Regulating Autonomous Ride-Hailing Services for an Equitable Multimodal Transportation Network

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1 INTRODUCTION

This paper assesses the equity impacts of for-hire autonomous vehicles (AVs) and investigates regulatory policies that promote spatial and social equity in future autonomous mobility ecosystems. To this end, we consider a multimodal transportation network, where a ride-hailing platform operates a fleet of AVs to offer mobility-on-demand services in competition with a public transit agency that offers transit services on a transportation network. A game-theoretic model is developed to characterize the intimate interactions between the ride-hailing platform, the transit agency, and multiclass passengers with distinct income levels. An algorithm is proposed to compute the Nash equilibrium of the game and conduct an ex-post evaluation of the performance of the obtained solution. Based on the proposed framework, we evaluate the spatial and social equity in mobility benefits using the Theil index, and find that although the proliferation of for-hire AVs in the ride-hailing network improves overall mobility, the benefits are not fairly distributed among distinct locations or population groups, implying that the deployment of AVs will enlarge the existing spatial and social inequity gaps in the transportation network if no regulatory intervention is in place. To address this concern, we investigate two regulatory policies that can improve transport equity: (a) a minimum service-level requirement on ride-hailing services, which improves the spatial equity in the transport network; (b) a subsidy on transit services by taxing ride-hailing services, which promotes the use of public transit and improves the spatial and social equity of the transport network. We show that the minimum service-level requirement entails a trade-off: as a higher minimum service level is imposed, the spatial inequity reduces, but the social inequity will be exacerbated. On the other hand, subsidies on transit services improve mobility for low-income households in underserved areas. In certain regimes, the subsidy increases public transit ridership and simultaneously bridges spatial and social inequity gaps. These results are validated through realistic numerical studies for San Francisco.

2 METHODOLOGY

Consider a city divided into M geographic zones. These zones are connected by a multimodal transportation network which consists of a road network and a public transit network. The passenger demand is subdivided into K classes based on income levels in each zone. In the multimodal transport system, the TNC platform operates a fleet of AVs to provide mobility-on-demand services on the road network, and the public transit agency provides transit services through the transit network, and passengers in different classes make mode choices over the multimodal transport network. The decision-making of passengers, the TNC platform, and the public transit agency interact with each other and constitute the market equilibrium. A game-theoretic model is presented below to capture the competition between the TNC platform and the public transit agency over a transportation network.

2.1 Passenger behavior model

In the multimodal transportation system, passengers in distinct income classes choose among direct AMoD services (mode a), public transit (mode p), the bundled of first leg AMoD with transit (mode b_1), the bundle of last leg AMoD with transit (mode b_2), the bundle of first and last leg of AMoD with transit (mode b_3), and outside option (mode o) to reach their destinations at the minimum cost. Let $\mathcal{T} = \{a, p, b_1, b_2, b_3, o\}$ be the set of possible travel modes in the multi-modal transportation network. The disutility/generalized travel costs of different mobility modes collectively determine passenger demand. We use a multinomial logit model to characterize the passenger demand over distinct travel modes:

$$\lambda_{ij,k}^t = \lambda_{ij,k}^0 \frac{\exp\left(-\mu c_{ij,k}^t\right)}{\sum_{t' \in \mathcal{T}} \exp\left(-\mu c_{ij,k}^{t'}\right)}, \quad t \in \mathcal{T}, \tag{1}$$

where $\lambda_{ij,k}^t$ represents the arrival rate of passengers of mode t from origin zone i to destination zone j in income class k, $\lambda_{ij,k}^0$ is the arrival rate of potential passengers from zone i to zone j in income class k, $c_{ij,k}^t$ is the expected disutility/generalized travel costs for passengers from origin i to destination j in income class k by choosing mode t, μ is the scaling parameter in the mode choice logit model. The average generalized travel cost $c_{ij,k}^t$ comprises the waiting time, in-vehicle travel time, monetary cost and the access and egress cost of walking (if any), which are associated with the operational decisions of the TNC platform and the transit agency and can be characterized separately for distinct mobility mode t.

2.2 TNC platform model

Consider a for-hire fleet of N autonomous vehicles. Each TNC vehicle is in one of the following statuses: (a) cruising on the street and waiting for the passenger; (b) on the way to pick up a passenger; and (c) carrying a passenger. The total number of vehicle hours N should satisfy the following conservation law:

$$\begin{aligned} N = & \sum_{i=1}^{M} N_i^I + \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K} \left(\lambda_{ij,k}^a w_i^a + \lambda_{ij,k}^{b_1} w_i^a + \lambda_{ij,k}^{b_2} w_j^a + \lambda_{ij,k}^{b_3}\left(w_i^a + w_j^a\right)\right) + \\ & \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K} \left(\lambda_{ij,k}^a \frac{l_{ij}^a}{v_a} + \lambda_{ij,k}^{b_1} \frac{d_{i,k}^{b_1}}{v_a} + \lambda_{ij,k}^{b_2} \frac{d_{j,k}^{b_2}}{v_a} + \lambda_{ij,k}^{b_3}\left(\frac{d_{i,k}^{b_3}}{v_a} + \frac{d_{j,k}^{b_3}}{v_a}\right)\right), \end{aligned} \tag{2}$$

where N_i^I is the number of idle AVs in zone i, w_i^a is the average waiting time of AMoD services in zone i, l_{ij}^a is the average trip distance from zone i to zone j by AMoD, $d_{i,k}^{b_1}$ represents the average access distance (first-mile distance) by AMoD in origin zone i when choosing mode b_1, $d_{j,k}^{b_2}$ denotes the average egress distance (last-mile distance) by AMoD in destination zone j when choosing mode b_2, and $d_{i,k}^{b_3}$ and $d_{j,k}^{b_3}$ represent the average access and egress distance by AMoD in zone i and zone j when choosing mode b_3, respectively.

The TNC platform determines the base fare b, the per-distance rates r_i^a, the spatial distribution of idle AVs N_i^I, and the fleet size N to maximize its profit subject to the passenger behavior model (1) and the vehicle conservation (2). Let C_{av} be the hourly operating cost of an AV. The profit maximization for the TNC platform can be formulated as:

$$\begin{aligned}\max_{b,\mathbf{r^a},\mathbf{N^I},N} \quad & \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K}\lambda_{ij,k}^{a}\left(b+r_i^a l_{ij}^a\right)+\lambda_{ij,k}^{b_1}\left(b+r_i^a d_{i,k}^{b_1}\right)+\lambda_{ij,k}^{b_2}\left(b+r_j^a d_{j,k}^{b_2}\right)\\ & +\lambda_{ij,k}^{b_3}\left(2b+r_i^a d_{i,k}^{b_3}+r_j^a d_{j,k}^{b_3}\right)-NC_{av}\\ \text{s.t.} \quad & (1)\text{-}(2)\end{aligned} \tag{3}$$

2.3 Transit agency model

Consider a public transit agency that operates the transit network with L transit lines. Generally, a budget constraint is imposed to guarantee the economic sustainability of the transit agency, which requires that the difference between the operating cost and revenue be smaller than the operational budget π_0:

$$\sum_{l=1}^{L} f_l C_l - r^p \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K}\lambda_{ij,k}^{p} l_{ij,k}^{p}+\lambda_{ij,k}^{b_1} l_{ij,k}^{b_1}+\lambda_{ij,k}^{b_2} l_{ij,k}^{b_2}+\lambda_{ij,k}^{b_3} l_{ij,k}^{b_3}\le \pi_0, \tag{4}$$

where f_l is the service frequency of transit line l, C_l is the per-vehicle hourly operating cost of transit line l, r^p is the per-distance transit fare, $l_{ij,k}^{t}, t\in\{p,b_1,b_2,b_3\}$ represents average trip distance by public transit from zone i to zone j for income class k when choosing transit-related mobility mode t.

The public transit agency determines the transit fare r^p and the service frequencies f_l to maximize the public transit ridership subject to the passenger demand model (1) and the budget constraint (4). The ridership maximization for public transit can be cast as:

$$\begin{aligned}\max_{r^p,\mathbf{f}} \quad & \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{K}\lambda_{ij,k}^{p}+\lambda_{ij,k}^{b_1}+\lambda_{ij,k}^{b_2}+\lambda_{ij,k}^{b_3}\\ \text{s.t.} \quad & (1),(4)\end{aligned} \tag{5}$$

2.4 Equilibrium of the game

The profit maximization for the TNC platform (3) and the ridership maximization for the transit agency (5) constitute the game problem. The game is at equilibrium if the TNC platform cannot increase its profit and the public transit agency cannot increase the transit ridership by unilaterally changing their operational strategies. Let $\xi^a=(b,\mathbf{r^a},\mathbf{N^I})$ and $\xi^p=(r^p,\mathbf{f})$ be the operational strategy of the TNC platform and the public transit agency, respectively, and denote $\pi^a(\xi^a,\xi^p)$ and $\pi^p(\xi^a,\xi^p)$ as the TNC platform profit and the transit ridership, respectively. We can formally define the equilibria $\xi^*=\left(\xi^{a^*},\xi^{p^*}\right)$ that satisfies:

$$\begin{cases}\pi^a(\xi^{a^*},\xi^{p^*})\ge \pi^a(\xi^{a},\xi^{p^*})\\ \pi^p(\xi^{a^*},\xi^{p^*})\ge \pi^p(\xi^{a^*},\xi^{p})\end{cases}, \quad \forall \xi^a,\xi^p\ge 0. \tag{6}$$

which is consistent with the general definition of Nash equilibrium. In practice, each player in the game may be indifferent to a small change in its objective function (e.g., the change only accounts for a negligible portion of the objective value). This motivates a more relaxed solution concept that encapsulates a broader range of equilibrium solutions, where players will not unilaterally change their strategies as far as the current solution is approximately optimal. More rigorously, we can define such relaxed solution as the ϵ-Nash equilibrium, denoted as $\xi^*=\left(\xi^{a^*},\xi^{p^*}\right)$, which satisfies:

$$\begin{cases}\pi^a(\xi^{a^*},\xi^{p^*})\ge \pi^a(\xi^{a},\xi^{p^*})-\epsilon\\ \pi^p(\xi^{a^*},\xi^{p^*})\ge \pi^p(\xi^{a^*},\xi^{p})-\epsilon\end{cases}, \quad \forall \xi^a,\xi^p\ge 0. \tag{7}$$

Note that the optimization problem of each player in the proposed game-theoretic model is highly non-convex. We solve the game problem via best response methods and conduct an ex-post evaluation of the performance of the obtained solution by showing that the derived solution is at least as good as an ϵ-Nash equilibrium, where the value of ϵ can be computed numerically. In particular, for the TNC's profit maximization problem, we use primal decomposition to compute the globally optimal solution to a relaxed reformulation of the problem, which establishes a tight upper bound to evaluate the performance of TNC's decisions. For the transit ridership maximization subproblem, we adopt a grid-based search algorithm to compute its globally optimal solution. The detailed algorithms can be found in Gao & Li (2024).

3 RESULTS

We measure the mobility benefits of for-hire AVs as the difference in expected consumer surplus before and after introducing AVs for ride-hailing services and use the Theil index to quantify both spatial and social inequity to investigate the equity impacts of AV deployment in the absence of regulations. Through realistic numerical studies for San Francisco, we find that:

- Although the proliferation of AVs improves overall mobility, the benefits are not fairly distributed across different geographic locations and among distinct population groups, and the deployment of AVs will exacerbate both spatial and social inequity gaps at the same time.
- The increase in spatial inequity arises from the geographic concentration of ride-hailing services in high-demand areas due to the for-profit nature of the TNC platform, and the increased social inequity gap is due to the fact that the benefits of AV-enabled ride-hailing services are primarily enjoyed by individuals with higher income, whereas those with lower income are disproportionately transit-dependent.

The above insights motivates us to consider distinct regulatory policies that improves the spatial and social equity of the multimodal transportation network. We evaluate the equity impacts of two regulatory policies, including (a) a minimum service-level requirement on ride-hailing services, which improves the spatial equity in the transport network; (b) a subsidy on transit services by taxing ride-hailing services, which promotes the use of public transit and improves spatial and social equity of the transport network. The major policy implications are summarized below:

- The minimum service-level requirement entails a trade-off: as a higher minimum service level is imposed, the spatial inequity reduces, but the social inequity will be exacerbated. The regulatory agency should evaluate the trade-off between spatial equity and social equity and carefully control the minimum service-level requirement.
- Subsidies on transit services by taxing ride-hailing can promote the use of public transit and improve spatial and social equity at the same time. However, when transit services are over-subsidized, excessive taxation significantly deteriorates AMoD services, which sacrifices the mobility of medium-income and high-income classes and enlarges the spatial inequity gaps. The regulatory agency should choose the proper subsidy/tax level to reach an equitable distribution of mobility benefits across distinct income classes and geographic zones.

References

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