Contract design for MaaS integration in congested multi-modal mobility systems

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1 Introduction

The adoption of Mobility-as-a-Service has fallen well below expectation due to the intertwined challenges of demand-side reluctance Caiati *et al.* (2020) and supply-side coordination inefficiency. Previous studies suggested that the multi-modal trips, which is intended to be door-to-door and seamless as promised by MaaS, are often hindered by the additional waiting time and transfer inconveniences (Garcia-Martinez *et al.*, 2018, Pan & Sun, 2024), highlighting the need for the more proactively integrated mobility services beyond mere travel information-sharing. Yet, the current MaaS landscape remains fragmented, where different providers, such as government-backed public transit agencies and private ride-hailing firms, control separate modes and lack coordinated scheduling. Without a business framework that aligns platform and transportation service provider (TSP) incentives while accounting for operational constraints, MaaS will still struggle to scale and sustain multi-modal integration.

Designing a MaaS business model requires careful consideration of multi-modal trip characteristics. Certain modes, like subways and feeder services (e.g., taxis or buses), are naturally complementary. While some studies have considered this complementarity in MaaS business models (van den Berg *et al.*, 2022), they overlook the fundamental constraint in transportation: congestion. TSPs can mitigate congestion by expanding capacity or optimizing operations. yet multi-modal trips and single-mode trips inherently compete for shared capacity, meaning improved multi-modal services could induce demand shifts that increase congestion for single-mode travelers. To date, only Huang *et al.* (2024) has incorporated congestion effects into a business model for MaaS, while with a focus on trading between TSPs.

Furthermore, most MaaS platforms, such as Whim (Finland) and Ubigo (Sweden) (Daniela *et al.*, 2023), do not operate transportation services directly. And their specific roles and impacts remain theoretically underexplored. Pricing and information integration are the two most commonly mentioned functions of platforms. While studies discuss multi-modal pricing strategies to travelers (Xi *et al.*, 2023), the task allocation revenue-sharing agreement between TSPs and platforms are lessly analyzed. Additionally, the platform's role in reducing transfer inconvenience through information integration is rarely analyzed in depth, leaving the question of how these efforts should be incentivized unresolved.

This study develops a framework for optimizing MaaS business models while incorporating capacity constraints and platform-TSP collaboration. Specifically, we address the following key questions:

- Under what conditions is lump-sum fare for multi-modal trips feasible? What are the implications for both travelers and platform?
- Under a platform-guided, TSP-responsive organizational structure, what are the optimal platform investments in TSPs, and how should TSPs allocate capacity in response?
- Beyond setting a lump-sum fare for multi-modal trips, how should the platform contribute to further integrate multi-modal trips?

To answer these questions, we adopt contract dsign theory and develop a one-principal multi-agent model to study the strategic interactions between a MaaS platform and two TSPs, one providing on-demand services and the other offering fixed-route transit. TSPs are incentivized by the platform to improve their capacities, which benefits all travel demands. Demand is assumed to be elastic to trip fares and mode capacity. In particular, we analyze two scenarios: (1)shared capacity between multi-modal and single-mode trips, (2) dedicated capacity for multi-modal trips.

2 The Model

The model consists of three three entities: travelers, TSPs, and the platform. The two TSPs provide mode 1 and mode 2, respectively, serving the corresponding single-mode travel demands d_1 and d_2. In addition, a group of multi-modal travelers utilizes both modes, with their travel demand denoted as d_m. Under MaaS integration, the trip fare of multi-modal travels is controlled by the platform, while their travel time is influenced by both the TSPs' provided capacity and the platform's effort in mitigating the burden of transfers.

The Market Setting Single-model travelers are assumed to have quadratic utility and linear cost, both dependent on demand. By Roy's identity, the (inverse) elastic demand function can be derived. The congestion effect is captured through travel time, which is determined by both demand d_i and capacity q_i. As an example, the inverse single-mode demand function for mode i, when single-mode and multi-modal trips share capacity q_i, is given by

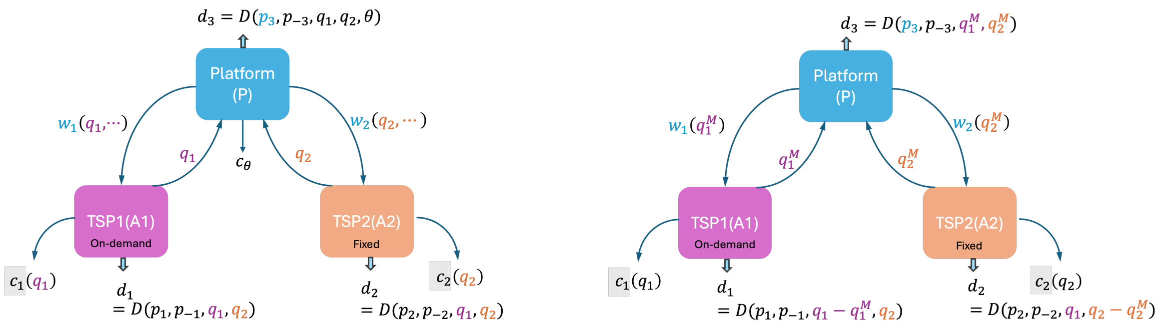
$$p_1 = \alpha_1 - \beta_1(d_1 + d_m) - \zeta d_2 - \gamma\big(t_1(q_1, d_1 + d_m) + \frac{\partial t_1}{\partial d_1}(d_1 + d_m)\big) \tag{1a}$$

In this equation, α_1 represents the maximum fare when demand is zero. The parameter $\beta_1 > 0$ indicates that a fare reduction leads to increased demand. The parameter ζ is negative, suggesting that the two modes are complementary, even when excluding the multi-modal trip demand d_m. Additionally, $|\zeta| < \min\{\beta_i\}$, $i = 1, 2$, as the two modes are imperfect complement. The value of travel time is denoted by γ. Here, the in-vehicle travel time for two single-mode travels are denoted t_1 and t_2, respectively, where the functions satisfying $\frac{\partial t_i}{\partial d_i} \geq 0, \frac{\partial t_i^2}{\partial d_i^2} \geq 0, \frac{\partial t_i}{\partial q_i} < 0, \frac{\partial t_i^2}{\partial q_i^2} \leq 0, \forall i \in \{1, 2\}$ given the congestion effect.

For multi-modal trips, if a lump-sum trip fare p_m is given, the demand function can be expressed as:

$$p_m = \alpha_m - \sum_{i=1,2} \beta_i d_i - \sum_{j=1,2,m} d_m - \gamma\Big(\sum_{i\in\{1,2\}} \big(t_i(q_i, d_i + d_m) + \frac{\partial t_i}{\partial d_m}(d_i + d_m)\big) + t_m^\theta\Big) \tag{1b}$$

Differing from the single-mode, d_m is a perfect substitute for the single-mode demands d_1 and d_2. Here, we assume $\alpha_m >> \alpha_1 + \alpha_2$, suggesting the high valuation of multi-modal trips. In addition



(a) *Scenario I: Shared capacities for single- and multi-modal trips*

(b) *Scenario II: Dedicated capacities for multi-modal trips*

Figure 1 – *The contract design framework*

to travel time, mode-to-mode transfer time t_m also influences d_m, introducing an additional disutility factor. This transfer disutility captured by t_m^θ, where $t_m > 1$ and $\theta > 1$, implying that travelers exhibit risk-averse during transfers.

The Platform's Functions. The platform plays a dual role in the MaaS system, influencing both travelers and TSPs. On one hand, the platform is responsible for information integration and setting the lump-sum fare for multi-modal trips. While information integration does not reduce the physical transfer time t_m, it alleviates the inconvenience associated with transfer denoted by θ. Consequently, the lump-sum fare p_m depends on θ, which we denote as $p_m(\theta)$.

On the other hand, the platform engages in the contractual agreements with TSPs, requiring them to improve single modes' compensating them with payments w_i to incentivize improvements in single-mode capacities. We assume that the TSPs' effort is observable to the platform. The platform's objective varies depending on its ownership structure: 1) If it is privately owned, we assume the platform aims to maximize profit, represented by $\max_{p_m,\theta,w_i(q_i)} p_m d_m - \sum_{i\in\{1,2\}} w_i(q_i) - c_\theta$, where c_θ represents the cost of reducing transfer disutility. 2) If it is government-owned, it prioritizes minimizing total travel time for multi-modal trips, formulated as: $\min_{p_m,\theta,w_i(q_i)} p_m d_m - \sum_{i\in\{1,2\}}(t_1 + t_2 + t_m)d_m$.

The TSPs' Efforts The TSPs extert effort to improve capacity q_i, incurring a cost denoted by $c_i(q_i)$. As profit-maximizing entities, each TSP solves an optimization problem with objective $\max_{q_i} U_i = p_i d_i + w_i(q_i) - c_i(q_i)$. The TSPs must also satisfy the individual rationality (IR) constraint, ensuring that their utility under the optimal effort level q_i is at least as high as their utility in the absence of a contract.

When TSPs allocate dedicated capacities to multi-modal trips, denoted as q_i^M, e single- and multi-modal trips are disentagled. Correspondingly, the inverse demand functions can be reformulated as:

$$p_1 = \alpha_1 - \beta_1 d_1 - \zeta d_2 - \gamma\big(t_1(q_1 - q_1^M, d_1) + \frac{\partial t_1}{\partial d_1} d_1\big) \tag{2a}$$

$$p_m = \alpha_m - (\beta_1 + \beta_2 + \beta_m)d_m - \gamma\Big(\sum_{i\in\{1,2\}} \big(t_i(q_i^M)d_m + \frac{\partial t_i}{\partial d_m} d_m\big) + t_m^\theta\Big) \tag{2b}$$

Finally, **Fig.** (1) illustrates the interactions between TSPs and platforms under each of the two capacity allocation scenarios.

3 Preliminary Results

Before deriving the optimal contract, we first compare the status quo (without lump-sum pricing) and the optimal lump-sum fare scenario. The objective is to assess the economic viability of implementing a dedicated fare structure given a certain level of information integration. In this analysis, the TSPs do not enhance their capacity q_i, thereby incurring no additional costs. Furthermore, no monetary transfers occur between the platform and the TSPs. Given space limit, we present only the key findings.

Lemma 1 (Multi-modal demand without lump-sum pricing) *Without a lump-sum fare, the multi-modal demand is linear to the single-mode demands and transfer disutility. The formulation is given by*

$$\hat{d}_m = \frac{1}{\beta_b}\big(\zeta(d_1 + d_2) + \alpha_m - \gamma t_m^{\theta}\big) \tag{3}$$

Proposition 1 (Economic viability of lump-sump pricing) *Suppose the unit cost for information integration is $c^{\theta_n+1-\theta}$, where θ_n is the original diutility level without integration. With elastic demand and improvement cost being $c < p_1 + p_2 - \beta_m \hat{d}_m$, then providing integrated multi-modal mobility services with a lump-sum fare generates additional surplus for both customers and the MaaS platform.*

Proposition 2 (Optimal level of information integration) *Let $\theta^t = \frac{(\theta_n+1)ln(c)+ln(ln(c))-ln(\gamma)-\ln(\ln(t_m))}{\ln(t_m)+\ln(c)}$. The optimal level of information integration, denoted by θ^*, is determined as follows*

- *If$\frac{ln(c)}{ln(t)} < \frac{\gamma t^{\theta_0}}{c}$, $\theta^* = \theta^t$. item If $\frac{ln(c)}{ln(t)} \geq \frac{\gamma t^{\theta_0}}{c}$, $\theta^* = \theta_n$*

These preliminary results confirm the conditions under which it is economically viable to provide a more integrated multi-modal mobility service.

4 Next Steps

Given the complexity of contract design, we proceed by specifying cost functions for TSPs to facilitate the analysis. In particular, we assume that only variable costs are dependent on capacity, modeled as $c_i = c_{v,i} q_i^{\kappa_i}$, where κ_i represents economies of scale. To derive the optimal strategies, we will employ a backward induction approach, analyzing the decision-making process from TSPs to the platform. Given the risk-neutral utility functions of TSPs, we assume a linear payment structure in the contract design. Finally, we will validate our findings through numerical examples using real-world data, providing a more tangible and illustrative evaluation of the proposed framework.

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