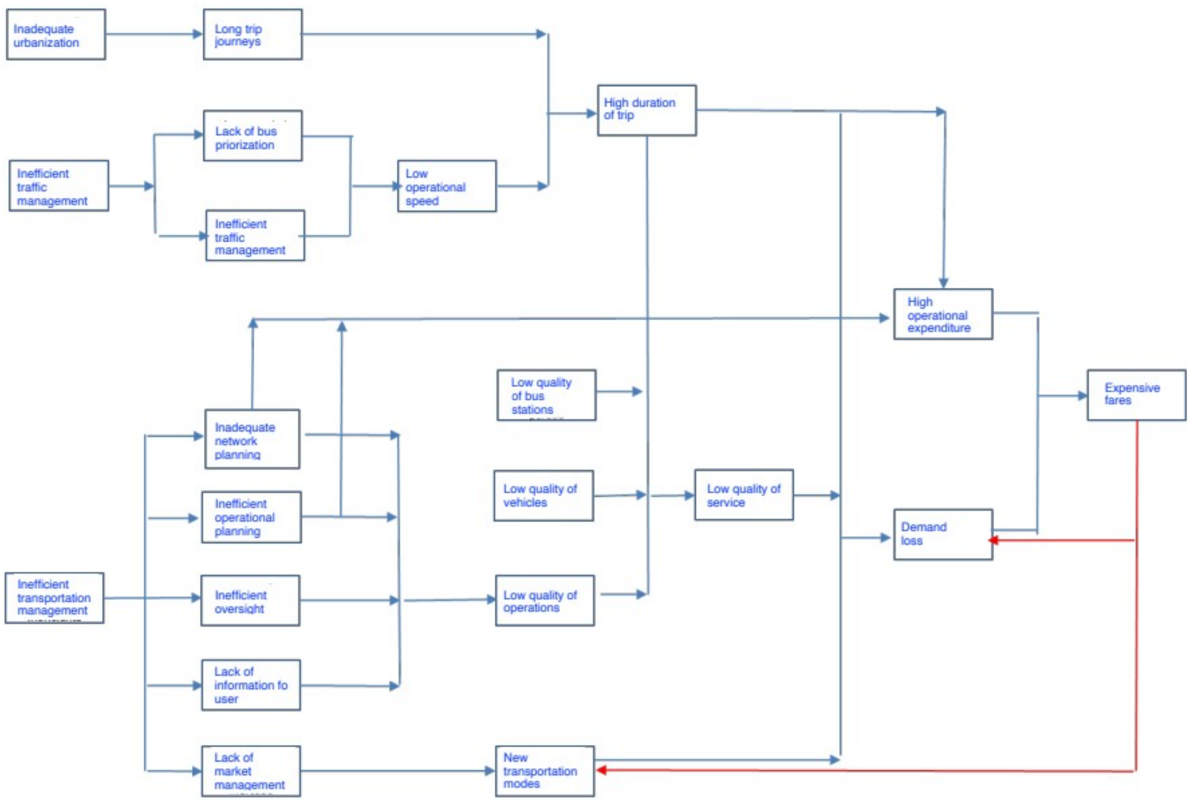
The methodological approach follows a phased structure, starting with data collection and diagnosis of mobility conditions, then formulation of interventions, simulation of alternatives, and assessment (PASFOR, 2019a; PASFOR, 2019b). However, PASFOR sets its primary objectives and indicators before the diagnosis, which could potentially limit the identification of problems and accessibility constraints.

2.5.1 PASFOR - Diagnosis

The PASFOR diagnosis presents a segmented approach to each transport modes, evaluating subsystem - public transport, individual, non-motorized, and cargo - independently, which limits the assessment. It focuses primarily on operational and infrastructural aspects, reinforcing a solution-oriented rather than a problem-oriented perspective. As a result, the document risks reinforcing existing inequalities, instead of addressing them (PASFOR, 2019a).

Also, although accessibility is mentioned as a guiding principle of PASFOR, the diagnostic phase does not provide an analysis of accessibility restrictions. While it includes a range of indicators on infrastructure, demand, and level of service, it does not explicitly identifies how systemic accessibility constraints impact different social groups, particularly vulnerable populations (PASFOR, 2019a).

Figure 16 – PASFOR’s public transport diagnosis



Source: Translated from PASFOR (2019a)

Regarding public transport, Figure 16 (PASFOR's public transport diagnosis), included in the PASFOR report, presents the main issues identified in Fortaleza's public transportation system. This schematic representation aims to organize and synthesize the challenges faced, providing a structured view of the difficulties affecting the operation and accessibility of public transport in the city (PASFOR, 2019a). PASFOR's findings about public transport system problems are described as follows:

– **Urbanization and Travel Time Issues:** Urban distribution results in long travel distances for users. Inefficient traffic management and lack of priority for buses lead to low operational speeds, increasing travel times and making public transport less attractive.
– **High Operational Costs and Expensive Fares:** Extended travel times cause higher operational costs due to increased fuel consumption and fleet requirements. These high costs result in expensive fares, reducing system affordability.
– **Service Quality and User Experience Issues:** Inadequate network and operational planning added to poor bus stop infrastructure, low-quality buses, and deficient operational performance contributes to an uncomfortable user experience, discouraging public transport use.
– **Governance and Information Gaps:** Inefficient transport management affects regulatory enforcement, passenger information systems, and market regulation.
– **Demand Loss and Alternatives:** Poor service quality leads to demand loss as users shift to alternative transport modes (*e.g.*, ride-hailing, informal transport). Lower demand exacerbates financial pressures, resulting in fare increases that further reduce ridership, creating a negative cycle.

While Figure 16 highlights various issues within the public transport system, these problems are still largely related to operational aspects. As a result, there are gaps in the process of identifying accessibility restrictions that could lead to a more comprehensive understanding of the system's challenges. These gap as described as follows.

– **Vague Problem Identification:** the use of unspecific terminology to describe transportation issues, such as "inadequate," "inefficient," "poor quality," and "precarious" makes it unclear how to establish quantifiable definitions. Without objective problem definitions, it is challenging to assess the magnitude of the issues, prioritize interventions, and justify decisions. A more explicit characterization of inefficiencies would improve the diagnosis utility.

- **Absence of Explicit Constraints:** the lack of clearly outlining accessibility constraints - such as land use inadequacies, transport restrictions, or individual characteristics - influences transport planning decisions. The absence of well-defined constraints can lead to misaligned policy recommendations. Since strategic and tactical choices must be justified within the boundaries of existing restrictions, an unclear constraint identification risks producing unrealistic or ineffective interventions.
- **Mobility rather than accessibility:** the focus on mobility results in misalignment with principles of justice, such as those proposed by the Capabilities Approach (Sen, 2011; Pereira *et al.*, 2016; Wee; Mouter, 2021). PASFOR characterizes the factors influencing accessibility issues but does not effectively assess whether these factors are direct causes of problems. Also, PASFOR also does not explicitly state which constraints impact the components of accessibility.

Moving forward on this analysis, the various constraints associated with the PASFOR plan are examined from the Public Transport Intervention Formulating Framework perspective. These constraints, derived from a critical evaluation of the document, highlight significant omissions that have not been explicitly addressed by PASFOR.

- **Personal capacity and individual constraints:** physical and motor limitations - *e.g.*, among older adults, children, and people with disabilities - are compounded by inadequate sidewalks, lack of tactile signage, high-step vehicles, and non-adapted infrastructure.
- **Physical infrastructure and transport system constraints:** deteriorated sidewalks, insufficient pedestrian crossings, and poor network connectivity hamper walkability. Discontinuous road layouts and fragmented bike lanes inhibit active travel, while overcrowded terminals and unsafe bus stops further discourage public transport use.
- **Spatial and temporal constraints in the land use system:** limited coordination between transport planning and urban form leaves large distances between homes and job hubs. As the city expands, public transport often fails to keep pace, leaving peripheral areas underserved and forcing low-income workers into lengthy, expensive commutes.
- **Temporal constraints in the transport system:** irregular service frequencies increase

waiting times, with the heaviest impact on low-income individuals.

- **Financial constraints in both the transport system and the individual system:** steep fares, lack of fare integration, expensive parking, and other related charges impose an important burden on lower-income populations. Given lower resources, these groups face disproportionately high transport expenditures.
- **Economic constraints in the land use system:** intensified competition for access to essential services — such as healthcare, schools, or retail hubs — places residents of poorly connected regions at a disadvantage, compounding broader accessibility inequalities.
- **Vulnerabilities:** gender, age, and income disparities shape how opportunities are reached. Safety issues - like harassment, crime, and poor lighting in transit corridors - further reduce accessibility for women and children.

2.5.2 PASFOR - Objectives

The objectives outlined by PASFOR are divided into four axis: urban planning, public transport management, traffic management, and infrastructure. The integration of urban development policies and mobility policies is pointed as crucial to produce a sustainable city: measures that encourage population to move near transportation axes can increase demand for public transportation and increase operational efficiency (PASFOR, 2019b). Nonetheless, these axis are not explicitly connected to the specific characteristics of the problem, such as existing constraints.

The plan recognizes that the improvement of public transportation services depends on its management, financing, planning, and provision control. Traffic management, on the other hand, is necessary to prioritize public transportation and reduce conflicts with other modes of transportation. Infrastructure investments are also necessary to improve the quality of public transportation services, including the construction of corridors and the improvement of terminals, stations, and stops (PASFOR, 2019b). As can be seen, this approach is solution-oriented, rather than problem-oriented.

For example, under the urban planning intervention axis, causes such as urban sprawl and spatial segregation are identified, leading to consequences such as long and motorized-dependent trips. The objective in this case should not be to build a more compact and dense city around collective transportation axes. The presented element is associated with a solution, *i.e.*, a denser city, which is not appropriate for the "objective" element, which should be associated with a constraint. The objective should be "reduce spatial mismatch". **Yet, no formulation set to reduce distances between residences and job locations is identified**.

Similarly, under the transportation management intervention axis, causes such as lack of integration are identified, leading to consequences such as route overlap and system overload. The objectives include developing a new unified and integrated intermodal network and enhancing bicycle integration with the collective transportation network (PASFOR, 2019b).This method is solution-oriented, proposing a new integrated intermodal network, which is not appropriate for the ’objective’ element that should address a constraint. The element presented here should be a strategic formulation.

All other strategic objectives outlined in PASFOR are also structured around solutions or generic goals, which may not align with the role of objectives in accessibility planning:

- **Integrate Urban and Transport Planning:** Align PASFOR interventions with municipal and regional plans like Fortaleza 2040, the *Plano Diretor Participativo 2019*, and the *Plano Municipal de Caminhabilidade (PMCFor) 2019*. Ensure coordination between urban expansion and mobility infrastructure.
- **Enhance Public Transport Efficiency:** Increase connectivity and accessibility in the transit network. Prioritize infrastructure investment in high-demand corridors. Improve integration between different transport modes, including active mobility.
- **Promote Sustainable and Equitable Mobility:** Reduce dependency on private vehicles. Prioritize non-motorized and public transport modes. Enhance accessibility for vulnerable groups such as the elderly, disabled, and low-income populations.
- **Increase Road Safety and Traffic Management:** Implement systematic traffic safety measures to reduce accidents. Develop intelligent transport systems (ITS) for real-time traffic monitoring. Improve road design to protect pedestrians and cyclists.
- **Ensure Financial Sustainability of the Transport System:** Establish policies to sustain public transport funding. Balance fare policies with service provision needs.

2.5.3 PASFOR - Interventions

Based on these objectives, PASFOR suggests a new structured network of public transportation, organized around high and medium-capacity axes. The proposed network includes metro and LRT lines, as well as bus corridors with exclusive or preferential lanes (PASFOR, 2019b).

The methodology for proposing a new regular bus system begins with an appraisal of each existing route to decide on its suppression or maintenance. Ridership data (passenger volumes, peak travel times, and overall demand patterns) were used to understand the usage and popularity of different bus routes. Route efficiency (travel time, coverage of key areas, and demand patterns) aimed to identify routes that effectively serve the population's transportation needs (PASFOR, 2019b).

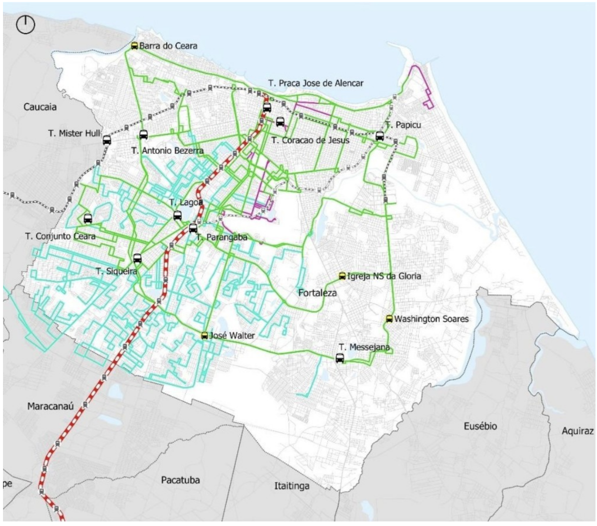
Integration between bus lines and other modes of transportation was used to evaluate overall connectivity and convenience for passengers. Also, redundant bus lines serving similar routes were identified as opportunities for eliminating inefficiencies (PASFOR, 2019b). It is noted that there is no evidence of accessibility analysis; the guiding principles are related to mobility (demand) patterns, excluding those with very low or no opportunity to travel.

The demand for transportation services in specific areas and corridors is analyzed again to identify gaps in the existing network and opportunities for new services. PASFOR (2019b) argues that introducing new services where most needed, ***i.e.* where the demand is higher**, makes the system more efficient; however, this utilitarian approach may not be fair, as already discussed in *Section 1.2 Gaps and Research Questions*.

The connectivity and coverage of the system in specific areas are also mentioned as indicators for route conception (PASFOR, 2019b); however, it is unclear how this is executed or which areas are considered. Finally, The regular bus network - illustrated in Figure 17 (Example of a transit project proposal from PASFOR) is proposed to complement the identified structural axes, providing feeder routes to improve accessibility.

Although more efficient, this solution increases transfers, and highly depends on public policies beyond municipal control, such as the improvement of the Rail Rapid Transit (RRT) system.

Figure 17 – Example of a transit project proposal from PASFOR



Source: PASFOR (2019b)

As mentioned, PASFOR proposes implementing priority treatment for public transportation. However,it doesn't objectively justify the set of streets where the intervention will be implemented. It includes segregating bus infrastructure, qualifying sidewalks, controlling corridor operations, and controlling unauthorized vehicles. The study suggests expanding the exclusive bus lane network from 116 km to 271.2 km, with 37.8 km of high-quality BRT and 233.4 km of exclusive lanes (PASFOR, 2019b).

The plan also proposes adjusting the frequency of 280 bus lines (77% of the total), removing 100 lines (28%), and segmenting 62 others (17%). Additionally, 12 new routes will be created to address service gaps, while the bus system's coverage is reconfigured to better connect with metro and LRT services, particularly through feeder routes (PASFOR, 2019b).

Regarding interventions on bus frequency, the PASFOR proposes concentrating demand on structural axes, allowing for a reduction in the number of lines but, an increase in capacity, with larger buses and higher frequency. PASFOR acknowledges that this will require more transfers - and, maybe, more travel time - for users to reach their destinations but argues that the inconvenience of transfers will be compensated by gains in efficiency, regularity, safety, and comfort (PASFOR, 2019b).

This intervention shows inconsistency with a problem-oriented approach. If the accessibility problem is associated with time restriction, then trips must be shorter. The proposal to increase transfers and concentrate demand on structural axes is likely to result in longer travel times.

PASFOR (2019b) argues that the reduction in the number of routes is derived from suppressing overlapping lines and the reliable integration allowed by the *Bilhete Único* (Single Pass) (BU). Additionally, the expected integration with an improved Rail Rapid Transit system, such as reduced intervals and improved stations, would rationalize the network while maintaining service quality and coverage. Furthermore, the speed benefits from bus prioritization would improve operational conditions.

Other propositions for the public transportation system are revitalizing bus terminals, improving accessibility, safety, and comfort for users, and enhancing bus stop conditions, including shelters, signage, and access for people with reduced mobility (PASFOR, 2019a).

Finally, to tackle financial restriction, PASFOR (2019b) interventions are reviewing concession contracts, ensuring quality and operational efficiency requirements, and adopting sustainable financing mechanisms, seeking alternatives to guarantee the economic viability of collective transport.

Regarding the proposed interventions for non-motorized transport, the plan includes expanding pedestrian-friendly zones, ensuring adequate crossing conditions, and improving sidewalk quality. Upgrades to bike lanes and the bike-sharing system are prioritized, focusing on route continuity and efficient integration with major public transport hubs, promoting greater inter-modal connectivity (PASFOR, 2019b).

Regarding infrastructural interventions, PASFOR (2019b) indicates public space rehabilitation and road redesign to increase pedestrian safety by minimizing risks at crossings. Efforts are made to reduce conflict between motorized and non-motorized users, for a safer and more harmonious sharing of streets.

2.6 Hypothetical Proposition for Fortaleza *versus* The Pasfor Plan

A comparative analysis of the hypothetical proposition for Fortaleza and the *Plano de Acessibilidade Sustentável de Fortaleza e sua Área de Influência* (Plan for Sustainable Accessibility of Fortaleza and its Influence Area) shows differences in their diagnostic approaches. While the hypothetical scenario utilizes academic research to identify accessibility constraints, PASFOR relies on a technical, municipal-oriented diagnosis emphasizing operational inefficiencies and demand patterns. This makes direct comparisons challenging but allows for a dual application of the proposed framework: first, to formulate a hypothetical intervention, and second, to evaluate an existing accessibility plan.

Both diagnoses recognize similar accessibility restrictions, particularly for peripheral and low-income populations. However, PASFOR fails to explicitly identify time constraints in the transit system. Consequently, while the hypothetical model addresses excessive travel times, PASFOR reinforces a trunk-and-feeder structure that risks increasing travel durations instead of mitigating them. Despite its name, PASFOR does not conduct a genuine accessibility analysis; rather, it employs mobility-based evaluations that exclude individuals with little or no travel opportunities (Sousa, 2019; Siqueira *et al.*, 2022).

Another major oversight is spatial mismatch. While PASFOR acknowledges the issue, it proposes no interventions to reduce it. Instead, by emphasizing transport efficiency over land-use coordination, it may unintentionally contribute to urban sprawl. The plan's strong efficiency focus aligns with a utilitarian perspective, prioritizing overall operational performance rather than equity in accessibility distributions.

PASFOR also suffers from redundancy in its objective definitions, frequently repeating similar goals across intervention categories. For example, both pedestrian and cycling infrastructure plans target network expansion and modal integration without clear coordination. Implementing a structured framework would help distinguish between strategic objectives (*e.g.*, "expanding cycling infrastructure") and tactical actions (*e.g.*, "installing bike racks at bus terminals").

Although PASFOR includes both strategic and tactical elements, it does not clearly differentiate them. By contrast, the hypothetical proposition systematically aligns interventions with accessibility constraints, providing a more robust justification for each action.

Regarding the formulation of transit interventions, PASFOR's indicates a review of the bus network focusing on efficiency. This goes against the reduction of the temporal restrictions and, therefore, tends to increase accessibility problems.

2.7 Conclusion

This chapter proposed and validated a structured framework for systematically formulating public transport interventions based on an evidence-based diagnosis. The theoretical foundations for developing transit alternatives through problem-driven analysis were discussed, leading to a methodology that ensures interventions are directly linked to identified accessibility constraints.

The framework was applied to a case study in Fortaleza, demonstrating its capacity to objectively formulate and justify public transport interventions based on prior diagnosis. The hypothetical approach successfully identified and addressed key accessibility constraints, particularly time and financial restrictions, and proposed interventions that directly tackled these issues.

Tactics such as express services, and new fare rules were developed to reduce travel times and improve affordability. The structured problem-based nature of this approach allowed for a clearer justification of each intervention, strengthening the logical coherence of urban transport planning.

Moreover, the framework proved valuable in analyzing PASFOR, highlighting overlooked constraints. While PASFOR identified issues such as spatial mismatch and financial barriers, it failed to explicitly recognize time constraints, leading to transit isolated interventions that can inadvertently prolonged travel distances.

Additionally, PASFOR focused on operational efficiency rather than accessibility, prioritizing demand-driven transport planning that excluded individuals with low travel frequencies. The plan also lacked a structured differentiation between strategic and tactical objectives, resulting in redundancy and misaligned objectives and interventions.

However, despite its strengths, the framework does not exhaust all possible interventions and transit attributes. Instead, it provides a systematic way to identify elements that may have been previously neglected in planning analyses, as well as to provide a structure way to incorporate new transit characteristics. Furthermore, this structured approach has implications for *ex-post* evaluations, as it clarifies causal relationships between interventions and accessibility outcomes. It makes assessments more aware by explicitly linking transport solutions to diagnosed constraints.

A key limitation is that the framework does not engage in the diagnostic phase itself but instead transfers inherent limitations from the problem identification stage to the intervention formulation stage. For instance, it does not fully account for individuals who work and reside in the same location in Fortaleza, as noted by Sousa (2019).

Future research should further explore specific constraints within the transport system that shape accessibility distribution. Additionally, analyzing the interconnections between different transport attributes, categories, and modes could enhance the understanding of how the system’s components collectively influence accessibility outcomes. These refinements would contribute to a more comprehensive and adaptive planning approach, ensuring that transit interventions effectively address urban mobility challenges while promoting social equity.

3 INCORPORATING EQUITY PRINCIPLES IN THE FORMULATION OF PUBLIC TRANSPORT INTERVENTIONS

Abstract

Public transport interventions have traditionally focused on maximizing accessibility while minimizing costs, often overlooking the importance of equity in distributional outcomes. This study integrates Rawls' Egalitarianism and Sen's Capability Approach into a novel optimization framework for public transport intervention formulation. The proposed methodology explicitly prioritizes vulnerable populations by ensuring that accessibility benefits are distributed in a way that reduces disparities and prevents accessibility deprivation. The framework treats both transit supply and fare levels as decision variables, allowing for a balanced trade-off between affordability and service provision. The approach is validated through an application in Fortaleza, Brazil, comparing four scenarios: Problem Evolution, Do Nothing, Alternative Optimal, and Equitable Optimal. Results show that land use policies alone provide moderate improvements but fail to address accessibility inequities effectively. In contrast, equity-driven interventions significantly reduce the proportion of individuals in critical accessibility conditions and improve accessibility distribution, lowering the Palma Ratio from 4.31 to 1.65. This research demonstrates that an equitable transit system does not require maximizing service provision but rather a strategic redistribution of resources. It highlights the necessity of integrating justice principles in transport planning and provides a replicable framework for policymakers to design inclusive and accessible transit networks.

3.1 Introduction

The purpose of transport planning in light of the accessibility planning paradigm is to promote social justice and quality of life, where all people have sufficient access to opportunities and services (Soares, 2022; Cavalcante, 2023). This implies taking into account equity issues when planning, such as the equitable distribution of benefits of transport interventions, the reduction of spatial inequalities and the promotion of social inclusion (Garcia, 2016; Pereira *et al.*, 2016).

As discussed on *section 1.4 Relevance*, public transport has a fundamental role to play in this context, as it is a more affordable and sustainable mode, and can reduce inequalities in accessibility distribution, fostering social emancipation. However, although accessibility has gradually supplanted cost minimization in transit planning, there remains a gap in employing equity principles on the formulation of interventions.

Early transport formulation research shifted from cost-based approaches to accessibility (Antunes *et al.*, 2002; Niehaus *et al.*, 2016), but often prioritized equality over equity, overlooking vulnerable populations. Even though progress have been made, some authors frequently failed to distinguish individuals needing accessibility improvements from those already well-served, and efforts to reduce variance or close group gaps did not always benefit disadvantaged communities (Ferguson *et al.*, 2012; Zhang *et al.*, 2016; Caggiani *et al.*, 2017).

Studies on spatial accessibility inequalities also failed to consider intersecting vulnerabilities, such as income and gender (Wang; Chen, 2020; Wang *et al.*, 2024). A crucial step in addressing these disparities is the diagnostic phase, used to identify the most affected communities (Fan; Machemehl, 2011; Handley *et al.*, 2019; Zhang; Khani, 2020). Yet, many studies either omitted this step or focused solely on evaluating existing projects without critically assessing their formulation (Garcia, 2016; Pereira, 2019; Freire, 2019; Freiberg 2022; Deweese et al., 2022; Amorim; Silva, 2024; Vecchio et al., 2020).

From the discussion above, the research question addressed in this section is *"how to formulate public transport interventions in the light of promoting equitable accessibility distributions?"* This is relevant because a fair evaluation of public transport interventions would require a method that is more comprehensive and consistent in terms of representing the human capacity to achieve opportunities (Sen, 2011; Wee; Mouter, 2021; Vecchio; Martens, 2021).

Given the large number of people who depend on public transport and the high budgets invested in its infrastructure, the investigation of methods to propose transit investments is fundamental for the implementation of efficient and effective solutions to urban mobility problems. Therefore, **there is a methodological gap regarding the formulation of public transport interventions in the light of promoting equitable accessibility distributions**.

To provide an answer to this research question, the objective of this chapter is **to propose and validate a framework to objectively formulate public transport interventions based on equity principles**. This work advances on previous research by providing an optimization problem for formulating public transport interventions based on the Capability Approach.

3.2 Equity Principles in Transportation

The ethical principles of justice regarding transportation policies originate from the discussion about what benefits derived from the transport investment must be distributed, and in which distribution pattern these benefits should be allocated (Wee; Geurs, 2011; Karner *et al.*, 2020; Wee; Mouter, 2021; Willberg *et al.*, 2023).

These norms vary across different contexts and, while some degree of inequality is inevitable in any society, it is crucial to assess whether such inequalities stem from fair processes. Unfair inequalities arise when individuals are either penalized or privileged based on factors that are morally arbitrary, such as their race, gender, or socioeconomic background. That is because an individual's accomplishments are not solely determined by personal decisions and cannot be completely isolated from the environmental and societal circumstances (Lucas, 2012; Pereira *et al.*, 2016).

On the other hand, not all forms of inequality are unfair, and there are instances where fairness may require treating individuals differently. Inequalities can be considered fair if they stem from a situation where all individuals have equal access to opportunities. In a society where everyone has an equal chance to succeed based on their abilities and efforts, resulting inequalities can be seen as justifiable (Karner *et al.*, 2024; Pereira *et al.*, 2016).

3.2.1 The fair Distribution of Benefits

The two main approaches for distributional equity are the Rawls' Egalitarianism and the Sen's Capability Approach. Rawls' Egalitarianism holds that social and economic inequalities are just only if they benefit the least advantaged. Its "difference" principle prioritizes improving conditions for the worst-off, meaning a transport policy would be evaluated based on the impacts on those with the poorest transportation conditions (Martens, 2012; Behbahani *et al.*, 2019; Karner *et al.*, 2024; Vecchio *et al.*, 2020).

Rawls' egalitarianism focuses on reducing inequities between groups by disproportionately distributing the benefits of interventions in favor of the least advantaged. Instead of aiming for equal treatment, its "difference" principle justifies unequal distribution of benefits when they improve the conditions of those with the worst access to resources (Karner *et al.*, 2020; Meyer; Roser; Pereira *et al.*, 2016).

Under this principle, transportation decisions must prioritize investments in communities with the poorest transportation services, even if it results in an uneven distribution of benefits. By allocating greater resources and improvements to the most disadvantaged groups, Rawlsian egalitarianism seeks to correct structural disparities and ensure that transportation policies reduce unfair inequalities (Behbahani *et al.*, 2019; Willberg *et al.*, 2023; Amorim; Silva, 2024).

The capabilities approach, on the other hand, focuses on what the transport system allow people to do and to be. This approach is concerned in delivering a minimum acceptable level of transportation services for all. Additionally, capability approach values pluralism, recognizing that different people may have different needs and that justice means enabling each to pursue their own life plans (Nussbaum, 2013; Sen, 2011; Vecchio; Martens, 2021).

This principle — also called sufficientarianism — asserts that everyone should be sufficiently well off, *i.e.* above a minimum threshold. In this context, threshold values for transportation services must be defined, below which individuals are at risk of social exclusion. Defining such thresholds is a methodological challenge, as social exclusion depends on the accepted norms and standards of the society in which individuals live (Amorim; Silva, 2024; Lucas *et al.*, 2015; Luz; Portugal, 2021).

The focus on vulnerable groups with insufficient transportation services ensures that the most pressing inequalities are tackled, even if complete equality is not achieved. In this way, reducing disadvantaged individuals under minimal thresholds contributes to a more equitable distribution of resources and opportunities, ultimately fostering a more just and inclusive society (Wee; Geurs, 2011; Willberg *et al.*, 2023).

Ultimately, policies in transportation planning should be designed to prioritize the needs of vulnerable and marginalized groups in society. A transport policy is fair if prioritizes investments to support vulnerable groups, addressing moral concerns and ensuring individuals can access opportunities effectively (Pereira *et al.*, 2016; Luz; Portugal, 2021).

3.2.2 Accessibility as Capability

Transportation equity should not focus only on provide infrastructure, but ensure that people can effectively use it to reach essential opportunities like jobs, healthcare, and education. That is because justice should be evaluated by people's real freedoms to achieve meaningful life outcomes, rather than just the availability of transport services (Sen, 2011; Nussbaum, 2013; Pereira *et al.*, 2016).

This principles, rooted in the Capability Approach, emphasize the importance of considering the capabilities of individuals to access and utilize transportation services and opportunities. This definition takes into account not only the physical ability to access transportation but also the social and economic factors that may impact an individual's ability to fully participate in society (Pereira *et al.*, 2016; Vecchio; Martens, 2021).

Accessibility is a core concept in transportation equity, and refers to individuals' ability to reach and use the services, activities, and destinations they need and want, considering their social and spatial characteristics and constraints (Geurs; Wee, 2004; Wee; Geurs, 2011). In the case of formulating transit interventions, they should be assessed from an accessibility perspective, as it reflects a person's overall capability to reach opportunities (Pereira *et al.*, 2016; Luz; Portugal, 2021; Pot *et al.*, 2024).

However, traditional accessibility measures focus on physical infrastructure or travel time, and may not fully consider individual and social constraints. Factors such as affordability, and safety concerns can prevent people from converting transport options into real access. For example, a low-income worker may live near a transit stop but cannot afford the fare, or a person with disabilities may lack necessary accommodations to board a bus (Vecchio; Martens, 2021; Luz; Portugal, 2021).

In that sense, measuring accessibility as capability requires indicators that capture its nature as such, ensuring the consideration of factors that may restrict individuals' ability to convert accessibility into functioning (Ferreira, 2023). Effective indicators should account for economic, social, and personal constraints, such as affordability, safety, disability, and cultural norms, which influence whether access to transport translates into real opportunities. Without incorporating these dimensions, accessibility measurements risk overestimating the effectiveness of transport policies.

3.3 Current Gaps in Transit Formulating

As accessibility began to be prioritized, studies on transit formulation aimed to strike a balance between minimizing costs and maximizing accessibility (Antunes *et al.*, 2002; Benenson *et al.*, 2016; Zhang *et al.*, 2016; Gulhan *et al.*, 2017; Handley *et al.*, 2019; Zhang; Khani, 2020; Fu *et al.*, 2020; Michailidis *et al.*, 2023a; Yang *et al.*, 2020). However, these researches frequently overlooked how benefits were distributed among different population groups. This often led to favoring areas where accessibility improvements were cheaper, possibly exacerbating inequalities rather than mitigating them.

Attention later shifted towards evaluating spatial inequalities in accessibility distribution (Fan; Machemehl, 2011; Volotskiy *et al.*, 2018; Wang; Chen, 2020; Wang *et al.*, 2024). However, focusing solely on spatial aspects of accessibility fell short of capturing the full inequities at play, as spatial inequality alone is insufficient to characterize an unfair condition. As discussed, inequality only becomes unfair when it systematically disadvantages vulnerable groups, perpetuating conditions of socioeconomic exclusion (Wee; Geurs, 2011).

While some progress was made in considering social distribution, researches failed to distinguish between those in need of accessibility improvements and those already well-served. Vulnerable individuals are not always in a problematic situation, as some may benefit from sufficient levels of accessibility. Current approaches often focus on reducing variance in accessibility (Ferguson *et al.*, 2012; Zhang *et al.*, 2016) or aim at minimizing the gap between groups (Caggiani *et al.*, 2017), which does not always effectively reduce the challenges faced by disadvantaged communities (Niehaus *et al.*, 2016).

A critical step in addressing these accessibility problems is the implementation of a diagnostic process to clearly identify individuals and communities in need (Sousa, 2019). Many studies lacked such a diagnostic phase or failed to embed it within a strategic framework (Fan; Machemehl, 2011; Ferguson *et al.*, 2012; Handley *et al.*, 2019; Zhang; Khani, 2020; Fu *et al.*, 2020; Michailidis *et al.*, 2023b). Even where diagnostics were present, the focus often remained on evaluating projects already formulated or implemented, without critically questioning their underlying rationale (Garcia, 2016; Pereira, 2019; Freire, 2019; Freiberg, 2022; Deweese *et al.*, 2022; Amorim; Silva, 2024; Vecchio *et al.*, 2020).

Lastly, while recent discussions have explored the integration of equity principles into transport planning (Behbahani *et al.*, 2019; Pavia *et al.*, 2023; Alogdianakis; Dimitriou, 2024; Amorim; Silva, 2024; Wang *et al.*, 2024; Michailidis *et al.*, 2023a; Wang; Chen, 2020; Caggiani *et al.*, 2017; Ferguson *et al.*, 2012), no existing research has incorporated both Rawls' Egalitarianism and Sen's Capability Approach within a framework for formulating public transport interventions.

3.4 Equity in the Formulation of Public Transport Interventions

This chapter deals with the formulation of public transport as a network optimization problem. Optimization in transit systems analysis focuses on the application of mathematical models to minimize - or maximize - various aspects of transit operations (Vuchic 2005).

Network optimization is a field of operational research that handles with problems involving networks, such as transportation networks, communication networks, and social networks. The goal of network optimization is to find the most efficient way to utilize resources within a network towards a goal, like minimizing costs or maximizing overall performance (Dantzig; Thapa, 1997; Theubl *et al.*, 2020).

There are various types of transportation network optimization problems, including the shortest path problem, which is to find the shortest path between two nodes in a network; the minimum spanning tree, which is to find the tree that connects all nodes in a network with the minimum total edge weight; the maximum flow problem, which is to determine the maximum amount of flow that can be sent through a network from an origin to a destination; and the network design problem, which is to optimize the design of a network by selecting the best design of a network to meet specific criteria, *e.g.* maximizing accessibility (Dantzig; Thapa, 1997; Theubl *et al.*, 2020; Yang *et al.*, 2020).

The optimization problem considered in this research can be generalized as a network design problem, and is represented by (i) an objective function, (ii) a set of decision variables, and (iii) a set of constraints. These elements are described as follows.

3.4.1 Objective Function

The objective function is designed to align with Rawls' Egalitarianism and Sen's Capability Approach by prioritizing interventions that reduce the number of individuals in a problem situation, defined as vulnerable individuals falling below a critical accessibility threshold. The function seeks to minimize the weighted number of such individuals, ensuring that the intervention effectively improves access for those most at risk of social exclusion.

An individual is classified as being in a problem situation if he or she is both vulnerable (*i.e.*, socially or economically disadvantaged) and have accessibility below the critical threshold. Privileged individuals who fall below this threshold, on the other hand, are not considered in a problem situation, as their financial resources enable them to overcome accessibility barriers through alternative means, such as private transport.

Moreover, not all vulnerable individuals face the same urgency. Some experience greater disadvantage due to intersecting socioeconomic factors, making their accessibility constraints more severe. To reflect this, the objective function is weighted by each individual's original vulnerability, ensuring that those in more precarious conditions contribute more significantly to the optimization criteria. The objective function is depicted as follows.

$$\text{To minimize:} \quad \sum_i \frac{p_i}{u_i} \begin{cases} \text{if } a_{project,i} < a_{critical} \text{ and } v_i = 1, & p_{project,i} = 1 \\ \text{else,} & p_{project,i} = 0 \\ u_i = \left(\dfrac{a_{baseline,i}}{a_{baseline}} \right) & \end{cases}$$

- $p_{project,i}$ is a dummy indicating whether the individual (i) is in situation of problem (1) or not (0) in the projected scenario;
- u_i is the original vulnerability for individual (i);
- $a_{project,i}$ is the accessibility for individual (i) in the projected scenario;
- $a_{baseline,i}$ is the accessibility for individual (i) in the baseline scenario;
- $a_{critical}$ is the minimum acceptable accessibility threshold;
- v_i is a dummy indicating whether the individual (i) is a vulnerable individual (1) or not (0);

The weighting factor is determined using the inverse of an individual's original accessibility relative to the average accessibility of the population. This means that, for instance, if an individual has half (a quarter) of the average accessibility in the baseline scenario, their weight is two (four). This approach ensures that those experiencing the most severe accessibility deficits are given greater importance in the optimization process.

Furthermore, the accessibility indicator used in this model must represent capability as potential, meaning it must capture not just the existence of transport options but the real ability of individuals to convert those options into meaningful opportunities.

While sufficientarianism is embedded in the objective function by ensuring all individuals reach a minimum accessibility level, it does not fully capture the equity concerns related to excessive disparities between privileged and vulnerable groups. Therefore, rather than incorporating egalitarian principles into the objective function, this research argues that egalitarianism should be enforced as a constraint, ensuring that accessibility improvements do not disproportionately benefit privileged groups or exacerbate disparities.

3.4.2 Decision Variables

The decision variables have already been discussed in section *2.2.6 Transport System Restrictions and Public Transport Specifications*, and are depicted as follows.

$D = \{n_j, t_j, s_j, v_j, f_j\}$

where

- n_j is the network layout for scenario j;
- t_j is the timetable for scenario j;
- s_j is the station design for scenario j;
- v_j is the vehicle design for scenario j;

– f_j is the fare level for scenario j;

The strategic interventions discussed in chapter 2 are designed to focus on specific decision variables, depending on the nature of accessibility restrictions in a given context. For example, interventions targeting fare levels may be most effective in situations where affordability is the primary barrier. Similarly, in cases where physical barriers disproportionately affect individuals with disabilities, modifying station and vehicle features could be prioritized.

By structuring interventions around selected decision variables, transport planners can develop targeted strategies that efficiently address critical accessibility deficits while ensuring that improvements align with equity principles.

Also, the accessibility indicator used in the objective function must be sensitive to each of these decision variables. The effectiveness of transport interventions in reducing the number of individuals in a problem situation depends on how these variables shape actual accessibility outcomes.

This research treats both costs and revenues as decision variables, allowing the optimization model to balance transit supply and fare levels. Traditional transport planning often considers supply variables only (Alogdianakis; Dimitriou, 2024; Behbahani *et al.*, 2019; Arbex; Cunha, 2015), limiting the flexibility of policy interventions.

Depending on the specific context, this novel approach may prioritize lower fares at the expense of reduced service frequency, leading to longer travel times but greater financial accessibility. Conversely, in scenarios where affordability is less restrictive, the model may allocate resources toward higher service levels while maintaining current fare structures.

3.4.3 Constraints

The egalitarian principle of justice requires improving the situation of the worst-off while ensuring that existing disparities do not widen. In this research, this principle is translated into a constraint that ensures that accessibility for individuals in a problem situation (*i.e.*, vulnerable individuals below the critical accessibility threshold) must not decrease due to the proposed intervention. This requires that the change in accessibility for individuals in a problem situation must be zero or positive, preventing any further disadvantage. This is shown as follows.

$$\min_i \left\{ \Delta a_i \cdot p_{baseline,i} \right\} \geq 0 \quad \begin{cases} \text{if } a_{baseline,i} < a_{crtical}, & p_{baseline,i} = 1 \\ \text{else,} & p_{baseline,i} = 0 \end{cases}$$

where

- Δa_i is the accessibility gains for individual (i) in the projected scenario;
- $p_{baseline,i}$ is a dummy indicating whether the individual (i) is in situation of problem (1) or not (0) in the baseline scenario;
- $a_{baseline,i}$ is the accessibility for individual (i) in the projected scenario;
- $a_{critical}$ is the minimum acceptable accessibility threshold;

Conversely, accessibility reductions for individuals above the critical accessibility threshold are permissible, provided that their accessibility remains above the critical level. This restriction ensures that no individual is pushed below the critical threshold, serving as a safeguard for individual rights and preventing situations where accessibility losses impose unjustified burdens.

Moreover, this principle aligns with the Kaldor-Hicks efficiency criterion in the context of transport equity. While interventions may reallocate accessibility benefits, they must ensure that vulnerable individuals are not left in a worse-off situation, even without compensatory mechanism. This can be represented as follows.

$$p_{project,i} \leq p_{baseline,i}$$

where

- $p_{project,i}$ is a dummy indicating whether the individual (i) is in situation of problem (1) or not (0) in the projected scenario;
- $p_{baseline,i}$ is a dummy indicating whether the individual (i) is in situation of problem (1) or not (0) in the baseline scenario;

Additionally, this promotes a gradual reduction of inequality by preventing interventions from exacerbating existing disparities. By ensuring that accessibility gains and losses are structured equitably, the approach fosters a fairer distribution of transport benefits, aligning with justice principles while maintaining flexibility in system-wide adjustments.

The third constraint ensures that the optimization problem remains financially viable by limiting the total cost of interventions. The budget constraint is structured similarly to the decision variables, where each decision variable has a unitary cost associated with it. The exception is fare levels, which generate revenue instead of incurring costs. This restriction is represented as follows.

$$B \geq n_j \cdot c_n + t_j \cdot c_t + s_j \cdot c_s + v_j \cdot c_v + f_j \cdot c_f$$

where

- B is the budget for implementing the intervention;
- n_j is the network layout for scenario j;
- t_j is the timetable for scenario j;
- s_j is the station design for scenario j;
- v_j is the vehicle design for scenario j;
- f_j is the fare level for scenario j;
- c is the cost factor for each decision variable;

The total net cost of the intervention, considering the sum of individual decision variable costs and the revenue generated from fare changes, must be equal to or lower than the available subsidy. This ensures that the intervention is economically feasible and aligns with financial constraints imposed by policymakers or funding agencies.

3.5 Equity in the Formulation of Public Transport Interventions in Fortaleza

To validate the proposed optimization problem, this research applies it to a case study for the city of Fortaleza, Brazil. As discussed in the previous chapter, the interventions formulated for Fortaleza address two major challenges faced by low-income individuals: long travel times and high transit costs. As land use patterns in Fortaleza evolve, economic activities have become increasingly concentrated in central areas, while low-income populations remain in peripheral zones with limited accessibility. This spatial mismatch leads to longer, more complex commutes, especially for those reliant on public transport. Additionally, high fares disproportionately affect vulnerable populations, creating further barriers to accessing employment, healthcare, and education.

To mitigate these issues, the tactical objective is defined: minimizing trip duration and travel costs for the low-income individuals. The first objective focuses on the implementation of express services, reducing transfers and increasing service frequency on critical routes. Also, synchronizing feeder and trunk routes further enhances connectivity, reducing delays at transfer points. Additionally, prioritizing public transport through dedicated bus lanes, expanding Bus Rapid Transit (BRT) corridors, and introducing traffic signal priority measures improves transit speed and reliability.

The second objective focuses on reducing travel costs, ensuring that affordability is improved for low-income individuals. A critical measure is implementing targeted fare discounts, applying income-based and demographic-specific reductions to support low-income users, ensuring that financial constraints do not limit their access to essential services and opportunities.

3.5.1 Validation Method

Four scenarios are set to validate the proposed method for incorporating equity into transit intervention formulation (Figure 18 - Validation Scenarios). Each scenario represents a different combination of land use patterns, bus system configurations, and rail system expansion.

Figure 18 - Validation Scenarios

	Problem Evolution	***Do Nothing Bus***	***Equitable Optimal***	***Alternative Optimal***
Land-Use	Increase sprawl	Reduce sprawl	Reduce sprawl	Reduce sprawl
Rail System	Original	Expansion	Expansion	Expansion
Subsidy	Original	Original	+25%	+25%
Bus System	Original	Original	Optimal 1	Optimal 2

Source: Prepared by the author.

The Problem Evolution scenario assumes that urban sprawl continues to increase without policy intervention, exacerbating accessibility challenges, particularly for low-income individuals. The bus system remains unchanged, operating at its original configuration, and no expansions are made to the rail network. This scenario represents a business-as-usual approach where current trends persist without corrective measures.

The Do Nothing (Bus) scenario assumes that urban sprawl is reduced, due to land use policies, and the rail system undergoes an expansion and integration. However, the bus system remains in its original configuration, meaning no improvements are introduced. This scenario represents a counterfactual for the regular bus optimization scenarios, a *ceteris paribus* reference.

The Equitable Optimal scenario assumes that urban sprawl is reduced, and the rail system is expanded. The bus system is optimized using the proposed optimization problem and an additional 25% of subsidy. This scenario represents the actual application of the method developed in this chapter. In contrast, the Alternative Optimal scenario follows the same land use pattern and rail system as the Equitable Optimal scenario. However, it features a different bus system optimization strategy, applying alternative objective function and constraints.

The alternative optimization problem is based only in the Rawls' maximin criterion. In transportation equity, this principle translates into prioritizing accessibility improvements for individuals with the lowest levels of access (Lucas *et al.*, 2015; Martens; Ciommo, 2017; Pereira *et al.*, 2016). Maximin involves maximizing the minimum accessibility level in a given scenario (Karner *et al.*, 2020), and provides a strong ethical foundation for transport planning (Michailidis *et al.*, 2023a; Behbahani *et al.*, 2019). The objective function for the maximin is as following.

to maximize: $\min\{a_{project,i}\}$

In the Alternative Optimal scenario, only the budget constraint applies, as the egalitarian principle is already considered in the objective function.

The scenario evaluation process is structured around two core justice-based perspectives: the sufficientarian perspective, and the egalitarian perspective. The sufficientarian perspective examines how effectively interventions elevate individuals above a minimum accept- able accessibility threshold. The effectiveness of each intervention is measured by the proportion of vulnerable individuals (low-income groups) remaining below accessibility threshold after implementation.

A higher proportion of individuals in critical conditions indicates a less effective intervention, whereas a lower proportion signifies a more successful strategy in mitigating transport deprivation. This evaluation provides an objective measure of the magnitude of accessibility inequality, ensuring that policies directly address the needs of the most disadvantaged. Additionally, equity constraints are assessed to confirm whether interventions protect the worst-off and prevent further disparities.

The egalitarian perspective assesses whether accessibility benefits are fairly distributed across socioeconomic groups, *i.e.* evaluates whether transit interventions actively reduce disparities between privileged and disadvantaged groups. This approach aligns with Rawlsian justice principles, which emphasize reducing inequities rather than simply increasing overall accessibility levels. This analysis is performed in two steps.

First, individuals are divided into deciles based on their original vulnerability level (u_i), with lower deciles representing the most vulnerable individuals. The effectiveness of each intervention is analyzed by examining how accessibility improvements are distributed across these deciles. If accessibility gains are disproportionately concentrated in higher deciles (privileged groups), the intervention is considered inequitable. If accessibility gains increase progressively in lower deciles, the intervention effectively prioritizes disadvantaged individuals, aligning with egalitarian justice principles.

Second, the Palma Ratio is used to quantify disparities by comparing mean accessibility levels between the top 10% (better-off group) and the bottom 40% (worse-off group) (Pereira; Herszenhut, 2022). A higher Palma Ratio signals greater inequality, indicating that accessibility benefits are concentrated among the already advantaged. A lower Palma Ratio suggests a more balanced accessibility distribution, ensuring that transport improvements do not disproportionately favor privileged groups.

3.5.2 Accessibility Measure

It is important to ensure that accessibility measures are practical and user-friendly for stakeholders. For these measures to be valuable in guiding policy formulation, they must be coherent, transparent, and easily understandable to all parties engaged in urban planning activities (Bertolini *et al.*, 2005; Soares, 2022; Pinto *et al.*, 2022).

Additionally, when considering accessibility as a capability, complex questions arise. It should refers to the individual's ability to reach desired destinations and engage in activities, considering factors such as socio-economic characteristics, preferences, and needs (Pereira *et al.*, 2016; Soares, 2022).

As already discussed, Geurs e Wee (2004) identify four main accessibility components: land use, transport, time, and individual. Accessibility indicators varies on how they address these components, and can be categorized as infrastructure-based, location-based or person-based.

Infrastructure-based indicators are related to physical characteristics of the transport system, such as network mileage, number of stops, or network performance measures like coverage, travel time, and congestion levels. They are simple to compute and interpret but lack consideration for land use and individual factors (Garcia, 2016).

Location-based indicators are related to spatial distribution of activities and their connection to transport networks. They use separation indicators (*e.g.* distance, travel time, cost) or contour indicators (areas reachable within a set travel time or cost) to assess accessibility. While they include land use, they often neglect individual preferences and time constraints.

Lastly, person-based indicators are related to individual perceptions and constraints, using utility indicators based on the expected benefit of different travel choices or time-space indicators that consider individual limitations and activity schedules. They are theoretically sound but complex to calculate and interpret (Garcia, 2016).

The adequacy of the indicator depends on the specific accessibility restriction category being analyzed. Garcia (2016) brings up an important discussion on which accessibility indicators are suitable for each accessibility restriction. From this discussion, Table 1 (Accessibility indicators adequacy by categories of accessibility restriction) summarizes the adequacy of accessibility indicators, considering the transport system restrictions previously identified in Figure 6 - Transport system restrictions and transport planning. Also, Garcia (2016) highlights that combining multiple accessibility indicators with complementary strengths can provide a more comprehensive analysis of the urban mobility network.

Table 1 – Accessibility indicators adequacy by categories of accessibility restriction

Restrictions:	**Physical Infrastructure**	**Space-Time**	**Financial**
Infrastructure indicators	+	±	-
Separation indicators	-	±	±
Contour indicators	-	±	±
Potential indicators	-	±	+
Competition indicators	-	+	+
Utility indicators	-	-	+
Time-space indicators	-	+	-

Source: Adapted from Garcia (2016).

Ferreira (2023), however, argues that these measures fall short on representing accessibility as a capability, and proposes a novel accessibility-as-capability measure, adapting the cumulative opportunities measure to incorporate individual constraints, particularly income and fare policies.

The proposed method quantifies the maximum number of opportunities an individual can access, considering their financial limitations and conversion factors. It maximizes accessibility within a given budget and time threshold, incorporating monetary constraints and travel time impedances.

The model accounts for fare policies (such as subsidies and student discounts) and individual resources (income and transport modes available). Unlike traditional accessibility measures that often use aggregated income statistics, the proposed approach considers individual affordability, avoiding biases that overestimate accessibility for the least advantaged.

This thesis uses an adaptation of the one proposed by Ferreira (2023), and is presented as follows.

$$A_i = \frac{\sum_k jobs_k \cdot W_{ik}}{\sum_k jobs_k} \cdot b_i$$

where

$$W_{ik} = e^{-\frac{(d_{ik}/\sigma)^2}{2}}$$

and

$$b_i = \min\left\{\frac{i_i \cdot 10\%}{198},\ 1\right\}$$

A_i represents the proportion of reachable jobs in a month for individual i, from a given location k, where each job is weighted by the weighting factor W_{ik}, and the total reachable jobs is constrained by the individual's budget factor b_i. W_{ik} follows a Gaussian decay, where travel time d_{ik} is adjusted by a sigma parameter σ to model the influence of distance. The sigma value is chosen such that jobs 60 minutes away receive a weight of 0.5.

It is important to note that, for the accessibility estimates, this research considers that jobs are segmented by complexity levels, with lower-complexity jobs associated with low-income individuals and higher-complexity jobs accessible to higher-income groups. This assumption enhances the realism of the accessibility measure by reflecting the actual employment opportunities available to different social groups.

However, this consideration also introduces limitations, as it reinforces existing market inequalities and may underestimate potential job accessibility improvements resultin from education, skill development, or policy interventions. Additionally, this approach assumes a fixed correlation between income and job type, which may not fully capture labor dynamics, informal employment opportunities, or shifts in economic structure, particularly in rapidly changing urban environments.

b_i, in turn, is the individual's budget constraint factor that represents whether a person's income can afford the monthly transportation cost for commuting to work. The rationale for this formula is to determine a normalized affordability factor that assesses whether a household's per capita income can cover the monthly cost of essential transportation (R$ 198 for two daily trips, and 22 working days) without exceeding 10% of their income - a reasonable transport expenditure (Armstrong-Wright; Thiriez, 1987). b_i also accounted for student subsidy (1/3 of the cost of regular fare), formal employment subsidy and elderly subsidy.

Finally, The $a_{critical}$ is defined as the median accessibility for the low-income individuals in the baseline scenario. Freire (2019) argues that using the median as a benchmark ensures a robust evaluation by accounting for existing socio-spatial disparities and setting a threshold that reflects a context-specific, equitable level of accessibility.

Ferreira's (2023) work represents an important contribution by proposing an accessibility measure deeply anchored in the Capability Approach (CA), specifically designed to address the individual-level factors that constrain people's access to opportunities. His method innovatively integrates crucial personal constraints — primarily individual income levels and fare policies — into cumulative opportunity measures, thereby enabling a granular evaluation of accessibility poverty. By doing so, Lucas addresses a gap in accessibility literature, overcoming the bias of aggregated income statistics that typically conceal the real deprivation levels among vulnerable populations.

Building upon this conceptual foundation, this thesis expands the analytical scope beyond measuring accessibility constraints to developing a methodological framework explicitly aimed at formulating and evaluating equity-driven public transport interventions.

3.5.3 Land Use and Individual Data

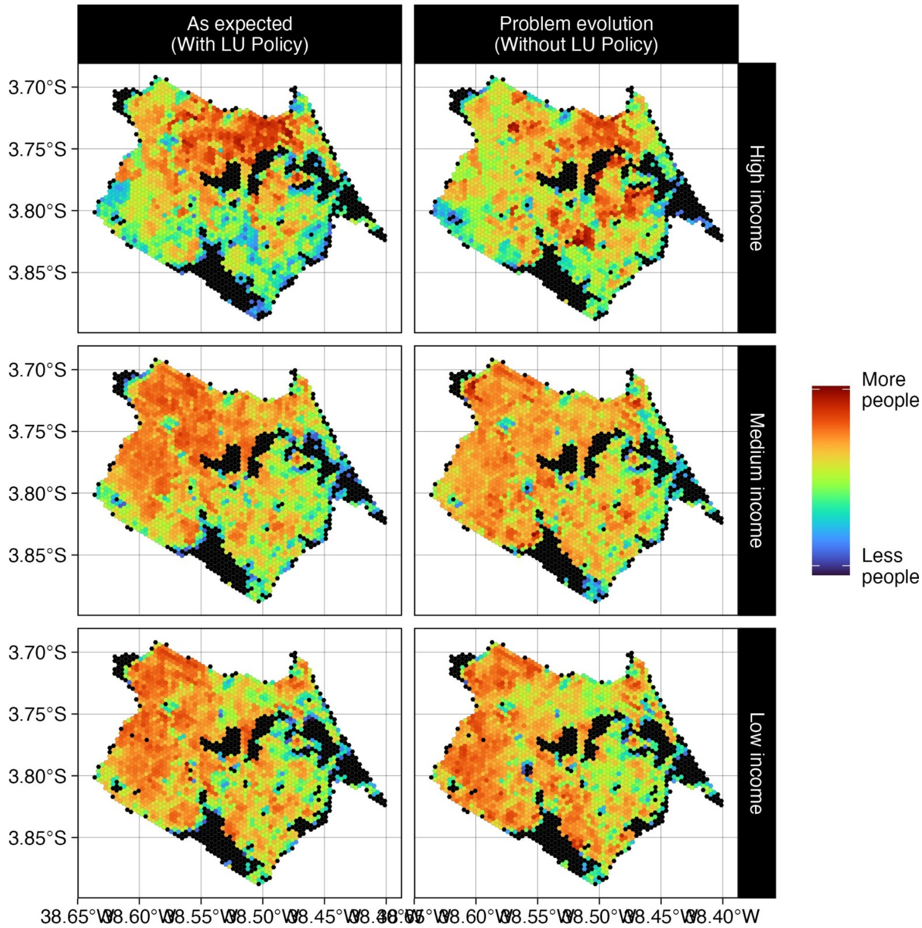
Jobs data and zoning information come from on the Access to Opportunities Project (Pereira *et al.*, 2022), growth rate for land use comes from Sousa (2019), and individuals' information on zone of residence, class of occupation (formal job), age, income, and gender comes from Ferreira (2023). The AOP methodology divides cities into a hexagonal grid, where each hexagon spans an area of 0.11 km², *i.e.* each side of the hexagons is 205 meters long. The jobs are characterized by high-, medium- and low-complexity employment opportunities, for each income level.

The future land use was modeled using a growth factor estimated from Sousa (2019), capturing urban expansion trends over a 15-year horizon (2000-2015). A growth factor was estimated for population across each zone and income class (high, medium, and low), as well as for jobs in each zone.

Two scenarios were considered. The expected scenario assumes that residential patterns have recentralized, with populations shifting closer to the city center, while jobs have decentralized, leading to a more spatially balanced employment distribution. This scenario reflects the impact of a strategic-level land use intervention (Chapter 2) aimed at improving overall accessibility.

The problem evolution scenario assumes that no land use policy is implemented, resulting in further exacerbation of urban sprawl. In this case, both residential decentralization and employment centralization continue, intensifying the spatial mismatch between low-income residential areas and job opportunities, further challenging accessibility.

Figure 19 – Land use distribution for the individuals.



Source: Prepared by the author.

Figure 19 (Land use distribution for the individuals) shows the population distribution of different income groups (high, medium, and low income) under two land use scenarios: “As expected” (with land use policy intervention) and “Problem evolution” (without land use policy intervention).

In the As Expected scenario, the high-income population remains mostly centralized. The medium-income an low income populations have more similar patterns, concentrated around the urban center and along and intermediate zones.

In the Problem Evolution scenario, without land use intervention, high-income individuals spread out more, increasing suburbanization. The medium-income population disperses further away from the city center, making commutes longer. The low-income population is pushed even farther into peripheral areas, increasing spatial inequalities and further isolating vulnerable groups from job opportunities and essential services.

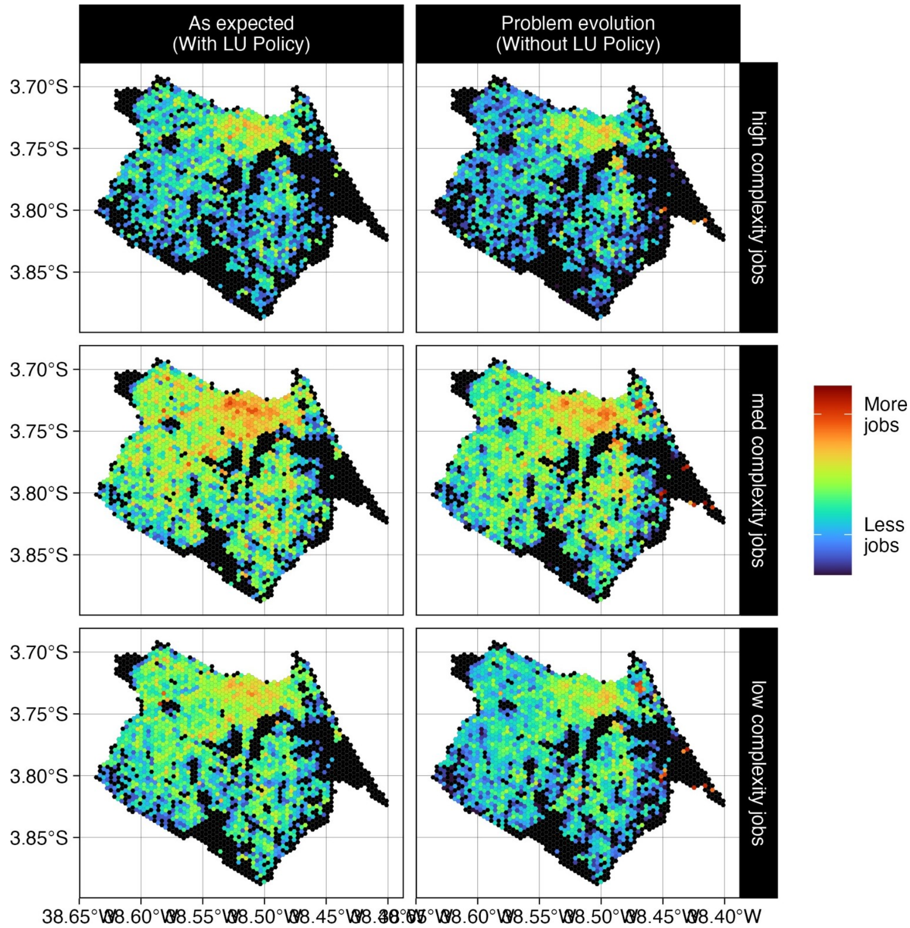
The vulnerability dummy (v_i) is used to identify individuals from economically disadvantaged households, assigned a value of 1 for those residing in households with a total income below three minimum wages, and 0 otherwise. This threshold follows the approach used by Sousa (2019) to define low-income groups, ensuring consistency with previous research used in the diagnosis of the problem. Also, household income is a more suitable measure than individual income because transportation expenses are commonly shared within families.

Figure 20 (Land use distribution for the jobs positions) shows the spatial distribution of jobs across different job complexity levels (high, medium, and low complexity jobs) under two land use scenarios: “As expected” (with land use policy intervention) and “Problem evolution” (without land use policy intervention).

In the As Expected scenario, high-complexity jobs are more evenly distributed across the city, with some decentralization from employment hubs. Medium-complexity jobs remain concentrated in key corridors, particularly in northern and central areas, while low-complexity jobs are less concentrated in the city

In the Problem Evolution scenario, without land use policy intervention, high-complexity jobs remain highly centralized. Medium-complexity jobs show a similar pattern, with high concentrations in established employment zones but little expansion into new areas at the east portion of the city. Low-complexity jobs are also mostly restricted to existing employment hubs, with fewer opportunities in peripheral areas.

Figure 20 – Land use distribution for the jobs positions.



Source: Prepared by the author.

3.5.4 Public Transport Data Manipulation

Among the supply models in the technical field, General Transit Feed Specification (GTFS) stands out due to its ease of use, widespread adoption by transit agencies and major open routing platforms, and for explicitly detailing each trip, enhancing the accuracy of transit operations representation (Nuzzolo *et al.*, 2001). GTFS data granularity enables analyses of how different routes and trips cater to diverse demographic groups, aiding in the identification, characterization, and diagnosis of mobility and accessibility issues (Hamdouch *et al.*, 2014).

The General Transit Feed Specification, created by Google in 2005, is an open standard maintained by MobilityData (NGO) with the purpose of addressing the lack of standardization in public transportation programming. It consists of 6-to-21 txt files with comma-separated values that describe stops, trips, routes, geographic and fare, among other information. GTFS tables use relational id's to uniquely describe schedule programming and enable public transport operators to release their transit data in formats usable in many software applications (Mesquita, 2023; Google, 2023).

The use of GTFS can improve the planning, maintenance, operations, and management of public transportation systems, as well as facilitate coordination and interoperability with transportation providers and public safety organizations. It has been widely adopted due to its public and open-source nature, as well as its rapid acceptance by developers and transportation software (Mesquita, 2023).

While GTFS has become the standard for transit data sharing and has proven valuable for various applications (Prommaharaj *et al.*, 2020; Wessel *et al.*, 2017), there remains a significant gap in comprehensive, unified, open-source, user-friendly platforms to analyze and manipulate these files.

Although computational tools exist, they often require users to write custom scripts and use multiple solutions, which adds complexity, involves interoperability, and demands experience with several tools. Available applications focus on specific features, such as data loading (Herszenhut *et al.*, 2024a), data exploration and filtering (Poletti *et al.*, 2024; Herszenhut *et al.*, 2024b;), or route planning and isochrones analysis (Vágner, 2021; Pereira *et al.*, 2021b; Branigan, 2014; Poletti *et al.*, 2024), rather than providing a unified framework for extracting multiple service metrics and manipulating transit supply attributes at trip and stop level. This presents a noteworthy barrier to the extensive use of GTFS data on leveraging transit planning.

To fill this gap for this doctoral research, Quesado Filho e Guimarães (2024) published GTFSwizard, a set of functions for exploring and manipulating General Transit Feed Specification files in R language. Its main purpose is to provide researchers and practitioners with a seamless and easy way to explore and simulate changes within a GTFS file. The package allows users to filter data, generate spatial visualizations, and perform detailed analyses and manipulation, including generating travel time matrices.

These functions (Quesado Filho; Guimarães, 2024) facilitate the analysis, simulation, and evaluation of public transportation systems. They assist the replication of real-world transit interventions, enabling researchers, planners, and policymakers to test and refine system modifications in a controlled and efficient manner.

The applications for the experiment in this chapter are outlined below.

• Bus Rapid Transit (BRT) and Exclusive Lanes: BRT systems often rely on exclusive corridors to reduce travel times and enhance reliability. Using edit_speed(), users can represent changes towards smaller travel times on these corridors by adjusting travel speeds. In addition, edit_dwelltime() allows the representation of optimized boarding and alighting processes, reflecting reduced dwell times at stations due to level boarding, pre-payment mechanisms, or increased operational efficiency;

• Frequency Modifications: Frequency adjustments are among the most common transit interventions. By using filter_trip() to select trips to be doubled, delay_trip() to change its first departure_time, and merge_gtfs() to add them to the original GTFS, users can represent increased frequencies, reflecting higher service levels. Conversely, filter_trip can be used to reduce service frequencies, allowing for the evaluation of cost-saving measures or temporary schedule adjustments;

• Route Segmentation and Partial Adjustments: With split_trip(), on can divide existing routes into smaller segments, enabling partial route adjustments. This is particularly relevant in studies assessing the feasibility of feeder services, route rationalization, or service redundancy elimination;

• Express Services: Transit stops significantly influence travel times, operating costs, and network coverage. Using edit_dwell() and filter_stop() can subtract dwell times from total trip durations and remove unused stops, representing the introduction of express services.

The GTFS data used in this study are from Braga *et al.* (2022), which includes feeds for the baseline scenario for regular bus and metro, and future scenario for metro. These feeds are combined to form the public transport network across different scenarios.

3.5.5 Travel Time Estimates

The travel time estimates obtained in this work is based on the shortest-path algorithm used in the R5R tool, an open-source software developed for detailed multimodal transport network modeling on a large spatial and temporal scale (Pereira *et al.*, 2021b). It integrates road network and pedestrian infrastructure data from OpenStreetMap with public transport network information in GTFS format to construct a graph representation of the transport system.

R5R provides precise travel-time calculations for door-to-door journeys, accounting for walking duration to access public transport stops, waiting times, actual travel times including transfers, and walking distances to the final destination. Moreover, it considers trip timings and the impact of temporal variations in public transport service availability on travel-time estimations (Pereira *et al.*, 2021b).

The R5R simulations were based on a travel scenario where trips are initiated between 06:00:00 and 08:00:00 a.m., with a maximum duration of 120 minutes. The date for the simulation is a typical weekday, and the model performs one simulation draw per minute. It uses the 50th percentile for travel time estimates, and a maximum walking time of 15 minutes is considered for both accessing and egressing the transit system.

3.5.6 Search Algorithm

While programming algorithms are powerful for solving optimization problems with linear or quasi-linear constraints, the solution for other complex problems with non-linear relationships are, sometimes, too big[5] and not always straight-forward. Machine learning techniques, on the other hand, offer more flexibility and adaptability for optimizing these type of problems. They can handle diverse variables types (categorical, continuous, and ordinal, for instance), without requiring strict assumptions about its distribution, allowing for more accurate modeling (Charypar; Nagel, 2005; Roorda *et al.*, 2006).

Furthermore, machine learning models are robust in the presence of outliers and missing data. In transportation planning, where data may be uncertain or limited, Genetic Algorithm (GA), a particular class of machine learning algorithms, can provide more reliable results compared to other algorithms, as they are less likely to "get stuck" in local optima (Koushik *et al.*, 2020).

Genetic Algorithm is an optimization technique inspired by the process of natural selection and genetics. In the field of urban mobility planning, it is useful for route planning, traffic signal optimization, and public transportation scheduling (Roorda *et al.*, 2006; Charypar; Nagel, 2005). It's routine is as follows:

1. Initialization: The process starts by creating an initial population of potential solutions to the optimization problem.
2. Evaluation: Each solution in the population is evaluated based on a fitness function that quantifies how well it performs in achieving the optimization objectives.
3. Selection: Solutions with higher fitness values are more likely to be selected for the next generation. This mimics the concept of "survival of the fittest" in natural selection. Various selection techniques such as roulette wheel selection or tournament selection

5 Transportation planning problems often involve complex interactions and dependencies between different variables, where the size of solutions space to find optimal or near-optimal solutions can be vast (Charypar; Nagel, 2005).

can be used.

4. Crossover: Selected solutions are combined through crossover operations to create new offspring solutions.
5. Mutation: To introduce diversity and prevent premature convergence to suboptimal solutions, random changes are applied to some of the offspring solutions. This mutation process helps explore new regions of the solution space.
6. Replacement: The new offspring solutions replace some of the existing solutions in the population based on their fitness values. This ensures that the population evolves towards better solutions over generations.
7. Termination: The algorithm iterates through these steps for a predefined number of generations or until a termination condition is met, such as reaching a satisfactory solution or running out of computational resources.

By iteratively applying selection, crossover, mutation, and replacement operations, Genetic Algorithm explore the solution space efficiently and converge towards optimal or near-optimal solutions for complex optimization problems in urban mobility planning. GA offers the advantage of handling non-linear relationships, exploring a wide range of solutions simultaneously with parallel processing, and adapting to changing conditions, making them well-suited for addressing the challenges in urban mobility optimization (Scrucca, 2013; Koushik *et al.*, 2020).

To solve both the optimization problems described in subsection 3.5.1 Validation Method, the GA package (Scrucca, 2013; Scrucca, 2017) was used with a mutation probability of 25% and crossover probability of 80%. The population had 100 individuals (each individual is a different GTFS) that run for 15,000 generations before stop.

3.6 Equitable Public Transport Interventions in Fortaleza

This section details the operational characteristics of the optimal solution derived from the proposed formulation. Both optimization problems yielded highly similar results, focusing in fare elimination for vulnerable individuals, service reductions due revenue reduction, and transit prioritization strategies, effectively addressing accessibility inequalities while maintaining financial feasibility.

As discussed in *subsection 3.4.2 Decision Variables*, this research considers both costs and revenues as decision variables, allowing the optimization model to balance transit supply and fare levels. The optimal solution set the fare expenditure factor to R$ 0,00 for all low-income individuals, effectively implementing a fare exemption policy for this group.

This outcome underscores the importance of integrating the Capability Approach into both the accessibility indicator and the optimization problem. However, the inclusion of a 25% public subsidy was insufficient to fully offset fare costs, necessitating a 37% reduction in transit supply to compensate for an expected revenue loss of approximately 62%.

Also, To improve service reliability and operational efficiency, the optimization process identified the need for a network of transit corridors, adding up 278 km[6] of dedicated transit infrastructure. This intervention ensures that a greater share of trips occurs within prioritized infrastructure, with an estimated 7.9% increase in the transit trips operating speeds within dedicated lanes (Brito Filho, 2021).

The spatial distribution of these corridors is illustrated in Figure 21 (Transit Priority Corridors).

Figure 21 – Transit Priority Corridors

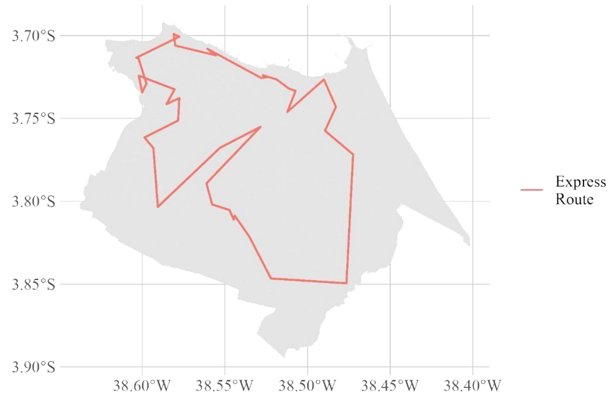
Source: Prepared by the author.

A new express bus service was introduced as part of the optimization solution. This service consists of a circular route covering 47.4 km with 29 located stops. Operating with a headway of 5 minutes, the service has an expected total duration of 3 hours and 10 minutes, with an average speed of 15 km/h. This intervention aims to provide a direct, high-speed alternative for long-distance commuters, particularly benefiting peripheral areas with poor connectivity to major employment centers.

6 Although 278 km of transit corridors might seem a big number, Fortaleza municipality announced the same amount of investiment within the PASFOR plan.

The express route configuration is presented in Figure 22 (Transit Express Service).

Figure 22 – Transit Express Service

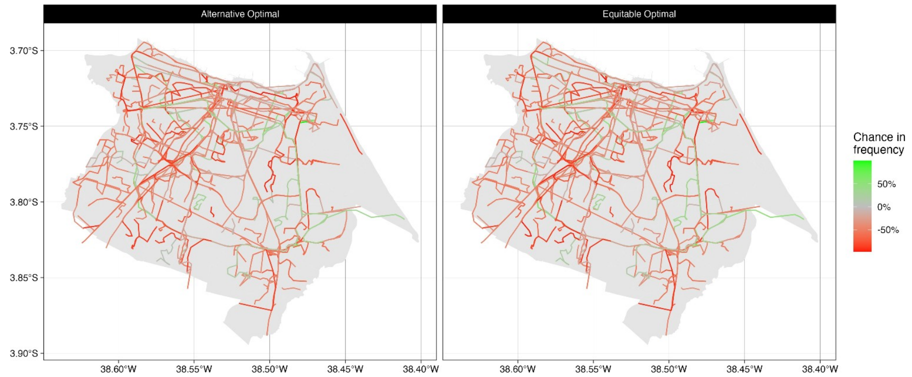


Source: Prepared by the author.

Given the necessity of reducing overall transit supply due to revenue constraints, service frequency adjustments were a key component of the optimal solution. As expected, the optimization process led to widespread frequency reductions across the network. However, these reductions were distributed relatively evenly across the service area, minimizing localized accessibility losses.

The spatial pattern of frequency reductions is depicted in Figure 23 (Spatial distribution of changes in frequency for bus routes).

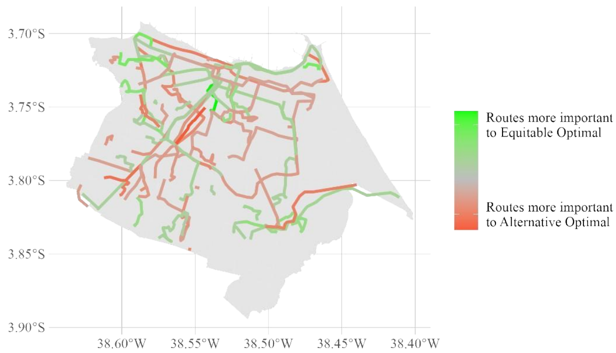
Figure 23 – Spatial distribution of changes in frequency for bus routes.



Source: Prepared by the author.

Additionally, when comparing the two optimization scenarios (Figure 24 - Differences in route priorization), it is evident that each prioritizes specific routes differently. This variation suggests potential avenues for further investigation into how different prioritization strategies impact overall accessibility outcomes.

Figure 24 – Differences in route priorization.



Source: Prepared by the author.

3.6.1 Scenarios Performance

The different land use and transit intervention scenarios impact accessibility analysis focuses on the proportion of individuals in a problem situation, measuring the effectiveness of each scenario in reducing accessibility deprivation. As a reference benchmark for this analysis, the baseline scenario had a weighted proportion of 83.2% of vulnerable individuals below critical accessibility levels. Additionally, the enforcement of equity constraints is assessed to determine whether interventions successfully protect the worst-off and prevent further disparities.

The Problem Evolution scenario exhibits the highest proportion of vulnerable individuals below the critical accessibility level, with 90% of the weighted vulnerable population in a problem situation. Compared to the baseline scenario, where 83.2% of vulnerable individuals experience accessibility deprivation, this represents a further deterioration, reinforcing transport disadvantages for low-income populations.

Table 2 – Scenarios Performance.

Scenario	Problem Magnitude	Restriction 1	Restriction 2
Problem Evolution	90.0%	81.1%	13.9%
Do Nothing (Bus)	81.1%	29.8%	0.4%
Equitable Optimal	14.3%	0.0%	0.0%
Alternative Optimal	15.7%	5.6%	1.3%

Source: Prepared by the author.
Problem magnitude: proportion of low-income individuals below critical accessibility levels.
Restriction 1: proportion of individuals that are in problem situation and that have accessibility worsen.
Restriction 2: proportion of individuals that are pushed below the critical threshold.

The Do Nothing (Bus) scenario, in which a land use policy is implemented but no transit intervention is applied beyond a rail expansion, reduces the problem magnitude to 81.1%. This indicates that land use changes alone provide moderate accessibility improvements, preventing further deterioration but failing to produce meaningful reductions in transport deprivation. Although this scenario performs better than Problem Evolution, it still leaves a high proportion of vulnerable individuals below the critical accessibility threshold.

A substantial reduction in accessibility problems is observed in the Equitable Optimal and Alternative Optimal scenarios, where the problem indicator drops to 14.3% and 15.8%, respectively. These results highlight that integrated transit and land use interventions - explicitly designed to improve accessibility for vulnerable populations, as done in chapter 2 Strategic and Tactical Choice of Public Transport Interventions - are highly effective in mitigating accessibility deprivation. While the difference between these two optimized scenarios appears small, it still represents a 10% relative improvement, reinforcing the benefits of strictly enforcing egalitarian constraints to further minimize accessibility disparities.

The effectiveness of these interventions is also reflected in the enforcement of egalitarian justice constraints, which ensure that accessibility for individuals in a problem situation does not worsen (Restriction 1) and that no individual is pushed below the critical threshold (Restriction 2). In the Problem Evolution scenario, these constraints are frequently violated, with 24.6% of individuals breaking the first restriction and 13.9% breaking the second.

In the Do Nothing scenario, constraint violations decrease significantly, with 9.1% of individuals violating the first restriction and 0.4% violating the second. This suggests that land use policies provide some level of accessibility protection, but a small subset of the population still experiences worsening accessibility conditions, likely due to localized shifts in transit availability and employment distribution.

The Equitable Optimal scenario strictly adheres to the equity constraints, with 0% violations for both restrictions. This confirms that the optimization process successfully protects the worst-off, ensuring that no vulnerable individual experiences a decline in accessibility. The Alternative Optimal scenario performs similarly, with 1.7% of individuals violating the first restriction and 1.34% violating the second.

3.6.2 Distributional Effect

The Table 3 (Scenarios' distributional effects) presents the distribution of accessibility across different population segments under each scenario, focusing on the better-off group (top 10% in accessibility), the worse-off group (bottom 40% in accessibility), and the Palma ratio. The results illustrate how different transport and land use policies impact the distribution of accessibility opportunities, highlighting the extent to which interventions promote equity or reinforce disparities.

Table 3 – Scenarios' distributional effects.

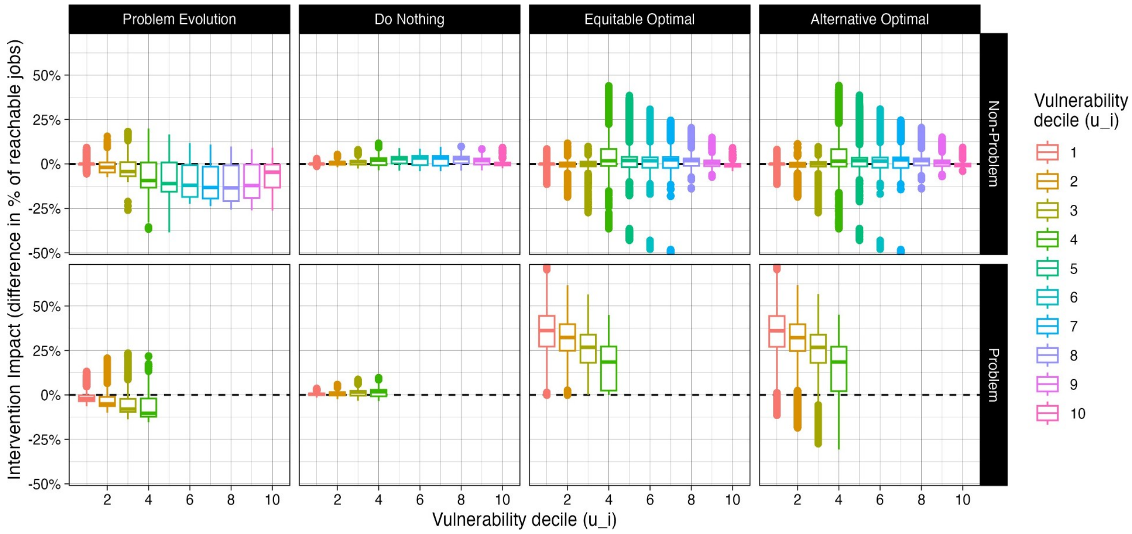
Scenario	10% Better-off	40% Worse-off	Palma Ratio
Problem Evolution	63.4%	14.7%	4.31
Do Nothing	70.7%	20.2%	3.50
Equitable Optimal	69.9%	42.4%	1.65
Alternative Optimal	70.0%	42.0%	1.67

Source: Prepared by the author.

The Problem Evolution scenario exhibits the highest level of inequality, with the better-off group having access to 63.4% of potential job opportunities, while the worse-off group can only reach 14.7%. This results in a Palma ratio of 4.31, indicating that the better-off group has access to over four times more jobs than the worse-off group. This scenario reflects uncontrolled urban expansion without corrective policies, leading to severe accessibility disparities where low-income individuals in peripheral areas remain spatially isolated from economic opportunities.

In the Do Nothing scenario, where land use policies are implemented but no transit interventions are introduced beyond a rail expansion, the better-off group's accessibility increases to 70.7%, while the worse-off group's accessibility to 20.2%. The Palma ratio decreases to 3.50, indicating a moderate reduction in inequality. This suggests that land use policies alone provide some improvement in accessibility for disadvantaged populations, particularly by bringing jobs and housing into closer proximity. However, the high Palma ratio shows that accessibility remains skewed in favor of individuals who already have better access, highlighting the limited impact of land use policies without transit optimization.

Figure 25 – Distributional impacts.



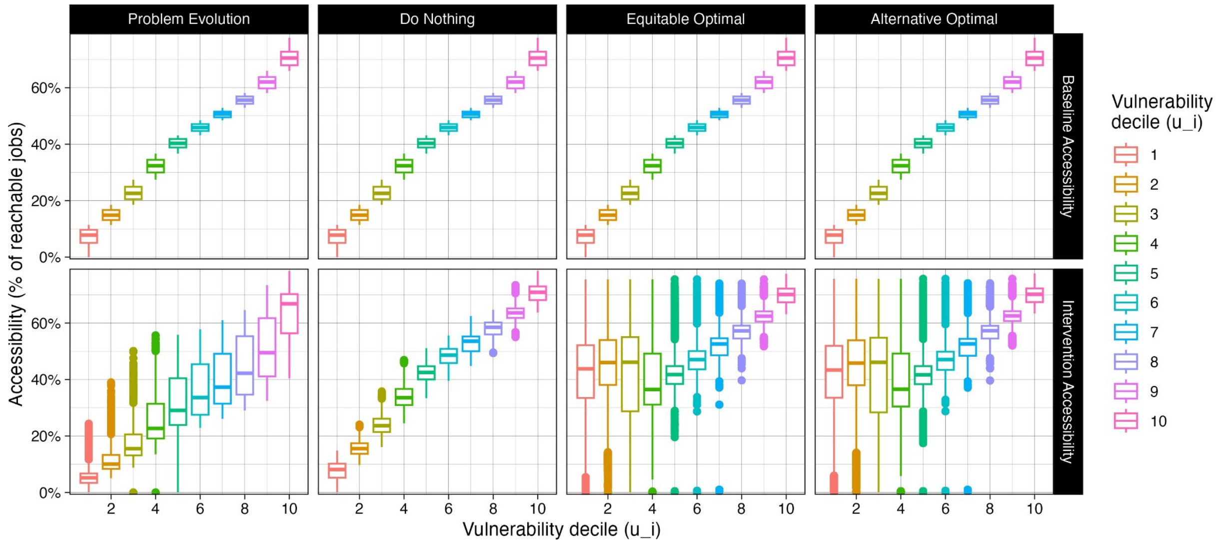
Source: Prepared by the author.

A substantial shift occurs in the Equitable Optimal scenario, where the worse-off group's accessibility increases significantly to 42.4%, meaning that individuals in the bottom 40% can now reach a much larger share of job opportunities. Meanwhile, the better-off group's accessibility increases to 69.9%, bringing the Palma ratio down to 1.65. This demonstrates that the equity-driven optimization successfully reduces accessibility inequality, ensuring that the worst-off individuals experience the greatest improvements in access to employment. By prioritizing the redistribution of transit supply and financial resources toward vulnerable populations, this scenario aligns with Rawlsian justice principles, ensuring that accessibility benefits first reach those in the most disadvantaged positions.

The Alternative Optimal scenario shows similar improvements, with the worse-off group reaching 42.0% of jobs, while the better-off group reaches 70.0%. The Palma ratio remains low at 1.67, indicating that this scenario also improves accessibility for disadvantaged populations, though slightly less than the Equitable Optimal scenario. The marginal difference suggests that both optimization strategies effectively promote accessibility equity, but the Equitable Optimal scenario provides a slightly more balanced distribution of accessibility opportunities.

The boxplot provides a granular perspective on the distribution of accessibility impacts across different vulnerability (u_i) deciles, distinguishing between problem and non-problem individuals under each scenario. This visualization complements the previous analysis by highlighting how accessibility changes are distributed within different vulnerability groups.

Figure 26 – Baseline accessibility *versus* scenario accessibility.



Source: Prepared by the author.

In the Problem Evolution scenario, accessibility impacts are relatively evenly distributed across deciles, but with most of impacts being negative among all individuals. This confirms that, without intervention, overall accessibility is likely to reduce. The Do Nothing scenario exhibits small improvements in accessibility impacts, with most changes hovering below 10% on accessibility gains.

In contrast, the Equitable Optimal and the Alternative Optimal scenario show strong positive impacts for the most vulnerable deciles, particularly for individuals previously in a problem situation. These groups experience significant accessibility gains, confirming that the equity-driven optimization effectively targets improvements toward the worst-off. The Alternative Optimal, however, still shows a few localized negative impacts for vulnerable individuals.

This plot provides a complementary view by illustrating the absolute accessibility levels across vulnerability (u_i) deciles before and after each intervention. In the Problem Evolution and Do Nothing scenario, accessibility remains highly unequal, with the most vulnerable individuals having fewer reachable jobs than those in higher deciles. The post-intervention distribution largely mirrors the baseline, confirming that without corrective policies, disparities persist, and the most disadvantaged groups remain isolated.

A redistribution occurs in the Equitable Optimal and the Alternative Optimal scenario, where accessibility gains are concentrated among the lowest deciles. The post-intervention distribution is much more balanced, reducing the gap between vulnerable and privileged groups.

Overall, this distributive analysis confirms that equity-driven interventions lead to substantial reductions in accessibility disparities, ensuring that vulnerable populations experience meaningful improvements. It also highlights that while land use interventions alone offer limited benefits, combining them with targeted transit interventions creates a more equitable accessibility distribution, reinforcing the effectiveness of justice-oriented transport planning.

3.7 Conclusion

This research has developed and validated a framework for formulating public transport interventions based on equity principles, integrating Rawls' Egalitarianism and Sen's Capability Approach. The proposed methodology demonstrates that transit interventions can be systematically designed to prioritize vulnerable populations, ensuring that those in the most disadvantaged accessibility conditions benefit first, and are protected against accessibility reduction.

The results confirm that without targeted interventions, accessibility disparities persist or worsen. The Problem Evolution and Do Nothing scenarios illustrate how existing spatial and socioeconomic inequalities reinforce transport disadvantages for low-income populations. Land use policies alone, while moderately beneficial, fail to reduce accessibility deprivation, highlighting the necessity of integrated transit policies.

Conversely, the Equitable Optimal and Alternative Optimal scenarios demonstrate that redistributing transit accessibility toward the worst-off significantly improves equity outcomes. These interventions successfully reduce the proportion of individuals in critical accessibility situations, lower the Palma ratio, and ensure a more balanced distribution of job accessibility across social groups. The strict enforcement of egalitarian constraints in the Equitable Optimal scenario results in the most equitable distribution.

A key methodological novelty of this research is the treatment of both transit supply and fare levels as decision variables. This allows for solutions where reduced service supply compensates for lower fares, making transit more affordable while maintaining a functional network.

This research also indicates that the optimization problem becomes computationally solvable by simplifying decision variables based on a diagnostic phase and strategic-level evaluations, ensuring that only the most impactful modifications are considered. It also suggest that an equitable transport system does not necessarily require maximizing service provision but rather a careful redistribution of resources to benefit the most vulnerable.

Despite these contributions, certain limitations must be acknowledged. The proposed method, while designed to reflect individual constraints, does not fully account for behavioral responses to transit service changes or the dynamic interaction between land use and transport. Further investigations should explore how integrating behavioral modeling, bi-level optimization, and price elasticity of demand can enhance the robustness of equity-based transit planning.

Future research should explore the factors that make certain regions more or less susceptible to trip reductions. It is possible that these reductions are linked to the structure of the transit system itself, particularly in areas served by feeder routes that connect to major trunk lines. Regions that experience more reductions may be those where the trunk-feeder system is less efficient or where alternative routes offer sufficient coverage, allowing for a scaling back of service without greatly impacting accessibility. Additionally, the socio-demographic characteristics of the population may play a role. If the low-income population is concentrated in zones with lower density, they could be more likely to experience service cuts.

Other shortcoming is related to methodological propositions that don't contemplate private transport - such as cars and motorcycles. As advantaged groups are more likely to use these faster transport modes, inequality may be underrated. This perspective also calls for complementary policies that discourage car use (*e.g.* congestion/parking charge and fuel tax) in highly congested and polluted areas to mitigate the negative externalities imposed by drivers on everyone else, particularly on vulnerable populations.

4 INCORPORATING RESILIENCE IN THE *EX-ANTE* ASSESSMENT OF PUBLIC TRANSPORT INTERVENTIONS

Abstract

Resilience is a key principle in the accessibility-based transport planning paradigm, yet its incorporation into *ex-ante* assessments of public transport interventions remains underexplored. This study develops and applies a resilience evaluation framework to assess the stability of accessibility under multiple disruption scenarios. By modeling 729 scenarios, considering variations in urban development patterns, transport infrastructure, and fare policies, the study measures how individual accessibility fluctuates under stress conditions. Unlike traditional resilience studies that focus on network-wide performance, this research adopts an individual-level approach based on Sen's Capability Approach, ensuring that resilience is framed in terms of people's ability to access jobs despite disruptions. Findings reveal systematic inequalities in accessibility resilience, where more vulnerable individuals experience greater accessibility losses and higher variability across disruption scenarios. The results highlight that disruptions do not affect all users equally but instead reinforce pre-existing transport inequalities, leaving transit-dependent and economically disadvantaged populations more exposed to mobility instability. Policy implications include the need for equity-based resilience planning, enhanced redundancy in transit networks, and targeted interventions in high-vulnerability areas. The study contributes to advancing resilience assessments in transit planning, ensuring that future mobility systems are not only efficient but also equitable and robust in the face of uncertainty.

4.1 Introduction

Resilience, defined as the capability of a system to adapt to varying scenarios, is one of the principles of the integrated accessibility planning paradigm (Cavalcante, 2023). Identifying the most resilient alternative during the planning phase is crucial to ensuring that the promotion of accessibility within transport systems is maintained, despite instabilities.

That is important because the partial implementation of transportation projects tends to worsen inequalities compared to the full network plan (Freiberg, 2022). This issue is especially critical in some context that are marked by delays, interruptions, and prolonged construction gaps. Also, a lack of resilience in public transport networks leads to significant economic and operational losses.

The study by Cats e Jenelius (2016) found that even small reductions in capacity can result in disproportionately large economic impacts. For instance, a 75% capacity reduction on Stockholm's Metro Line 14 increased average travel time by 22%. The highest recorded economic loss was $177,000 per hour, equating to $1.40 per passenger.

The author also found that high-demand corridors suffered the greatest welfare losses, reaching 45%. The economic damage was exacerbated by increased crowding and denied boarding, leading to longer waiting times and reduced travel reliability. The lack of redundancy in certain metro segments led to economic losses 19% higher than those in more interconnected routes (Cats; Jenelius, 2016).

Furthermore, Kurth et al. (2020) evaluated the economic implications that arise from the lack of resilience in transportation networks in 10 U.S. cities and found out that it leads to GDP losses, increased transportation costs, and reduced economic efficiency. For example, a 5% road network failure in San Francisco caused a 51% increase in transportation costs, resulting in a 6.64% GDP decline. The economic impact varied across cities, with wealthier and more economically productive urban areas being more vulnerable to disruptions.

Although some results are expected, other are not so much. A counter-intuitive finding was that the bus network is most vulnerable during late-night off-peak hours, even more so than during rush hours. This is because at night the transit system operates at minimal frequency and coverage; if a disruption occurs, there are few or no alternative routes available, leading to large accessibility losses for any affected area (Zhang *et al.*, 2023).

Studies that seek to associate equity and resilience often do so from an environmental perspective (Arora *et al.*, 2025; Fiitzgibbons; Mitchell, 2021), an economic standpoint (Cats; Jenelius, 2016), through analyses focused on mobility (Cats; Jenelius, 2016; Kurth *et al.*, 2020), or exploratory plan reviews (Doost *et al.*, 2023; Cavalcante, 2023). Some research has also examined this relationship from an accessibility perspective (Zhang *et al.*, 2016), but typically in a spatially aggregated manner, without incorporating principles of justice or considerations of vulnerability.

Considering the discussion above, the research question addressed in this chapter is *"How to incorporate the resilience dimension of accessibility planning paradigm into ex-ante assessment of transit interventions?"* This is relevant because transport poverty can intensify social and economic inequalities, particularly affecting low-income segments of the population (Lucas *et al.*, 2016).

Therefore, **there is a methodological gap on incorporating the resilience dimension of accessibility planning paradigm into the ex-ante assessment of transit interventions.**

To provide an answer to this research question, the objective of this chapter is **to propose and validate a framework to evaluate the resilience of proposed interventions based on equity principles**.

4.2 Resilience in Urban Mobility

Resilience in transportation refers to the ability of mobility systems to withstand, absorb, and recover from disruptions, ensuring continuity of service and minimizing negative impacts on users and infrastructure. It is closely related to concepts such as reliability, robustness, vulnerability, and adaptability, each of which captures distinct facets of how transportation networks respond to external disturbances (Wan *et al.*, 2017).

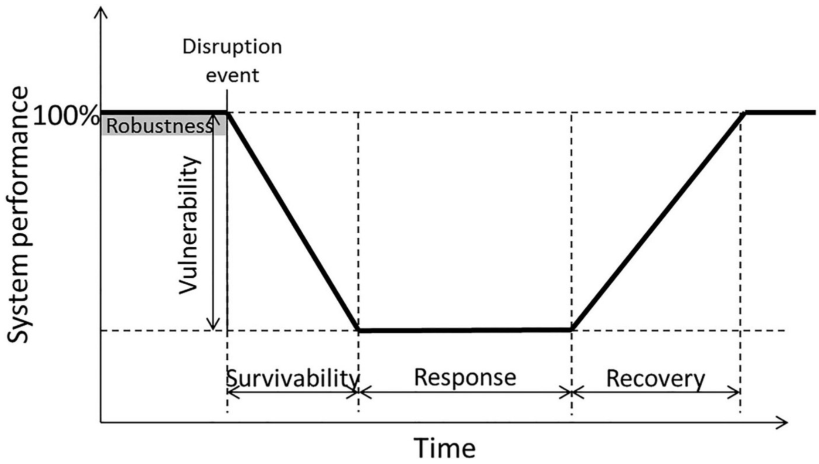
Resilience is often assessed through two primary perspectives: the ability to maintain functionality under disruptions and the time and resources required to restore performance levels after disruptions (Zhang *et al.*, 2016). It involves key components such as robustness, which determines how much of the system remains operational during a disruption, and redundancy, which ensures alternative routes and services to mitigate failures (Bešinović, 2020). Additionally, resourcefulness and rapidity influence how quickly and effectively the system can recover (Zhou *et al.*, 2019).

The concept of resilience has been applied in urban mobility studies, emphasizing the importance of integrating resilience into transport planning. The literature highlights that merely assessing the ability to recover after a failure is insufficient; rather, transport systems must be designed with proactive resilience strategies that enhance their capacity to adapt to climate change, economic shifts, and operational uncertainties (Bešinović, 2020).

Different methodological approaches have been proposed to measure resilience. Topological metrics analyze the structural characteristics of transport networks, often using graph theory to examine connectivity, redundancy, and network efficiency (Zhou *et al.*, 2019). However, these methods typically overlook real-world system dynamics and user behavior.

System-based metrics attempt to bridge this gap by incorporating operational characteristics, such as the number of disrupted trips, delays, and passenger rerouting strategies. Simulation and optimization models further enhance resilience assessment by evaluating multidisruption scenarios, optimal recovery strategies, and the economic costs of disruptions (Bešinović, 2020).

Figure 27 – Resilience cycle.



Source: Bešinovic´ (2020).

The resilience cycle includes vulnerability, survivability, response, and recovery, along with mitigation and preparedness. Vulnerability measures how much performance remains during a disruption, while robustness refers to handling minor delays. Response involves immediate actions to maintain service and safety, whereas survivability describes how the system transitions into disruption. Recovery restores normal operations, ranging from hours to weeks depending on severity. Some disruptions, like earthquakes, eliminate survivability, while minor ones, like power outages, may lead to direct recovery. Mitigation strengthens infrastructure, while preparedness involves planning for disruptions when mitigation is too costly (Bešinović́, 2020). This idea is presented in Figure 27 (Resilience cycle).

The concept of resilience encompasses the ability of the public, private, and civic sectors to face interruptions, deal with disruptions, act effectively during crises, adapt to changes, and evolve over time. The main aspect of building resilience is ensuring that the transport system can withstand stresses, avoid failures, adapt to disruptive circumstances, and involve both governmental and private entities. In the context of public transport, resilience is essential to maintain urban mobility continuity, as the system can be affected by variables that compromise the availability and efficiency of services (Liu *et al.*, 2025).

4.3 Evaluating Resilience in Transportation

Resilience in transportation is assessed through various methodological approaches, each with distinct strengths and limitations. These approaches generally fall into five categories: topological metrics, system-based metrics, simulation-based models, optimization techniques, and data-driven methods (Zhou *et al.*, 2019). Each of these methodologies contributes to a more comprehensive understanding of how transportation systems respond to disruptions and recover from them.

Topological metrics evaluate network resilience by analyzing structural characteristics through graph-based models. These methods assume the failure of a single component (*e.g.*, a link or node) in the network while neglecting dynamic system responses (Cats, 2015). They require minimal data and enable quick comparisons of different network structures, making them useful for identifying critical vulnerabilities in network design. However, these approaches fail to account for real-time system dynamics, such as passenger rerouting, congestion spillovers, and operator interventions.

System-based metrics assess disruption duration, the number of affected trains and passengers, and the system's recovery trajectory. This approach provides a more realistic evaluation of resilience, capturing both supply-side service disruptions (*e.g.*, train cancellations, delays) and demand-side impacts (*e.g.*, passenger displacement and extended travel times). Recent research increasingly focuses on how resilience assessments should account for passenger inconvenience, freight disruptions, and broader socioeconomic effects (Kurth *et al.*, 2020).

Simulation-based approaches improve upon topological methods by modeling transport services and passenger behavior during disruptions. These models allow researchers to evaluate how passengers adapt their routes and how operators respond to crises. However, due to high computational complexity, they are impractical for large-scale resilience assessments that require analyzing all possible disruption scenarios. Instead, simulations are often used for detailed analyses of specific, high-risk disruption cases (Bešinović, 2020).

Optimization approaches overcome both the static limitations of topological methods and the computational challenges of simulations by identifying extreme disruption scenarios and assessing optimal recovery strategies. These techniques have been widely applied to assess multiple simultaneous disruptions, optimize substitute services, and analyze passenger behavior under stress. Real-time passenger information systems, for example, are increasingly integrated into optimization models to mitigate congestion and improve system responsiveness (Wan *et al.*, 2017).

Data-driven approaches provide an alternative by leveraging real-world operational data to assess resilience without explicit modeling. These methods use indicators such as passenger ridership, vehicle kilometers, and station-level turnstile counts to evaluate resilience based on observed system performance. However, they depend on the availability of high-quality historical data, making them primarily suitable for ex-post resilience evaluations rather than predictive analyses (Bešinović, 2020).

4.4 Resilience Indicators

There are several resilience indicators in the literature, each capturing different aspects of a transportation system's ability to withstand and recover from disruptions.

Network Robustness measures a network's capacity to resist or absorb disruptions while maintaining service. It is typically quantified by the remaining connectivity or capacity during a disturbance. For example, robustness may be assessed as the proportion of network links or nodes that remain functional after an event or the percentage of origin-destination pairs that can still reach each other despite a disruption (Zhou *et al.*, 2019).

A robust transport network exhibits only a slight drop in performance, such as a minimal increase in travel times or small connectivity losses when a disruption occurs. In graph theory terms, robustness is high when the network retains a large connected component and short alternative paths despite failures (Zhou *et al.*, 2019).

Conversely, a non-robust (fragile) system experiences a sharp decline in performance even from minor incidents. Robustness is closely tied to redundancy, which ensures multiple pathways exist to serve demand. Robustness metrics are often complemented by vulnerability analyses, which identify weak points that, if disrupted, could lead to disproportionate network failures (Zhou *et al.*, 2019).

Recovery Time is a temporal indicator that quantifies how quickly a transportation system restores normal operations after a disruption. It can be measured at the network level - such as the time taken for average travel speeds or ridership to return to pre-disruption levels - or at the component level, reflecting the time required to repair infrastructure such as bridges or stations (Bešinović, 2020).

A shorter recovery time indicates a more resilient system, as it reduces the duration of disruptions experienced by users. Related metrics include rapidity, which measures the speed of recovery (*e.g.*, the percentage of functionality restored per day), and downtime, which represents the inverse of uptime (Zhou *et al.*, 2019).

Recovery assessments often require assumptions about response efficiency and resource availability. For instance, if two cities experience the same transit service disruption due to flooding, but City A restores full service in 24 hours while City B takes a week, City A demonstrates greater resilience in terms of recovery (Arora *et al.*, 2025).

Passenger Impact measures how disruptions affect travelers directly, in terms of delays, inconvenience, or safety risks. One basic measure is the number of affected passengers or trips. For example, a transit strike that disrupts 500,000 daily trips has a much greater impact than one affecting only 50,000 trips (Bešinović, 2020).

Another key metric is the additional travel time or cost incurred by passengers due to a disruption, often expressed as vehicle hours lost or extra minutes per passenger. In road networks, impacts are also measured by queue sizes or traffic delays. Beyond quantitative metrics, qualitative impacts — such as reduced reliability or increased discomfort — are harder to measure but significantly affect user experience (Kurth *et al.*, 2020).

A resilient transit system minimizes passenger impacts, ensuring that even when disruptions occur, delays are short and inconvenience is limited. If a single train failure triggers citywide gridlock and hours-long commutes, the passenger impact is severe, highlighting low resilience. Analysts often compute aggregate impact metrics, such as total user welfare loss or lost ridership days, to quantify the economic and social costs of disruptions (Cats; Jenelius, 2016).

By analyzing passenger impact, transportation agencies can prioritize resilience investments that maximize public benefit. For instance, enhancing real-time passenger information systems does not prevent disruptions but can significantly reduce their impact by helping passengers reroute effectively (Cats, 2015).

It is important to recognize that these resilience indicators are interrelated. Robustness and redundancy help mitigate initial accessibility losses and passenger impacts, while fast recovery processes minimize the duration of those losses. A comprehensive resilience assessment should integrate multiple metrics to provide a complete picture.

Such multi-dimensional analysis allows planners to determine whether the main resilience weakness lies in the immediate impact of a disruption or in the speed of system recovery. Additionally, evaluating how disruptions disproportionately affect certain user groups is critical for ensuring equitable resilience planning (Zhang *et al.*, 2023).

Traditional resilience metrics often focus on aggregate network performance, but recent approaches emphasize individual-level outcomes to incorporate equity considerations. This thesis adopts a human-centered perspective, defining resilience as the ability of individuals to maintain accessibility under different disruption scenarios.

In practice, this means evaluating the effects of disruptions on individual users, neighborhoods, or social groups, rather than relying solely on network-wide averages. The

Capability Approach, as developed by Sen, provides a strong theoretical foundation for this, asserting that resilience should be measured not only by infrastructure performance but also by people's ability to access essential services like jobs, education, and healthcare (Ferreira, 2023).

4.5 Method for Incorporating Resilience in the *Ex-Ante* Assessment

This chapter extends the analysis by incorporating resilience as a key dimension of transport evaluation. While previous assessments focused on the intended (planned) effects of interventions, this chapter examines how well accessibility is preserved under multiple simultaneous disruptions

Unlike most traditional resilience assessments, which focus on network-level performance, this study measures accessibility at the individual level. This capability-based approach ensures that resilience is evaluated not as a property of the transport system itself, but in terms of whether individuals can still reach opportunities and maintain their accessibility levels despite disruptions. The data sources and the accessibility formulation are described in Chapter 3.

4.5.1 Scenario Generation: Modeling Uncertainty

To assess resilience, we model 729 distinct scenarios reflecting potential changes in urban development, transport infrastructure, and fare policies. These scenarios allow for a structured *ex-ante* evaluation of whether the proposed intervention can withstand different forms of system stress.

The six dimensions of variation, each with three possible states, are describe as follows. The signal *(expected)* is used to identify the conditions in which the intervention was planned for.

1. Residence Distribution:
   - Urban sprawl increase: Residential expansion increases commuting distances.
   - Unchanged: The current residence distribution remains stable.
   - Urban sprawl decrease: More compact urban development brings homes closer to job centers (expected).
2. Job Distribution:
   - Urban sprawl increase: Employment centers decentralize, reducing commutes (expected).

   - Unchanged: No change in job location patterns.
   - Urban sprawl decrease: Jobs become more concentrated in central areas, reducing access.
3. Fare Policy:
   - R$ 0.00: Full fare subsidy, eliminating cost barriers (expected).
   - R$ 0.50: Optimist partial fare subsidy.
   - R$ 1.50: Pessimist partial fare subsidy.
4. Subway Expansion:
   - Expansion: Completion of the planned subway extension (expected).
   - Unchanged: No changes to the subway network.
   - Termination: Interruption of the subway operation.
5. Bus Route Disruptions:
   - 0%: No disruptions; full network operates as planned (expected).
   - 5%: Partial trips suspensions affect selected routes.
   - 15%: High service disruptions reduce network coverage.
6. Bus Station Suppression:
   - 0%: No stations removed (expected).
   - 5%: Partial station removals increase first/last-mile distances.
   - 15%: High station removals severely impact accessibility.

4.5.2 Accessibility Estimation

Unlike traditional resilience analyses that focus on network performance (e.g., connectivity, redundancy, travel time loss) (Cats; Jenelius, 2016; Kurth *et al.*, 2020; Proper, 2011), this study evaluates the capability of individuals to maintain accessibility under disruptions. This aligns with Sen's Capability Approach (Sen, 2011; Karner *et al.*, 2024), where resilience is measured in terms of whether people can still reach key opportunities despite changing conditions.

For each individual *i*, accessibility is estimated under all 729 scenarios, using the same accessibility measure that was used in Chapter 3. It captures the number of reachable opportunities weighted by a distance decay function and income. This individualized approach ensures that resilience is analyzed from a user-centered perspective, rather than as a system-wide average.

Then, the following indicators are computed for each individual:

- Minimum Accessibility $a_{min,i}$: The worst-case accessibility level across all scenarios, representing the most severe loss an individual might experience.
- Average Accessibility (excluding gains) $a_{\mu,i}$: The mean accessibility level across scenarios where accessibility remains the same or worsens (ensuring improvements do not artificially inflate resilience scores).
- Standard Deviation σ_i: Measures how much accessibility fluctuates across different disruptions, capturing individual vulnerability to transport instability.

This approach provides a resilience measure that reflects how well individuals' access to opportunities endures across various disruptions.

4.5.3 Resilience Analysis

To assess whether accessibility resilience is evenly distributed or disproportionately affects vulnerable individuals, two analyses are conducted. First, socioeconomic disparities are analyzed statistically comparing the mean and minimum accessibility levels across different vulnerability groups. This comparison uses box plots to visualize distribution differences and the Palma ratio to quantify disparities, particularly between the most and least advantaged individuals. The goal is to determine whether lower-income groups exhibit systematically lower accessibility under disruptions, suggesting greater exposure to mobility constraints.

Second, accessibility variability across social groups is examined by analyzing the standard deviation of accessibility for each individual. This metric captures how much accessibility fluctuates under different disruption scenarios. A significantly higher standard deviation among vulnerable individuals would indicate that their accessibility is more fragile, making them more susceptible to exclusion when transport systems face disruptions.

4.6 *Ex-Ante* Assessment of Public Transport Interventions in Fortaleza

The results in Table 4 (Resilience Indicators) highlight clear disparities in accessibility resilience between different population groups under disruption scenarios. On average, individuals in the better-off group retain 17.6% of their accessibility to jobs during disruptions, while those in the worse-off group retain only 9.34%. The Palma ratio of 1.88 indicates that accessibility preservation is nearly twice as high for better-off individuals, suggesting that the intervention's benefits are unevenly distributed. Although the intervention improves accessibility overall, its resilience disproportionately favors individuals who already had better mobility conditions, reinforcing existing inequalities in transport access.

Table 4 – Resilience Indicators

Indicator	Better-off	Worse-off	Palma Ratio
Average Disrupted Accessibility	17.6%	9.34%	1.88
Minimal Disrupted Accessibility	13.8%	3.96%	3.49
Standard Deviation of Disrupted Accessibility	2.30%	3.53%	0.653 (1.53)

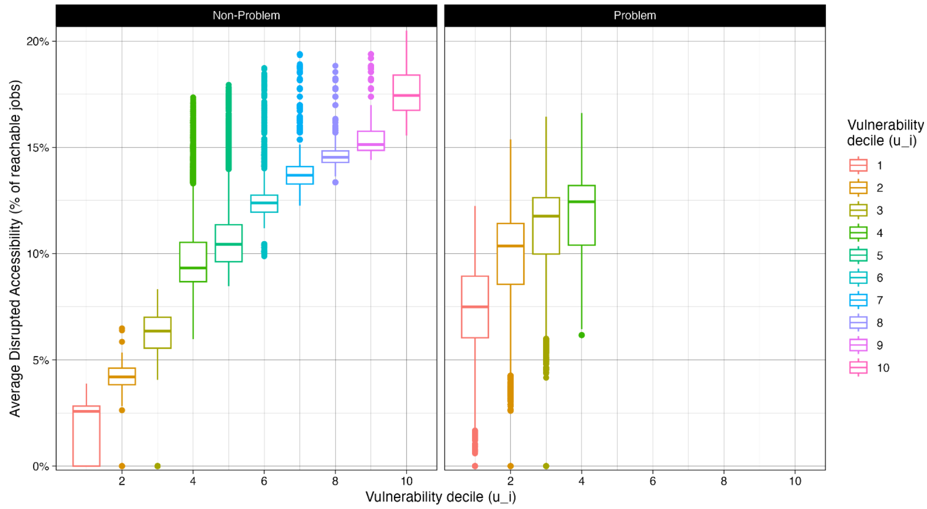
Source: Prepare by the author.

Looking at the minimum accessibility retained under disruptions, the disparities become even more pronounced. The least-advantaged individuals in the better-off group still maintain 13.8% of their baseline accessibility, whereas those in the worse-off group retain only 3.96%. The Palma ratio of 3.49 reflects an extreme gap, revealing that the most vulnerable individuals face significantly greater risks of experiencing accessibility losses when disruptions occur. This result suggests that those who were already in a disadvantaged position experience more severe accessibility cuts, while better-off individuals maintain a more stable ability to reach jobs and essential services.

Variability in accessibility across disruption scenarios also reflects these inequalities. The standard deviation of disrupted accessibility is 0.02 for the better-off group and 0.04 for the worse-off group, indicating that accessibility is not only lower but also more volatile for the worse-off group. This suggests that mobility for the most vulnerable populations is more uncertain, making them more exposed to accessibility instability. The Palma ratio of 0.653 (or 1.53 in the inverted form) suggests that accessibility levels fluctuate more unpredictably for those in the worse-off group, reinforcing their precarious mobility conditions.

The first plot, Figure 28 (Average disrupted accessibility distribution), shows the average percentage of jobs that remain reachable during disruptions across different vulnerability deciles. In the non-problem cases, accessibility increases gradually with vulnerability deciles, meaning that individuals in higher deciles (less vulnerable groups) maintain greater access to jobs during disruptions.

Figure 28 – Average disrupted accessibility distribution.



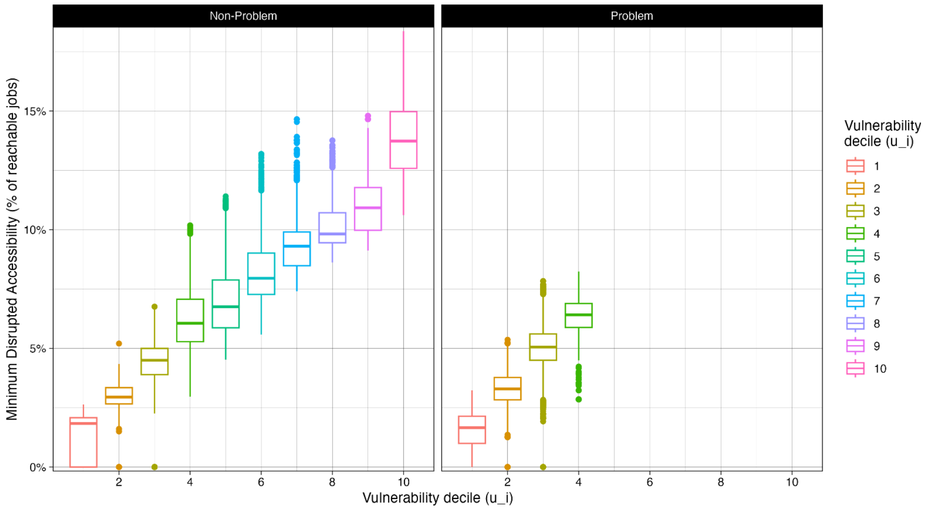
Source: Prepare by the author.

In contrast, in problematic cases, accessibility levels are considerably somewhat stable across all deciles, with a small drop for lower-decile individuals. The difference between the two cases highlights that disruptions disproportionately affect those in lower vulnerability deciles, particularly when not previously in a problem situation. This suggests that individuals with higher vulnerability levels not only start from a lower accessibility baseline but also have fewer resilience mechanisms to withstand disruptions.

The second plot, Figure 29 (Minimal disrupted accessibility distribution), presents the minimum level of accessibility that individuals in each decile experience during disruptions. The pattern is similar to the previous plot but even more pronounced. In non-problematic cases, higher vulnerability deciles retain more of their accessibility, though lower-decile individuals still show limited accessibility.

However, in problematic cases, accessibility collapses almost entirely for the most vulnerable deciles. This suggests that when disruptions are severe, low-income or transit-dependent populations face extreme accessibility losses, which could mean being effectively cut off from job opportunities. The widening gap between deciles in problematic cases further reinforces that disruptions exacerbate pre-existing accessibility inequalities, making already vulnerable populations even more isolated.

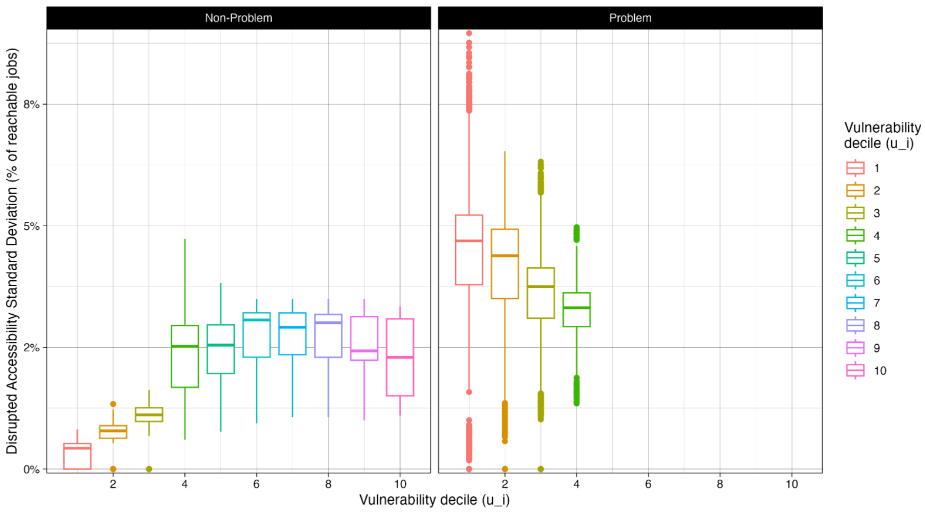
Figure 29 – Minimal disrupted accessibility distribution.



Source: Prepare by the author.

Finally, the third plot, Figure 30 (Resilience standard deviation distribution), depicts the standard deviation of accessibility across multiple disruption scenarios, capturing the stability or volatility of accessibility resilience. In non-problem cases, higher vulnerability deciles exhibit slightly higher variation, but the overall dispersion remains low.

Figure 30 – Resilience standard deviation distribution.



Source: Prepare by the author.

However, in problematic cases, standard deviations increase significantly, especially for lower deciles. This means that vulnerable individuals not only experience lower accessibility on average but also face greater uncertainty in their access to jobs and essential services. The large dispersion suggests that these individuals are more exposed to fluctuating accessibility conditions, making their mobility highly unpredictable.

4.7 Conclusion

This study aimed to assess the resilience of accessibility in urban mobility systems, focusing on how disruptions impact different social groups. Specifically, the objective was to determine whether accessibility resilience is equitably distributed or if certain populations - particularly vulnerable and transit-dependent individuals - face disproportionately greater losses and instability

The findings of this study underscore the critical relationship between vulnerability and accessibility resilience in urban transportation systems. The results demonstrate that individuals in lower vulnerability deciles - those with better baseline transport access - experience higher and more stable accessibility under disruptions, while those in higher vulnerability deciles, particularly the most transit-dependent and economically disadvantaged populations, face greater accessibility losses and higher volatility across disruption scenarios. This reinforces the reality that uncertainties do not impact all users equally; instead, they exacerbate existing spatial and social inequalities, disproportionately affecting those who already face mobility disadvantages.

From a policy perspective, this research highlights the urgent need for equity-focused resilience strategies. Strengthening transport infrastructure in vulnerable areas, enhancing redundancy in transit networks, and implementing targeted fare policies or demand-responsive transit services could help stabilize accessibility for the most affected groups. Furthermore, improving real-time information systems and prioritizing rapid service restoration in high-vulnerability areas could mitigate some of the most severe effects observed under problematic disruption scenarios. Without such interventions, resilience planning risks reinforcing existing inequalities, leaving disadvantaged populations at an even greater systemic disadvantage in terms of mobility and economic opportunity.

The study also highlights a fundamental gap in how resilience is currently addressed in transit planning. While most research has focused on post-disruption recovery, there remains a lack of proactive strategies for designing inherently resilient and flexible systems. This research demonstrates that resilience is not only a matter of restoring functionality but also of ensuring that accessibility remains equitable throughout disruptions. The variability of disrupted accessibility, particularly among the most vulnerable populations, suggests that resilience planning must extend beyond system-wide efficiency metrics and focus on the distributional impacts of disruptions.

Additionally, the importance of considering multiple simultaneous disruptions becomes evident. Actual transit failures often involve overlapping factors, such as infrastructure damage, operational constraints, and economic shifts. Given the combinatorial complexity of identifying critical elements and alternative operational strategies, optimization models are essential for ensuring that resilience is built into transit planning rather than treated as an afterthought. Future research should explore correlation and causality models between disruptions and accessibility distributions.

An important next step is the incorporation of behavioral responses to disruptions, which remains an underexplored area in resilience research. While this study evaluates accessibility from a structural perspective, actual traveler choices - including route changes, trip cancellations, and modal shifts - can significantly influence how disruptions manifest in practice. The inclusion of these dynamics could provide a more nuanced understanding of how individuals adapt to network failures and what measures could be implemented to support equitable adaptation strategies.

The introduction of resilience into the accessibility paradigm, as proposed by Cavalcante (2023), raises broader research questions that merit further investigation. What are the key determinants of urban transport resilience? How can resilience principles be embedded into the design of public transport projects? What role do community engagement and social equity play in creating resilient mobility systems? Additionally, how can advanced data-driven approaches, emerging technologies, and innovative planning frameworks be leveraged to enhance accessibility resilience in urban environments?

This study provides a foundation for addressing these questions by demonstrating that accessibility resilience is deeply tied to social equity and that resilience strategies must be explicitly designed to mitigate inequalities rather than passively assumed as a system-wide outcome. Moving forward, transportation planning must integrate a resilience-based accessibility framework that accounts for uncertainty, differential impacts, and long-term adaptability, ensuring that urban mobility systems remain inclusive, equitable, and robust in the face of future disruptions.

5. CONCLUSION

This doctoral research makes several key contributions to the field of public transport planning and equity-centered evaluation.

5.1 Integration of Mobility Planning and Transit Intervention Formulation

A novel, structured framework was developed to integrate strategic planning and problem diagnosis directly into the formulation of public transport interventions. Previous approaches often lacked this integration, with project design stages being vaguely described and disconnected from identified accessibility problems. By explicitly linking the diagnosis of accessibility restrictions to the specification of transit solutions, this work fills a gap in the literature where a detailed formulation-and-assessment framework for equitable transit interventions was absent. This integration ensures that interventions are grounded in identified needs and equity principles from the very beginning, representing a significant advancement over traditional methods.

5.2 Equity-Focused Optimization using the Capability Approach

The thesis incorporates Sen's Capability Approach and Rawlsian principles into a public transport network design optimization - an innovative contribution to transport planning. By formulating the objective function to prioritize vulnerable populations (those below critical accessibility thresholds), the model moves beyond standard accessibility maximization and explicitly targets equity outcomes. This capability-driven optimization ensures that improvements in transit supply (routes, frequencies, and fares) benefit those most in need, thereby operationalizing social justice theories in a practical planning tool. The result is an approach that not only improves overall accessibility but does so in a way that reduces disparities and prevents accessibility deprivation among disadvantaged groups.

5.3 Resilience in Ex-Ante Evaluation under Equity Principles

Another significant contribution is the introduction of a resilience dimension in the *ex-ante* evaluation of public transport projects, viewed through an equity lens. Traditionally, resilience of transport systems has been considered mostly in post-disaster contexts, and its proactive incorporation into project appraisal has been limited. This research developed a method to evaluate how well proposed transit interventions can sustain equitable accessibility under disruptive events (such as infrastructure failures or service interruptions) before those interventions are implemented. In doing so, it addresses a clear methodological gap identified in the literature regarding the integration of resilience into accessibility planning. The framework ensures that equity gains from an intervention are not fragile - that is, the improved access for vulnerable populations will remain robust even in the face of shocks or uncertainties. By bringing resilience into ex-ante evaluation, the thesis adds a forward-looking equity safeguard to transport project assessment, which is a novel addition to current transport planning practice.

5.4 Technical Recommendations

Beyond theoretical contributions, the findings translate into concrete frameworks and recommendations for policy-making and practice. The three core frameworks developed in Chapters 2, 3, and 4 provide practitioners and decision-makers with tools to design more equitable and resilient transit systems.

5.4.1 Framework from Chapter 2 – Equity-Oriented Planning Process

Chapter 2 presented an integrated planning framework that guides planners through diagnosing accessibility issues and formulating targeted public transport interventions. This framework systematically identifies areas and population groups with critical accessibility deficits and links those diagnostics to tailored solutions. By following this process, policy-makers can ensure that the projects they propose directly address the specific causes of accessibility inequity in their city. In practice, adopting this framework means that project identification and design are driven by data-informed equity needs, leading to interventions that are more likely to improve social inclusion. This approach can be used by transport agencies as a decision-support tool to prioritize investments where they yield the greatest social benefit, thereby making urban transport planning more proactive and justice-oriented.

5.4.2 Framework from Chapter 3 – Capability-Based Optimization Tool

Chapter 3 introduced an optimization model grounded in equity principles (via the Capability Approach and Rawlsian criteria) for designing public transport networks. This tool enables transit planners to evaluate different network and service scenarios under equity-based objective functions, rather than purely utilitarian metrics. The optimization framework considers transit supply variables (such as route configurations, frequencies, and fare levels) and finds solutions that minimize the number of people in accessibility poverty (those falling below a minimum access level). Implementing this tool in practice allows agencies to quantitatively assess trade-offs - for instance, slight reductions in overall efficiency or coverage can be weighed against significant gains for the least advantaged riders. The outcome is a set of “equitable optimal” solutions that decision-makers can use when allocating budgets or redesigning services. Policymakers are thus equipped to justify interventions not only on efficiency or demand metrics, but on the basis of how well they uplift underserved communities.

5.4.3 Framework from Chapter 4 – Resilience-Focused Ex-ante Evaluation

Chapter 4 delivered a framework to incorporate resilience analysis into the *ex-ante* evaluation of transit projects under equity principles. This protocol involves stress-testing proposed interventions against various disruption scenarios (such as transit infrastructure failures, extreme demand fluctuations, or other shocks) to observe how these events would impact accessibility for different population groups. By using this evaluation method, planners and engineers can identify which intervention options maintain acceptable accessibility levels for vulnerable groups even when disruptions occur. The practical implication is that agencies can screen and refine projects before implementation to favor those that are not only beneficial under normal conditions but also resilient in adverse conditions. This is especially important for policy-making in an era of uncertainty (*e.g.*, climate change, economic volatility), ensuring long-term sustainability of equity outcomes. Integrating this Chapter 4 framework into standard project appraisal processes would mean that considerations of robustness and social impact are front-loaded in project selection.

Collectively, the above frameworks form a comprehensive toolkit for improving public transport systems in line with equity principles. City authorities and transit agencies are recommended to incorporate these approaches into their planning cycle - starting from a clear diagnostic of accessibility inequities, through an equity-driven design of solutions, to a resilience-informed evaluation of project impacts.

5.5 Research Limitations

While the research advances the state of the art, it is not without limitations. The most notable limitation of the current modeling approach is its focus solely on the supply side of public transport provision. In formulating and evaluating interventions, the analysis concentrates on variables like transit routes, service frequency, and fares (supply measures), assuming a given distribution of travel demand.

Demand-side dynamics - such as how travelers might change their behavior in response to the new interventions - were not explicitly modeled. This means that potential feedback effects (for example, induced demand from improving service, or ridership loss/gain due to fare changes) are outside the scope of the present work. As a result, the outcomes and equity impacts are assessed under a static demand scenario. This supply-centric focus was useful for isolating the effects of interventions on accessibility distribution; however, it does not capture the full complexity of real-world systems where supply and demand interact.

A more holistic approach that integrates both supply and demand factors would provide a more complete picture of an intervention's impact. For instance, incorporating mode choice models or elasticity of transit demand could alter the estimated benefits of certain equity-focused interventions (either amplifying or mitigating their effects).

Likewise, the land-use side of accessibility (how the distribution of opportunities might change in the long term) was kept exogenous in this study. These simplifications suggest that while the findings are indicative of the potential equity improvements, they should be interpreted with caution. Future adaptations of the model should strive to overcome this limitation by embracing a systems perspective, wherein traveler behavior and land-use changes can coevolve with transit supply improvements.

5.6 Future Research Directions

Now that the a foundational framework has been established, future research should focus on increasing the model's complexity and broadening its applicability to address the above limitations and explore new questions. Promising directions are suggested below.

5.6.1 Incorporate Demand-Side Modeling

An next step is to integrate travel demand responses into the framework. This would involve coupling the supply-side intervention models with travel behavior models (*e.g.* mode choice, trip distribution, or activity-based models) to simulate how different populations would respond to changes in service and accessibility. By accounting for induced demand and modal shifts, researchers can evaluate whether equity-focused interventions retain their benefits once people adjust their travel patterns. For example, improving transit accessibility in underserved areas might attract new riders or enable more trips for existing riders - outcomes that could further enhance equity beyond what a static model predicts. Additionally, demand modeling can help identify any unintended consequences, such as overcrowding on certain routes or shifts of congestion to other parts of the network, allowing planners to refine interventions accordingly.

5.6.2 Refinement of Equity-Based Optimization Strategies

Building upon the equity-optimization model, future research can explore enhancements to make the approach even more robust and encompassing. One direction is to introduce multi-objective optimization techniques that consider additional goals alongside equity - for example, simultaneously minimizing cost or environmental impact while maximizing equity. This would reflect the reality that transport planners must balance multiple objectives. How to weight equity relative to other objectives in an optimization framework is an open question that future work could address, potentially involving stakeholders in defining acceptable trade-offs.

5.6.3 Expanded Resilience and Uncertainty Analysis

While this thesis introduced resilience into ex-ante evaluation, future research could go further by integrating resilience considerations directly into the planning and optimization stages. One idea is to develop an optimization model that includes resilience as an objective or constraint - for example, maximizing accessibility equity and the robustness of that accessibility under various disruption scenarios.

This stochastic or robust optimization approach would produce intervention plans that inherently account for uncertainty (such as variability in network performance or demand). Furthermore, subsequent work should examine a wider range of disruption types and frequencies, to test how different interventions perform under stress. Sensitivity analysis and probabilistic risk assessment would complement this, giving a clearer picture of the confidence in achieving equity outcomes under uncertainty.

Another aspect is studying the long-term adaptability of interventions: how well can a transit network, once optimized for today's conditions, accommodate future changes in demographics, technology (*e.g.*, autonomous vehicles), or economic conditions? By addressing these questions, researchers will enhance the longevity and transferability of the equity-based frameworks. This line of inquiry ensures that the pursuit of equity in transport planning remains effective not just for current scenarios but is resilient to future trends and shocks, aligning with the need for sustainable and future-proof urban mobility systems.

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