A Multi-Actor Mobility as a Service (MaaS) Framework: Modeling Interactions and System Performance

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Short summary

Mobility as a Service (MaaS) integrates multiple transport modes into a unified platform but requires coordination among multiple actors, including users, transport service providers (TSPs), operators, and public authorities. While existing studies examine key aspects such as pricing, user behavior, and service integration, these elements are often analyzed separately, with limited attention to their combined effects under competition and policy intervention.
This study develops an integrated bi-level optimization model to represent these interactions within a multimodal network. The upper level represents a network-level planner that determines user assignment, TSP wholesale pricing, and incentive-related constraints, while the lower level captures the MaaS operator's profit-maximizing retail pricing response.
Applied to an extended Sioux Falls network, results show that MaaS adoption increases from about 28% under static pricing to nearly 40% when dynamic pricing and coordinated incentives are introduced. Among the tested policies, performance-based incentives achieve adoption levels comparable to fixed per-trip subsidies while requiring lower public expenditure. Moreover, as total travel demand increases, performance-based incentives remain effective and sustain high MaaS adoption, whereas fixed subsidies become less efficient.
Keywords: Mobility as a Service, Multimodal transport, Bi-level optimization, Pricing strategies, Government incentives

1 Introduction

Urban transportation systems are increasingly facing challenges related to congestion, environmental sustainability, and the efficient use of infrastructure. The growing demand for flexible and integrated mobility solutions has led to the emergence of MaaS, a paradigm that combines multiple transportation modes such as public transit, ride-hailing, and shared mobility into a unified digital platform. MaaS enables users to plan, book, and pay for multimodal trips seamlessly, thereby improving accessibility and potentially reducing reliance on private cars Jittrapirom et al. (2020); Sochor et al. (2018). Existing research has examined different dimensions of MaaS systems. On the demand side, several studies analyze user adoption and travel behavior, emphasizing the influence of pricing structures, service attributes, and socio-demographic factors on MaaS uptake Ho et al. (2021); Bahamonde-Birke et al. (2023). On the supply side, research has explored business models and platform design, highlighting the importance of governance frameworks and coordination among public and private actors Hensher et al. (2021); van den Berg et al. (2022). In addition, studies on pricing strategies suggest that dynamic and usage-based pricing can significantly affect modal choices and system efficiency Hörcher & Graham (2020); Caiati et al. (2020). From a regulatory perspective, several contributions investigate policy instruments and incentive mechanisms, such as subsidies and environmental pricing, to support MaaS deployment and promote sustainable mobility Balzer et al. (2023); Xi et al. (2023).
Recent work by Yao & Zhang (2024) develops a multimodal MaaS framework that integrates network representation and pricing mechanisms for service allocation. Building on this line of research, the present study extends the modeling framework by explicitly capturing the interactions among multiple stakeholders, including users, TSPs, MaaS operators, and public authorities. In particular, this study incorporates TSP competition and structured government incentive mechanisms,

including performance-based and threshold-based schemes, within a unified bi-level formulation. The upper level represents a network-level planner that determines user assignment, TSP wholesale pricing, and incentive-related constraints, while the lower level represents the MaaS operator's profit-maximizing retail pricing response. The framework incorporates competition among TSPs and evaluates multiple government incentive mechanisms, including participation, environmental, and performance-based schemes. By analyzing different policy scenarios, the model provides insights into how pricing strategies and incentive design jointly influence MaaS adoption, stakeholder outcomes, and overall system efficiency.

2 Methodology

This section presents a bi-level optimization framework to model interactions among MaaS stakeholders, including users, TSPs, the MaaS operator, and the government. The framework integrates pricing decisions, user path choice and demand allocation, and government incentive mechanisms within a unified multimodal system.

System framework

The MaaS platform acts as an intermediary between users and TSPs, integrating Mass Transit (MT) and Mobility-on-Demand (MoD) services. Users can access services either through MaaS or directly from TSPs. TSPs compete through pricing and service quality, while government authorities influence the system through participation, environmental, and performance-based incentives Figure 1.
The problem is formulated as a bi-level optimization model. The upper level represents a network-level planner that determines user assignment, TSP wholesale pricing, and incentive-related constraints. The lower level represents the MaaS operator's profit-maximizing retail pricing response.

Network and service modeling

The transportation system is represented as a directed graph $G(N, A)$, where N is the set of nodes and A is the set of links. Let M denote the set of transport service providers (TSPs). Each user $i \in I$ is associated with an origin-destination pair $w(i)$ and selects a path l from a feasible set $P_{w(i)}$.
Travel time is defined at the link level. For ride-sharing services, congestion effects are modeled using a standard Bureau of Public Roads (BPR) function.

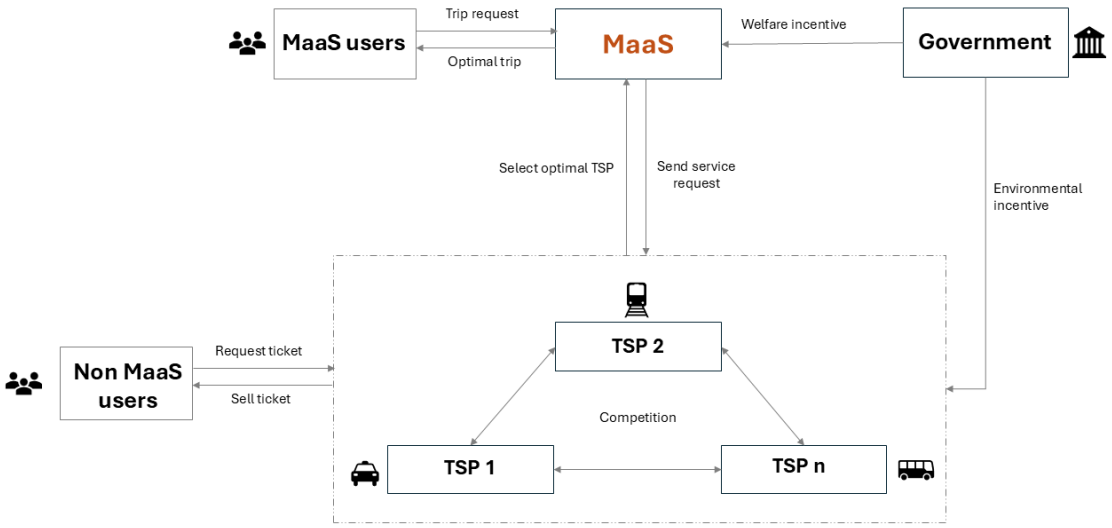


Figure 1: Relationship between different stakeholders

Service quality

For each provider $m \in M$, perceived service quality q_m is defined as:

$$q_m = \begin{cases} \ln\left(1 + \frac{t^{max}_{\text{pickup}}}{t_{\text{pickup,m}}}\right) & m \in M_{\text{MoD}} \\ \ln\left(1 + \frac{t^{max}_{\text{delay}}}{t_{\text{delay,m}}}\right) & m \in M_{\text{MT}} \end{cases} \tag{1}$$

where $t_{\text{pickup,m}}$ and $t_{\text{delay,m}}$ denote pickup time and service delay, and t^{max} parameters represent acceptable thresholds.
Path-level quality is aggregated as:

$$Q_l = \sum_{m \in M} \omega_{lm} \delta_{lm} q_m \tag{2}$$

where δ_{lm} is a binary parameter equal to 1 if service m is used on path l, and ω_{lm} is the share of distance traveled using service m on path l.
User satisfaction is defined as:

$$Sat_l = \beta \ln(1 + Q_l) \tag{3}$$

where β is a scaling parameter.

Service attractiveness

Service cost efficiency η_m is defined as:

$$\eta_m = \begin{cases} \frac{q_m}{P^S_m} \ln\left(1 + \frac{A_m}{V_m}\right) & m \in M_{\text{MoD}} \\ \frac{q_m}{P^S_m} \ln\left(1 + \frac{D_m}{S_m}\right) & m \in M_{\text{MT}} \end{cases} \tag{4}$$

where P^S_m is the wholesale price, A_m/V_m represents vehicle availability for MoD, and D_m/S_m represents service reliability for MT.
The normalized attractiveness index is:

$$\gamma_m = \frac{\eta_m}{\sum_{k \in M} \eta_k} \tag{5}$$

Utility modeling

User utility

$$PU_i = \sum_{l \in P_{w(i)}} \left[d^i_l (\theta Sat_l - P^{MaaS}_l) + \tilde{d}^i_l (\theta Sat_l - P^{Direct}_l) \right] \tag{6}$$

where d^i_l and $\tilde{d}^i_l$ are binary variables indicating MaaS and direct choices, P^{MaaS}_l and P^{Direct}_l are path costs, and θ converts satisfaction into monetary units.
TSP utility

$$SU_m = \sum_{i,l} \delta_{lm} \Omega_{lm} \left[\gamma_m d^i_l (P^S_m - C_m) + \tilde{d}^i_l (P^{Direct}_m - C_m) \right] + R_m + D_m E_m - TC_m \tag{7}$$

where Ω_{lm} is the distance traveled using service m on path l, C_m is the unit operating cost, R_m and E_m represent participation and environmental incentives, and TC_m denotes fixed costs.
MaaS operator utility

$$MU = \sum_{i,l,m} (P^{MaaS}_m - P^S_m) \delta_{lm} \Omega_{lm} d^i_l + I_{MaaS} - C_{MaaS} \tag{8}$$

where I_{MaaS} is a demand-based financial support triggered when MaaS usage exceeds a threshold.

Bi-level optimization

Upper level

$$\max_{P^S_m, d^l_i, \tilde{d}^l_i, z_m} \lambda_U \sum_{i \in I} PU_i + \lambda_S \sum_{m \in M} SU_m - \alpha \sum_{a \in A_{MoD-r}} x_a t_a(x_a) - \mu \sum_{m \in M_{MT}} N^{MT}_m t_{delay,m} \tag{9}$$

where λ_U and λ_S are weighting parameters, x_a is link flow, and N_m^{MT} is MaaS demand allocated to MT services.
subject to user choice constraints, TSP participation decisions (z_m), pricing bounds, and government budget constraints.
Lower level

$$\max_{P_m^{MaaS}} MU \tag{10}$$

subject to pricing bounds and incentive constraints.

Solution approach

The model is solved using an iterative procedure. The upper level determines demand allocation and wholesale prices, while the lower level updates MaaS retail prices. The process is repeated until convergence.

3 Results and discussion

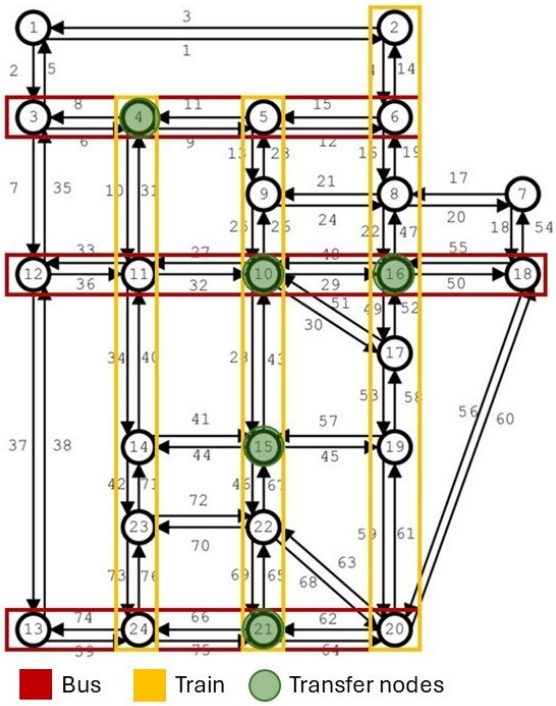


Figure 2: Sioux Falls network.

The proposed framework is evaluated on an extended Sioux Falls multimodal network derived from Yao & Zhang (2024). The original network contains 24 nodes and 76 directed links and is adapted to represent a MaaS platform integrating ridesharing, bikesharing, bus, and train services, while private cars remain available only outside MaaS. Bus and train operate on fixed corridors, and transfer nodes are introduced to enable intermodal trips. Figure 2 illustrates the case-study network.
To assess the effects of pricing, incentives, and competition, eight scenarios are considered (Table 1). These scenarios progressively introduce dynamic pricing, competition among TSPs, and alternative government support mechanisms. Scenario 7 is the main proposed configuration, combining dynamic pricing and competition with targeted incentives, while Scenario 8 serves as a benchmark based on a fixed per-trip subsidy.
Figure 3 presents MaaS demand share across the eight scenarios. Without incentives, MaaS adoption remains limited, ranging from about 28% to 31% in Scenarios 1, 3, and 5. Cost-based incentives increase adoption moderately, while the joint introduction of dynamic pricing, competition, and targeted incentives produces stronger effects. MaaS share rises to about 35% in Scenario 6, reaches

Table 1: Overview of experimental scenarios used to evaluate the MaaS platform under different pricing, policy, and market conditions.

Scenario	**Pricing**	**Incentives**	**Competitiveness**
Scenario 1	Static Prices	No incentives	No competition
Scenario 2	Static Prices	Cost-based incentives	No competition
Scenario 3	Dynamic Prices	No incentives	No competition
Scenario 4	Dynamic Prices	Cost-based incentives	No competition
Scenario 5	Dynamic Prices	No incentives	With competition
Scenario 6	Dynamic Prices	Cost-based incentives	With competition
Scenario 7	Dynamic Prices	Combined incentives	With competition
Scenario 8	Dynamic Prices	Fixed per-trip incentive	With competition

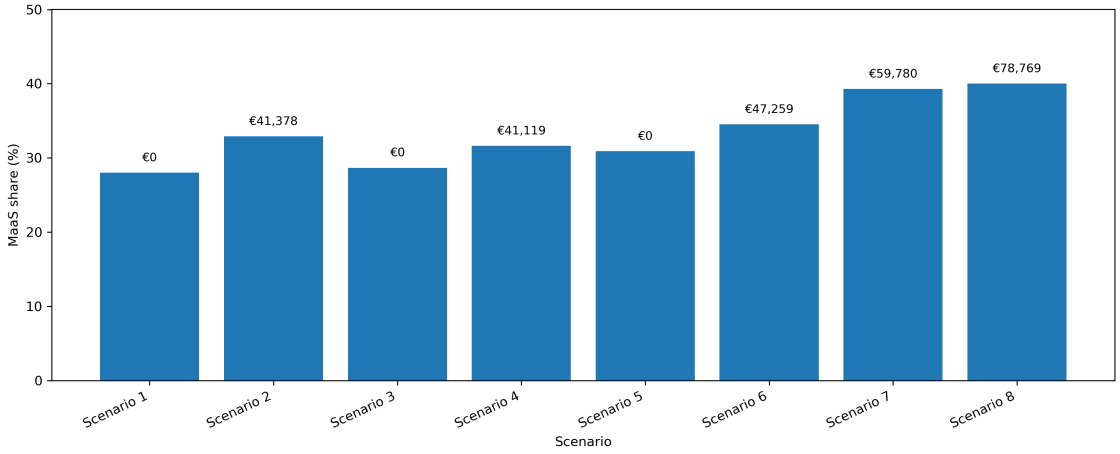


Figure 3: Total MaaS share across scenarios with total government support.

approximately 39% in Scenario 7, and slightly exceeds 40% in Scenario 8. Although Scenario 8 produces the highest adoption, the gain over Scenario 7 remains small relative to the additional public support required. This suggests that targeted incentives can achieve nearly the same adoption level as fixed subsidies with better fiscal efficiency.

To examine robustness under higher demand, the model is further evaluated for three representative cases: Scenario 5 (competition without incentives), Scenario 7 (targeted incentives), and Scenario 8 (fixed per-trip subsidy).

Figure 4 reports the resulting MaaS shares. At baseline demand, Scenarios 7 and 8 already outperform Scenario 5. As demand increases, Scenario 7 performs best: MaaS adoption rises strongly and remains high at larger demand levels. By contrast, Scenario 8 initially improves adoption but then declines at higher demand, indicating that a fixed subsidy becomes less effective when system conditions intensify. Scenario 5 remains lower throughout. These results show that the targeted incentive structure in Scenario 7 is more robust, since it sustains high MaaS participation under growing demand without requiring proportional support for each additional trip.

4 Conclusions

This study addresses an important gap in the MaaS literature by explicitly modeling the interaction between pricing strategies, TSP competition, and government incentive design within a unified framework. The proposed bi-level model captures user path choice, TSP wholesale pricing, MaaS operator decisions, and incentive mechanisms within a multimodal network.

The numerical results highlight the importance of combining dynamic pricing, competition, and targeted incentives. In the absence of incentives, MaaS adoption remains limited at around 28–31%. When these mechanisms are introduced, adoption increases significantly, reaching approximately 39–40% under coordinated policy and market conditions. Although a fixed per-trip subsidy achieves

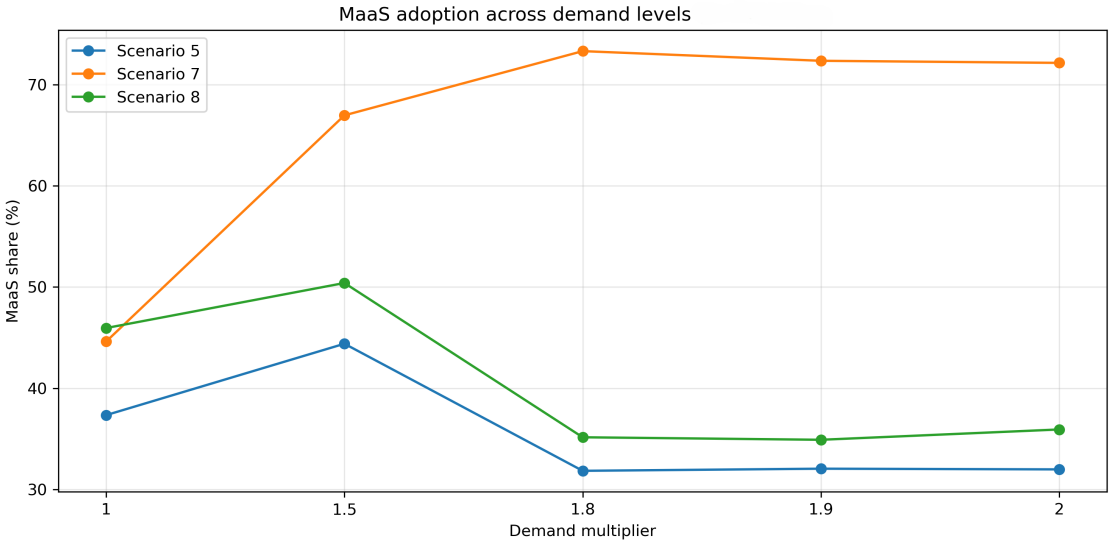


Figure 4: MaaS adoption across different demand levels.

slightly higher adoption, the improvement remains marginal relative to the additional public expenditure required.
A key finding is that performance-based incentive schemes provide a more efficient alternative. The proposed targeted mechanism achieves nearly the same MaaS adoption levels while maintaining better control over public spending. Moreover, under increasing demand, this incentive structure remains more robust, sustaining high MaaS participation while fixed subsidies become less effective.

Acknowledgements

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