Strategic coopetition for autonomous mobility on-demand systems under demand uncertainty: When competitors become friends?

Wentao Huang, Xiaoshu Ding, Sisi Jian*
Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR
*Corresponding author, E-mail: cesjian@ust.hk

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1 INTRODUCTION

Mobility-on-demand (MoD) services have been introduced in numerous cities worldwide in recent years. With the rapid development of autonomous vehicles (AVs), the combination of on-demand ride-hailing services and AVs, known as the autonomous mobility-on-demand (AMoD) system, is believed to be one of the most transformative innovations that may reshape the future urban mobility. Recognizing the potential of AMoD, several companies, including Apple, Amazon, Audi, and Baidu, are heavily investing in AMoD technologies. For example, Apollo Go, an AMoD platform developed by Baidu, has launched its services in over ten cities and has served more than six million riders across China. It is envisioned that AMoD services will be operated by multiple transportation network companies (TNCs), competing for traveler demand.

Although AMoD applications are still regarded as niche products, there has been extensive research on AMoD modeling, covering areas such as system design, fleet management, pricing, and dispatching strategies. Among these research challenges, effectively managing demand information and exploring its value are crucial for the success of AMoD applications (Wen *et al.*, 2019). A well-designed AMoD system will facilitate seamless information exchange between travelers and AMoD operators, allowing both parties to be better informed and improving the use of mobility resources (e.g., AVs). However, much of the existing literature has primarily focused on supply information provided to travelers, addressing the issue from the demand side perspective. From a perspective of TNCs, a common challenge is the spatial and temporal imbalance in travel demand, which often results in one TNC facing AV shortages while another has surplus AVs in the same area. The first TNC must relocate its available AVs from other areas to meet demand, while the second TNC may have to park or cruise its AVs, leading to lower utilization.

To address this issue, TNCs may collaborate to form a mobility resource exchange alliance (Chun *et al.*, 2017). Through this alliance, TNCs can borrow or lend AVs to optimize their usage and enhance profitability. Such alliances typically involve collaborative agreements between two or more TNCs to share the usage rights of idle AVs on an hourly, daily, or weekly basis. Alliances play a crucial role in business strategies and are common across various industries. For example, in airline alliances, a member can sell tickets for flights operated by other members, even if they are competitors. This collaboration allows airlines to expand their itinerary offerings, thereby increasing profitability.

However, modeling the interactions of multiple TNCs to understand the impacts of their AV exchange behaviors within AMoD systems has yet to be visualized. By joining the alliance, competing TNCs can cooperate to achieve the common goal of maximizing total profit for the alliance. This cooperative relationship between competitors is known as coopetition (Nalebuff *et al.*, 1996). Nonetheless, since TNCs often provide substitute AMoD services, competition among them may intensify, potentially discouraging participation in the alliance. This suggests that the coopetition dynamic among TNCs can be unstable, underscoring the importance of carefully designing the alliance rules.

Given both advantages and disadvantages, we raise several research questions: Is it possible to design an AV exchange alliance that benefits each TNC despite increased competition? If so, what would the alliance rules be, particularly regarding the revenue-sharing mechanism? Additionally, can an alliance achieve perfect coordination, treating all TNCs as a single entity? If not, how close can it come to that ideal? To answer these questions, we explore the design of AV exchange alliances for AMoD systems, considering demand uncertainty. We propose an exchange model that accounts for competition and revenue sharing among alliance members. A stochastic mathematical program with equilibrium constraints (SMPECs) has been formulated and solved using an efficient solution methodology. The impacts of resource exchange on TNCs' profit and social welfare under different levels of demand uncertainty will be examined.

2 Methodology

In this section we first present a profit maximization model for AMoD systems without and with an alliance in subsections 2.1 and 2.2, respectively. We consider a city where there are K TNCs, indexed by $k \in \mathcal{K} = \{1, ..., K\}$, providing AMoD services over a discrete time horizon of T periods, indexed by $t \in \mathcal{T} = \{1, ..., T\}$. The city is divided into Z geographic zones, indexed by $z \in \mathcal{Z} = \{1, ..., Z\}$. Each TNC k manages a fleet of AVs distributed across these zones, which is denoted by n^k_{it}. The demand of TNC k, denoted by d^k_{ijt}, in each zone at each period depends on the number of AVs as follows:

$$d^k_{ijt} = \bar{d}^k_{ijt} + \widetilde{\alpha}^k_{it} n^k_{it} - \widetilde{\beta}^k_{it} \sum_{k' \in \mathcal{K} \setminus \{k\}} n^{k'}_{it} \qquad \forall i, j \in \mathcal{Z}, t \in \mathcal{T}, k \in \mathcal{K} \tag{1}$$

where $\bar{d}^k_{ijt}$ represents the historical base demand. The terms $\widetilde{\alpha}^k_{it}$ and $\widetilde{\beta}^k_{it}$ are positive stochastic constants, unknown to each TNC. Demand function (1) reflects that the demand for TNC k's service increases with its fleet size in that zone and decreases with the fleet size of other TNCs.

2.1 Profit maximization problem of TNCs without alliance

In this subsection, we present the profit maximization problem of TNCs without alliance, which is modeled as a noncooperative game. The profit maximization problem of TNC k is given by

$$\pi^k = \max \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{Z}} \sum_{j \in \mathcal{Z}} \left(F^k_{ijt} d^k_{ijt} - C^k_{ijt} x^k_{ijt} \right) \tag{2}$$

subject to

$$n^k_{it} = n^k_{i(t-1)} - \sum_{j \in \mathcal{Z} \setminus \{i\}} (d^k_{ijt} + x^k_{ijt}) + \sum_{j \in \mathcal{Z} \setminus \{i\}} (d^k_{jit'} + x^k_{jit'}) \qquad \forall i \in \mathcal{Z}, t, t' \in \mathcal{T} \tag{3}$$

$$\sum_{j \in \mathcal{Z} \setminus \{i\}} (d^k_{ijt} + x^k_{ijt}) \leq n^k_{i(t-1)} \qquad \forall i \in \mathcal{Z}, t \in \mathcal{T} \tag{4}$$

$$\sum_{i \in \mathcal{Z}} n^k_{i0} \leq N^k \tag{5}$$

Objective function (2) means the TNC aims to maximize its profit by serving demand d^k_{ijt} with the constant price F^k_{ijt}. The term x^k_{ijt} is the number of AVs relocated from zone i to zone j where C^k_{ijt} is the unit relocation cost. Constraints (3) express the flow conservation, which state that the number of AVs in zone i must equal the number of AVs remaining from the previous time period, minus the number of AVs departing from zone i, and plus the number of AVs arriving in zone i which left from zone j at period t'. Constraints (4) represent the number of AVs departure from zone i should not exceed available AVs. Constraints (5) mean that the number of total AVs assigned to all zones at the initial time period should not exceed the maximum fleet size.

2.2 Profit maximization problem of TNCs with alliance

In this subsection we present an AVs' usage rights exchange alliance for AMoD systems. The AV exchange alliance design problem is presented as a two-stage problem. In the first stage, the alliance aims to maximize the total profit (i.e., common goal) of all TNC members by determining the optimal number of AVs to exchange among them. In the second stage, each TNC optimizes its vehicle allocation to meet its demand. As TNCs offer substitutive AMoD services and compete with each other, the first stage problem must consider the resulting competition in the second stage. We will further design a profit sharing mechanism and derive the situations by which such a alliance can be stabilized.

Let $y^{k',k}_{it}$ be the amount of AVs exchanged from TNC k' to TNC k in zone i at period t, which is determined by the alliance. For simplicity, let $\boldsymbol{y} = (y^{k',k}_{it})_{\forall i\in\mathcal{Z},t\in\mathcal{T},k\in\mathcal{K},k'\in\mathcal{K}\setminus\{k\}}$ be the AV exchange vector in the first stage and $\boldsymbol{x}^k = (x^k_{ijt})_{\forall i,j\in\mathcal{Z},t\in\mathcal{T}}$ be the relocation decisions of TNC k in the second stage. Given $\boldsymbol{y}$, the profit maximization problem of TNC k is rewritten by:

$$\pi^k = \max \pi^k(\boldsymbol{x}^k(\boldsymbol{y}), \boldsymbol{y}, \xi^k) = \sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{Z}}\sum_{j\in\mathcal{Z}}\left(F^k_{ijt}d^k_{ijt} - C^k_{ijt}x^k_{ijt}\right) \tag{6}$$

subject to

$$n^k_{it} = n^k_{i(t-1)} - \sum_{j\in\mathcal{Z}\setminus\{i\}}(d^k_{ijt} + x^k_{ijt}) + \sum_{j\in\mathcal{Z}\setminus\{i\}}(d^k_{jit'} + x^k_{jit'}) + \sum_{k'\in\mathcal{K}\setminus\{k\}} y^{k',k}_{it} \quad \forall i\in\mathcal{Z}, t, t'\in\mathcal{T}, k\in\mathcal{K} \tag{7}$$

$$\sum_{j\in\mathcal{Z}\setminus\{i\}}(d^k_{ijt} + x^k_{ijt}) \le n^k_{i(t-1)} + \sum_{k'\in\mathcal{K}\setminus\{k\}} y^{k',k}_{it} \quad \forall i\in\mathcal{Z}, t\in\mathcal{T}, k\in\mathcal{K} \tag{8}$$

$$\sum_{i\in\mathcal{Z}} n^k_{i0} \le N^k \tag{9}$$

where the meanings of Eqs. (6) – (9) are similar to their counterparts in Subsection 2.1, but they include the effects of exchanged AVs. The second stage demand is unknown in the first stage, and we model the demand as random variables. Let $\xi^k := (\widetilde{\alpha}^k_{it}, \widetilde{\beta}^k_{it})_{\forall i\in\mathcal{Z},t\in\mathcal{T}}$ denote the random data vector for TNC k and $\xi = (\xi^k)_{\forall k\in\mathcal{K}}$, which can be learned from the real-world data. In the first stage, the alliance maximizes the expected overall profits for the alliance with respect to the distribution of ξ. The objective of the first-stage problem (the alliance) is given by $\max_{\boldsymbol{y}} \Pi := \mathbb{E}_\xi\left[\sum_{k\in\mathcal{K}} \pi^k(\boldsymbol{x}^k(\boldsymbol{y}), \boldsymbol{y}, \xi^k)\right]$, where the expectation is taken in terms of the probability distribution of the random demand ξ. We next outline the solution approach. We assume that ξ^k has a discrete distribution with a finite support such that ξ^k can be approximated by a finite number of independent and identically distributed scenarios $\xi^k_1,...,\xi^k_{\mathcal{S}}$ with probabilities $h_1,...,h_S$, respectively, where $\sum_{s\in\mathcal{S}} h_s = 1$. The expected objective of the alliance can be written as the following sample average approximation (SAA) problem:

$$\max_{\boldsymbol{y}} \Pi = \sum_{s\in\mathcal{S}} h_s \sum_{k\in\mathcal{K}} \pi^k(\boldsymbol{x}^k(\boldsymbol{y}), \boldsymbol{y}, \xi^k_s) \tag{10}$$

2.3 Design of the profit sharing mechanism

In this subsection, we discuss the design of the profit-sharing mechanism, which is essential for maintaining stable cooperation. TNCs will agree to form an AV exchange alliance only if it results in increased profits. To ensure stability, the profit-sharing rule must guarantee that all TNCs either achieve higher profits or maintain their original profit after exchanging resources compared to what they would earn without the alliance.

We adopt an axiomatic approach following Nash *et al.* (1950), establishing three key axioms to guide the desired profit sharing rule: Pareto efficiency, symmetry, and invariance to affine transformations. Pareto efficiency ensures that no alternative profit-sharing scheme can improve one TNC's reward without reducing the reward of another TNC. Symmetry, as a fundamental principle of fairness, dictates that the profit-sharing rule must treat indistinguishable TNCs equally. Invariance to affine transformations implies that the profit-sharing outcomes should maintain the original order of contributions, even if the utility functions are transformed (e.g., through a linear transformation).

Let π_A^k and π_{NA}^k denote the profit of TNC k with and without an resource exchange alliance. We prove that the profit sharing rule satisfying all three mentioned axioms is as follows:

$$\pi_A^k = \pi_{NA}^k + \frac{\Pi - \sum_{k \in \mathcal{K}} \pi_{NA}^k}{N} \qquad \forall k \in \mathcal{K} \tag{11}$$

The profit-sharing rule (11) indicates that a feasible approach is to distribute the increased profit equally among all alliance members after establishing the alliance. This type of profit-sharing mechanism incentivizes TNC participation by ensuring that all members benefit equally, which helps maintain stability within the alliance. When TNCs perceive fair treatment, they are less likely to withdraw or engage in competitive behavior that could undermine the alliance. After establishing the profit-sharing rule, we replace the TNCs' problems with their KKT conditions and formulate a SMPEC to solve the problem.

3 Discussion

In this study, we propose an AV exchange alliance for AMoD systems, taking into account both intra-competition among TNC members and demand uncertainty within the alliance. A case study will be conducted to investigate the effects of different revenue-sharing mechanisms and varying levels of demand uncertainty. Additionally, we will explore the impact of travelers' retention rates: typically, as travelers increasingly utilize the services of TNC k, they are more likely to continue using it. Therefore, when TNCs join the alliance, they must factor this effect into their AV exchange processes.

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