Shared mobility services: exploring their impact on equity in multimodal transportation systems

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1 INTRODUCTION

Shared mobility services (SMSs) are gaining attention as flexible, congestion-reducing solutions that can complement traditional transport modes. However, SMSs demand is often concentrated in high-density areas, which can limit the effectiveness and accessibility for various commuter groups across a city. Thus, to create inclusive transport systems, it is essential to understand how SMSs impact spatial equity, ensuring equitable access to efficient and affordable travel options.

Achieving these equity goals therefore relies on a well-coordinated integration of SMSs within multimodal systems, particularly with public transport (PT) (Gao & Li, 2024). Multiple studies examine this integration. Some rely on static models that do not adequately capture the dynamics of SMSs operations and traffic propagation (e.g. Du *et al.* (2022)). Other studies used dynamic approaches but oversimplified the characteristics of SMSs by limiting the sharing to trips with identical origin-destination (OD) pairs and assuming homogeneity among commuters (e.g. Pi *et al.* (2019)). Moreover, most existing simulation tools are effective for traffic modeling but face challenges in representing the interactions with SMSs, optimizing intermodality, and/or formulating heterogeneity in the commuter choice models.

In this paper, we propose a novel dynamic modeling framework to represent intermodal urban transportation systems, capturing the heterogeneity of commuters. We evaluate the impacts of SMSs on commuters' choices and equity for different classes of users. This framework allows for the design of multimodal systems including SMS operations that are sensitive to equity, providing insights into how the benefits and costs of these systems are distributed across different geographic regions and user groups.

2 DYNAMIC MODELING FRAMEWORK

The proposed approach, illustrated by Figure 1, uses the rolling horizon technique to dynamically assign multimodal traffic. In each time-step τ, the assignment loop Γ_τ is iteratively executed considering the trips departing in the corresponding time interval. For this, the ***mode choice and traffic assignment*** module assigns the travel demand upon the available modes and paths. The ***SMSs optimizer*** receives the SMSs requests and handles the passenger-driver matching. The ***Traffic simulator*** then updates the performance parameters (estimation of speed and SMS waiting times) which are then used in commuters' choices in the new iteration of Γ_t. The convergence is achieved once these parameters do not change significantly between two consecutive iterations.

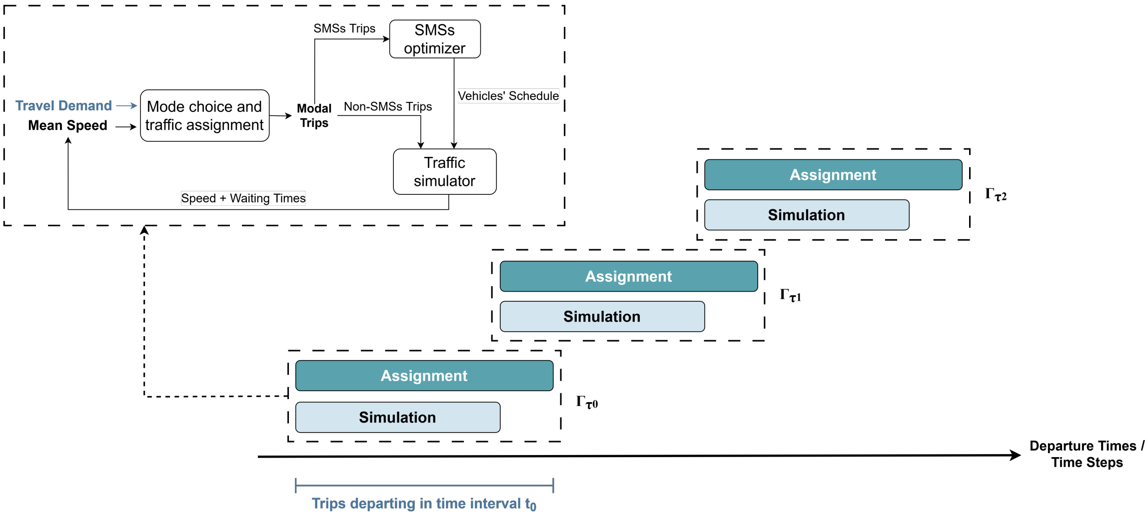


Figure 1 – *Dynamic Modeling framework for multimodal transportation systems*

The following two sections describe the demand (mode choice and traffic assignment) and supply (SMS and traffic simulator). We note that the main contribution of this work lies in the first section, and mainly point to models used for the second in Section 2.2.

2.1 Demand: Mode choice and traffic assignment

To allow equity considerations, we formulate a multi-class flow-based model that simultaneously assigns mode and path for heterogeneous travelers. The model employs the user equilibrium (UE) principle to minimize individual travel costs (Du *et al.*, 2022). The travel options are: private vehicles (PV), bus, metro/railway (M), carpooling as a passenger (CP), carpooling as a driver (CD), e-hailing (EH), ridesharing (RS), and soft modes walking (W) and biking (B); intermodal options between mode $m1$ and $m2$ with a transfer occurring at station t ($I_t(m1, m2)$) are also possible. Notations of this section are described in Table 1. Generalized costs ($c^{(i,j)}_{p,m,k}$) include travel, waiting and service times, as well as monetary and discomfort costs. Our mathematical formulation of the UE model is as follows.

Table 1 – ***List of notations.***

E	Set of nodes. Index: i,j
K	Set of commuters' classes. Index: k
Ψ	Set of travel modes ; Ψ = { PV, bus, M, CP, CD, EH, RS, W, B, $I_t(m1, m2)$ }. Index: m
P^m_{ij}	Set of paths for origin-destination (OD) pair (i, j) with mode m. Index : p
CAP_m	Maximum passenger capacity for the travel mode m.
y_{RS}	Number of ridesharing occupied vehicles.
$f^{(i,j)}_{p,m,k}$	Traffic flow of mode m on path p between OD pair (i, j) for user class k. [Integer Variable]
$c^{(i,j)}_{p,m,k}$	Generalized cost of path p with travel mode m between OD pair (i, j) for user class k.

$$min\ Z = \sum_{k\in K}\sum_{i,j\in E}\sum_{m\in\Psi}\sum_{p\in P^m_{ij}} a^{(i,j)}_{p,m,k}\cdot(c^{(i,j)}_{p,m,k} - c^{(i,j)*}_{k}) \tag{1}$$

$$a^{(i,j)}_{p,m,k} = \begin{cases} 0 & if\ f^{(i,j)}_{p,m,k} = 0 \\ 1 & if\ f^{(i,j)}_{p,m,k} > 0 \end{cases}$$

$$c^{(i,j)*}_{k} = \min_{p,m}\ c^{(i,j)}_{p,m,k}$$

subject to

$$q_{m,k}^{(i,j)} = \sum_{p \in P_{ij}^m} f_{p,m,k}^{(i,j)} \qquad \forall k \in K\ \forall m \in \Psi\ \forall i,j \in E \tag{2}$$

$$q^{(i,j)} = \sum_{m \in \Psi} \sum_{k \in K} q_{m,k}^{(i,j)} \qquad \forall i,j \in E \tag{3}$$

$$\sum_{i,j \in E} \sum_{k \in K} (q_{CD,k}^{(i,j)} + q_{I(CD),k}^{(i,j)}) \leq \sum_{i,j \in E} \sum_{k \in K} (q_{CP,k}^{(i,j)} + q_{I(CP),k}^{(i,j)}) \leq CAP_{CP} \cdot \sum_{i,j \in E} \sum_{k \in K} (q_{CD,k}^{(i,j)} + q_{I(CD),k}^{(i,j)}) \tag{4}$$

$$y_{RS} \leq \sum_{i,j \in E} \sum_{k \in K} q_{RS,k}^{(i,j)} + q_{I(RS),k}^{(i,j)} \leq CAP_{RS} \cdot y_{RS} \tag{5}$$

$$f_{p,m,k}^{(i,j)} \geq 0 \qquad \forall k \in K\ \forall m \in \Psi\ \forall p \in P_{ij}^m\ \forall i,j \in E \tag{6}$$

The objective function minimizes the cost gap between the used options and the best one, thus representing the UE conditions (Lin *et al.*, 2022). Constraints (2) and (3) ensure the flow conservation for each OD pair. Constraint (4) ensures that supply and demand are well balanced for carpooling. Similarly, (5) is a capacity constraint for ridesharing. Since the matching for SMSs is handled externally, we formulate these constraints independently of the OD pairs to be matched. Constraint (6) is the integrality condition.

2.2 Supply: SMSs Optimizer and the Traffic Simulator

The ***SMSs optimizer*** handles individual trip requests and available fleet vehicles using the matching algorithm developed by Alisoltani *et al.* (2021) for both carpooling and ridesharing services. The schedules are then executed using the shortest paths between origin and destination nodes. For the ***Traffic simulator*** we adopted a trip-based multimodal macroscopic fundamental diagram (Fu *et al.*, 2020), in which buses and vehicles share the road infrastructure and thus, impact and are impacted by congestion.

3 NUMERICAL EXPERIMENTS

We consider the Sioux Falls network to analyze the impacts of SMSs on modal share and spatial equity. We measure equity with Gini index, defined by equations (7)-(10), to assess how equally the benefits are distributed among different classes. We also calculate Gini per class, which will allow us to investigate whether the integration of SMSs favors certain classes more than others. We classify users into three categories according to their average income, ranging from low value of time (VoT) users in class 1 to high VoT users in class 3. We study the following scenarios: In scenario A, only PV, PT and soft modes are available. SMSs are introduced in scenario B. In scenario C, we incentivize commuters to combine SMSs with PT through price reductions.

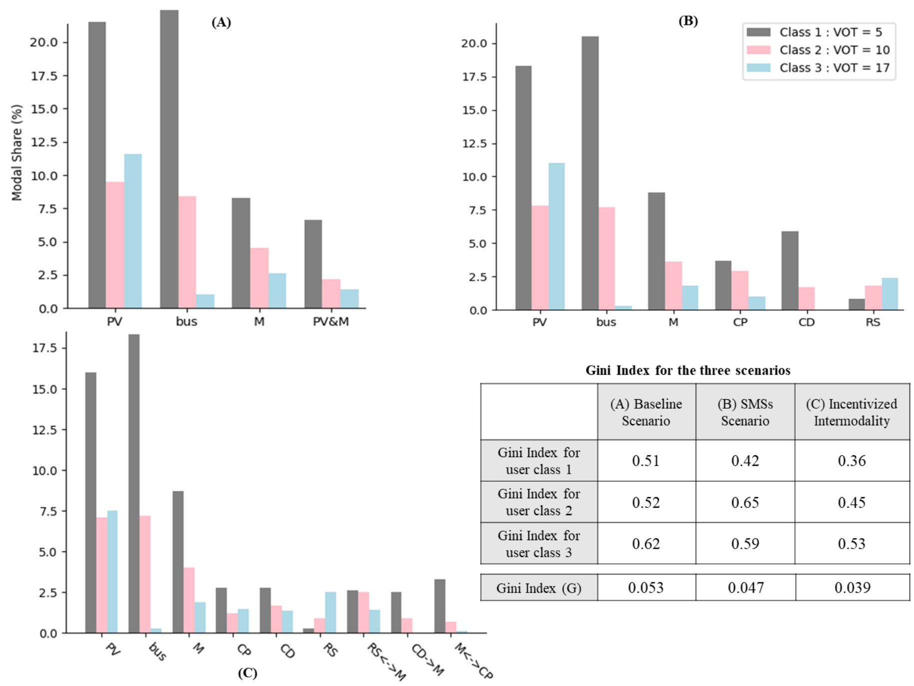
$$P_k^i = \sum_{j \in E} \sum_{m \in \Psi} q_{m,k}^{(i,j)} \qquad \forall k \in K \quad \forall i \in E \tag{7}$$

$$\overline{C}_k^i = \frac{\sum_{j \in E} (\sum_{m \in \Psi} q_{m,k}^{(i,j)}) \cdot c_k^{(i,j)*}}{P_k^i} \qquad \forall k \in K \quad \forall i \in E \tag{8}$$

$$\overline{C} = \frac{\sum_{i \in E} \sum_{k \in K} P_k^i \cdot \overline{C}_k^i}{\sum_{i \in E} \sum_{k \in K} P_k^i} \qquad \forall k \in K \tag{9}$$

$$G = \frac{\sum_{i \in E} \sum_{j \in E} \sum_{k1 \in K} \sum_{k2 \in K} P_{k1}^i P_{k2}^j |\overline{C}_{k1}^i - \overline{C}_{k2}^j|}{2 \cdot (\sum_{i \in E} \sum_{k \in K} P_k^i)^2 \cdot \overline{C}} \tag{10}$$

Figure 2 illustrates the results. Scenario (B) shows that introducing SMSs mainly attracts the demand from PV users. Few bus users from class 3 (high VoT) switch to CP and RS to decrease their travel times. Scenario (C) shows that commuters of classes 1 and 2 are more likely to adopt intermodality trips due to monetary cost advantages. The transfer delays and increased travel



	(A) Baseline Scenario	(B) SMSs Scenario	(C) Incentivized Intermodality
Gini Index for user class 1	0.51	0.42	0.36
Gini Index for user class 2	0.52	0.65	0.45
Gini Index for user class 3	0.62	0.59	0.53
Gini Index (G)	0.053	0.047	0.039

Figure 2 – *Impacts of SMSs on modal share and spatial equity in the Sioux Falls Network.*

times discourage the class 3 commuters. Moreover, the availability of SMSs improves overall spatial equity, as indicated by the decrease in the Gini index. In particular, class 1 users benefit from the decrease in their travel times, as well as their monetary expenses through intermodality, which leads to the highest benefits in terms of equity. Moreover, SMSs decrease the number of cars in the network, causing less traffic congestion. So, class 3 users experience less travel times with the introduction of SMSs and their Gini index improves. However, the effects on equity are not significant for class 2 users (with a negative impact in scenario B). This is due to the detours that SMSs generate and are not compensated by the monetary benefits for this class of users. The incentivization of intermodality helps alleviate this issue by further reducing the monetary cost and, thus, improving equity.

These results highlight SMSs' potential to improve spatial equity when integrated with PT, balancing the benefits across all user groups. This also demonstrates our model's ability to capture the multimodal interactions with heterogeneous users. More extensive results will be provided to analyze the distribution of equity across regions in the Sioux Falls network.

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