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Progressive subsidy allocations for transport equity and efficiency: Policy insights from the ABM-ETOP framework

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Abstract

Equitable outcomes for all socioeconomic groups are difficult to achieve in transport systems, even with considerable public investment. This study proposes the Agent-Based Model for Equity-Transport Optimization and Policy (ABM-ETOP) framework, a novel approach developed specifically for evaluating transport subsidy allocations with equity in mind. This methodology facilitates the rigorous assessment of such allocations based on established equity and efficiency criteria. We apply this framework to optimise subsidy distribution for three policy objectives: mode share equity, travel time equity, and total system travel time. By employing Bayesian optimization with Gaussian Process regression, we determined optimal subsidy allocation patterns across income groups and transport modes for each objective. When assessed against all policy goals in the study, progressive subsidy allocation consistently beat uniform distribution. Especially, the study showed that 55-65% of funding should allocate towards low-income groups.

The ABM-ETOP framework offers transport authorities a valuable tool for evidence-based decision-making. Our analysis showed an optimal overall subsidy level of 3,000-4,000 FPS units, noting that investments exceeding this range yield diminishing returns. This finding suggests a potential pathway to reconciling equity and efficiency objectives, which are frequently perceived as conflicting. The framework's capability to pinpoint subsidy configurations that mutually advance equity, and efficiency provides a robust foundation for transport authorities seeking to implement evidence-based policies that foster more inclusive and effective transport networks.

1 Introduction

Transport systems are vital infrastructure, connecting individuals with jobs, services, and social connections. However, these systems often create unequal outcomes for different socioeconomic groups. Lower-income households frequently bear a disproportionate share of transport challenges, facing longer commutes, fewer transport choices, and higher costs relative to their income (Lucas et al., 2016; Allen and Farber, 2019). These equity gaps persist, regardless of massive public investment in transport infrastructure and services globally.

To address these inequities, governments worldwide commonly use transport subsidies, allocating substantial funds to support public transport, shared mobility, and other alternatives. However, current allocation approaches frequently fall short of this goal (Banister, 2018; Zhao and Li, 2016). This shortfall occurs due to several key limitations that result in inefficient resource allocation: inadequate targeting of intended beneficiaries through uniform distribution regardless of socioeconomic circumstances, insufficient monitoring of how benefits are distributed across different population groups, single-mode focus that overlooks increasingly multimodal travel patterns, and non-adaptive frameworks that struggle to keep pace with evolving travel behaviours and technological integration. Understanding how financial aid allocation specifically impacts different demographic groups remains a challenge, largely because transport officials often lack the necessary frameworks to adequately assess this.

Transport research highlights a key issue: while studies show that fairness matters in transport planning (Pereira et al., 2017; Karner et al., 2020), there's a lack of clear guidance on how to

best allocate subsidies to achieve both fairness and effective achievement of policy objectives including equitable access and efficient system operation.

To address this gap, this paper applies the ABM-ETOP framework to present policy insights. We use 'optimal' to refer to allocations achieving best performance across our defined metrics, acknowledging broader economic considerations lie outside this scope. The ABM-ETOP framework is a novel approach that enables rigorous evaluation of transport subsidy allocations across multiple equity and efficiency dimensions.

2 Policy analysis framework

2.1 ABM-ETOP Framework Overview

We present the Agent-Based Model for Equity-Transport Optimization and Policy (ABM-ETOP), a framework designed for systematically evaluating and optimizing transport subsidy allocation with an eye towards both equity and efficiency. Its detailed technical specifications are covered in a companion paper, but here we provide a policy-focused overview of its main components. The ABM was originally developed by the authors using the Mesa library in Python and comprises three distinct types of agents. The commuter agents represent individual transport users. Provider agents represent the service providers in real life. A system coordinator agent operates much like a MaaS platform. The framework operates through iterative cycles where agent-based simulations generate policy outcomes for different subsidy allocations, Bayesian optimisation analyzes these results to predict promising allocation patterns, and the process continues until optimal configurations are identified.

2.2 Fixed pool and percentage-based subsidy mechanisms

The ABM-ETOP framework is used to assess two supporting transport subsidy policies here in this study, which are the fixed pool subsidy (FPS) allocation and percentage-based subsidy (PBS) allocation. The FPS mechanism represents the aggregate financial resources available for transport support by predefining total budgets for subsidies. The PBS mechanism controls the percentages of the subsidies distributed to a service cost, based on the service's transport mode and the socioeconomic background of the commuter who booked the service.

3 Cross-policy synthesis and guidelines

3.1 Distributional patterns and equity outcomes

Regardless of the specific policy goal, there is a consistent pattern of progressive allocation. Low-income groups consistently receive the largest share of the subsidies as 65.0% for Mode Share Equity, 55.4% for Total System Travel Time, and 67.7% for Travel Time Equity. This outcome provides a significant challenge to the conventional assertion that policies primarily focused on efficiency necessarily compromise equity considerations. Middle-income groups show the greatest variation in subsidy allocation between 25.3% to 35.9% across objectives, while high-income groups consistently receive the smallest share (5.7-8.7%). Such a consistent pattern highlights the critical importance of developing progressive resource allocation mechanisms to maximise effectiveness and efficiency within various policy environments.

4 Conclusion and future research

Our analysis reveals a key policy insight regarding transport subsidy allocation: progressive strategies consistently outperform uniform distribution across all equity and efficiency objectives. Progressive allocation directing 55-65% of resources to low-income groups achieves optimal performance across equity and efficiency objectives. The optimal investment range of 3,000-4,000 subsidy units demonstrates where effectiveness and cost-efficiency converge. Within this critical threshold, the balance between achieving performance enhancements and maintaining cost-effectiveness is most favourable.

Despite the promising insights, several limitations of the ABM-ETOP framework should be acknowledged. The model's assumption of algorithmic agent behaviour may not fully capture the complexities of human decision-making. The current implementation also utilises a simplified spatial map of the transport network and commuters, meaning spatial equity was not a considered area in this analysis. The simulations focus on daily decision-making. Its implications for long-term adaptation resulting from policy interventions might not be accurate.

To address the framework's limitations, future research should focus on integrating qualitative factors such as perceived safety and comfort and on better modelling longer-term behavioural adaptation through the incorporation of dynamic feedback mechanisms.

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