# An Integrated Simulation Framework for Evaluating Multimodal Mobility-as-a-Service Systems

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## SHORT SUMMARY

Existing Mobility-as-a-Service (MaaS) simulation studies often lack full integration between dynamic demand generation and multimodal supply coordination, limiting their ability to capture realistic demand-supply interactions across transport modes. This study presents an integrated simulation framework that combines activity-based travel demand generation using SimMobility, mesoscopic traffic simulation with Aimsun, and a centralized MaaS controller to coordinate multimodal services. The framework is implemented on a virtual urban network modeled after Singapore. Experiments indicate that MaaS subscription offering discounted public transport fares shifts users toward public transport, reduces overall road usage, and improves Mobility-on-Demand service performance. At the same time, public transport systems accommodate the increased demand without loss of service quality. The proposed framework captures key cross-modal interactions and provides a practical tool for evaluating MaaS policies under realistic urban conditions.

**Keywords**: Integrated simulation framework, Mobility-as-a-Service, Mobility-on-Demand, Multimodal transport

## 1 INTRODUCTION

Urban transport systems have evolved rapidly in recent years, with cities offering a growing mix of mobility options including public transport, ride-hailing, bike-sharing, and other shared services. While this expansion has improved accessibility and flexibility, it has also made travel behavior more complex and less predictable, as these services typically operate independently with separate platforms, booking systems, and pricing structures. Mobility-as-a-Service (MaaS) was proposed as a response to this fragmentation. MaaS aims to integrate public transport and private shared mobility services into a unified digital platform that enables seamless, personalized, door-to-door travel (Kamargianni et al., 2016; Jittrapirom et al., 2017). By offering flexible service options and subscription-based bundles, MaaS has the potential to reduce reliance on private car ownership, improve system efficiency, and support a transition toward more sustainable urban mobility (Daou & Leurent, 2024; An & Shen, 2025).

To assess the system-wide impacts of MaaS, agent-based simulation (ABS) approaches have been widely adopted, which allow the analysis of individual mode choice dynamics under varying scenarios, including changes in network conditions, service configurations, and pricing strategies (DeSoto, 2022; Nahmias-Biran et al., 2022; Postorino & Sarnè, 2024). Activity-based platforms such as SimMobility and MATSim can generate heterogeneous travel patterns from population-level data, capturing diversity in daily activity schedules and mode choice (Becker et al., 2020; Nahmias-Biran et al., 2022). On the supply side, studies have explored multimodal coordination through various approaches, including integration of car-sharing, bike-sharing, and public transit at city scale (Becker et al., 2020), multimodal supply-demand matching (Ding et al., 2023), and reinforcement learning for multimodal journey planning (Chu & Guo, 2023). However, these studies frequently assume fixed network travel times or rely on simplified grid networks (Ding et al., 2023; Postorino & Sarnè, 2024), bypassing the mesoscopic and microscopic dynamics of actual traffic flow. Consequently, the resulting MaaS systems are evaluated in isolation from real-world road capacity constraints, queue spillbacks, and congestion externalities. Recent work has addressed this challenge by

integrating activity-based models with mesoscopic traffic assignment through iterative equilibrium-seeking algorithms, and has applied this integration to evaluate on-demand mobility services at city scale (Agriesti et al., 2025a,b). However, these efforts focus on a single on-demand mode and do not incorporate multimodal service coordination. In parallel, whole-system simulation frameworks have been proposed that couple demand generation, multimodal service control, and physical network dynamics within a unified environment. These frameworks typically comprise four tightly coupled core modules: (1) a MaaS integrated controller that centrally manages trip booking and resource coordination across service providers; (2) demand generation and behavioral decision models that capture the dynamic evolution of daily activity chains; (3) integration of service provider control logic with physical network dynamics; and (4) a system-level evaluation mechanism for quantifying network-wide performance indicators (Kamargianni et al., 2019; Becker et al., 2020; Li, 2022). However, many proposed architectures remain in the conceptual design stage and have not been implemented as fully operational simulation systems (Kamargianni et al., 2019; Daou & Leurent, 2024), leaving their ability to capture realistic cross-modal feedback largely unvalidated.

This study develops an integrated simulation framework that combines activity-based travel demand, mesoscopic network dynamics, and a system-level MaaS controller coordinating multimodal transport services in real time. The objective is to examine the effects of supply-side resource allocation and demand-side MaaS subscription on multimodal service performance and interactions across transport modes at the network level. Methodologically, the activity-based simulation platform SimMobility is used to generate individual daily travel patterns and produce time-stamped origin-destination request streams as dynamic demand input. The generated demand is then integrated into the Aimsun mesoscopic traffic simulation environment. Meanwhile, a system-level MaaS controller communicates with Aimsun to coordinate multimodal resources and govern the evolution of network performance. By adopting this whole-system simulation perspective, this study takes a step toward bridging the gap between conceptual framework design and operational simulation execution, providing a fully implemented, dynamic assessment instrument for MaaS policy analysis under varying demand and operational conditions.

## 2 METHODOLOGY

### *Integrated Simulation Framework*

An integrated four-layer simulation framework is developed (Figure 1) to capture multimodal system interactions. The first layer, *Demand Generation*, uses population data to drive the activity-based simulation platform SimMobility, which generates individual daily activity chains and converts them into time-stamped origin–destination request streams that serve as dynamic demand input. The second layer, *Dynamic Traffic Simulation*, is implemented using Aimsun's mesoscopic traffic simulation, which models the road network and captures realistic vehicle travel times, queue formation, and congestion dynamics. The third layer is the *system-level MaaS Controller*, which interfaces bidirectionally with Aimsun. By continuously receiving real-time network state information, the controller monitors the operational status and manages service dispatching across multiple parallel transport modules: Mobility-on-Demand (MoD), Autonomous Mobility-on-Demand (AMoD), Bus, Mass Rapid Transit (MRT), and Micro-mobility. The fourth layer, *System Evaluation*, aggregates system performance metrics such as service rate, wait time, and vehicle-kilometers traveled (VKT). The framework also supports a day-to-day feedback mechanism that feeds performance outcomes back to SimMobility, enabling agents to update their travel behavior across successive simulation days.

### *MaaS System Controller*

The MaaS system controller is the centralized decision-making hub that coordinates all transport modes within a unified time-windowed assignment loop. The controller is invoked at a fixed interval of 60 seconds. At each run, it receives real-time network state information, including link travel times, vehicle positions, and queue lengths, from the mesoscopic traffic simulation, so that all assignment decisions reflect current congestion conditions rather than static or free-flow estimates. Newly arrived requests are classified by their designated mode, and the controller executes mode-specific assignment routines before updating vehicle commands.

Each transport mode operates through an independent assignment module. For MoD, the controller constructs a cost matrix based on the estimated pickup travel time from each available vehicle to each pending request, retrieved from the Aimsun Estimated Time of Arrival (ETA) API. Vehicle-request pairs exceeding a 10-minute pickup threshold are excluded, and the remaining assignments are optimized using the Hungarian algorithm (Kuhn, 1955) to minimize total pickup travel cost. Requests that remain unmatched for more

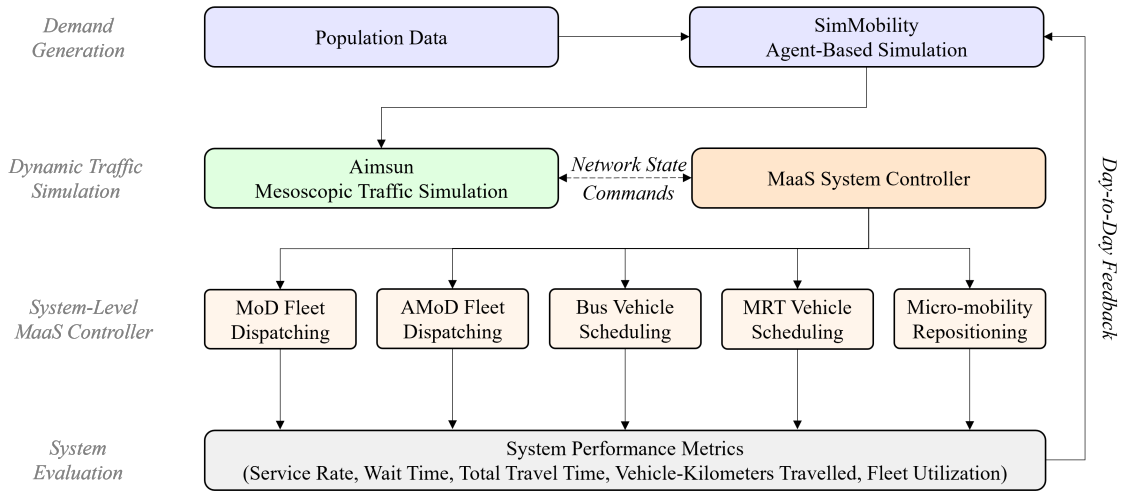



Figure 1: Architecture of the integrated MaaS simulation framework.

than 10 minutes after submission are marked as failed and removed from the active request pool, which means these requests are left unserved. For bus and MRT, vehicles operate according to their pre-defined routes and timetables, stopping at designated stops for passenger boarding and alighting. The allocation of passengers to specific transit lines is determined by Aimsun's built-in Dynamic Transit Assignment, which evaluates path costs by comparing transit and walking alternatives and selects the minimum-cost route for each origin-destination pair.

This architecture decouples the operational logic of individual modes from the system-level coordination layer: each assignment module manages its own fleet independently, while the controller synchronizes all modules through a shared real-time network view. Adding a new transport mode requires only the implementation of its corresponding assignment module. This design ensures both cross-mode independence and system-wide extensibility.

***Virtual City Network and Demand Scenarios***

This study uses Virtual City as the experimental environment, which is a prototypical urban network generated to resemble the land-use patterns, travel behavior, and activity schedules observed in Singapore (Basu et al., 2018). The total population is 351,000 individuals (approximately 10% of Singapore), with an average tour rate of 1.14 per person. The road network consists of 95 nodes, 286 segments, and 254 links. The public transit network comprises 12 bus lines and 86 bus stops, alongside 4 MRT lines serving 20 stations, together covering 24 Traffic Analysis Zones (Figure 2).

The baseline demand scenario is generated by SimMobility using daily activity schedules (DAS), which represent individual sequences of activities and associated travel over a day (Basu et al., 2018). Within the pre-day simulation, DAS are processed to generate trip chains that serve as input demand for Aimsun. The resulting travel demand spans four transport modes: MoD, bus, MRT, and private car. Here, MoD encompasses ride-hailing and shared rides, in which vehicles are dynamically dispatched to serve real-time passenger requests, in contrast to bus and MRT services that operate on fixed routes and timetables. Private car trips are not managed by the MaaS controller; instead, they are incorporated into Aimsun as time-varying origin–destination matrices, contributing to background road network congestion.

Two demand scenarios are considered. In the *baseline scenario*, 92,455 MaaS-controlled trip requests are distributed over a 24-hour period (03:00–03:00 the following day), comprising 19.9% MoD (18,373 trips), 63.5% bus (58,677 trips), and 16.7% MRT (15,405 trips), alongside 53,973 private car trips. In the *MaaS subscription scenario*, users adopt a MaaS package that provides a 50% fare reduction on both bus and MRT services. This 50% discount parameter setting aligns with recent agent-based MaaS simulation studies that apply a 50% flat discount across core transit modes to evaluate system-wide impacts (DeSoto, 2022; Li, 2022). The discount level is also consistent with attribute values used in empirical stated-preference experiments on MaaS bundle design (Wang et al., 2024). In this study, this policy increases MaaS-controlled demand to 99,612 trips (+7.7%) and induces a modal shift from MoD to public transport: MoD demand decreases by 9.2% (16,692 trips), while bus and MRT demand increase by 11.1% (65,202 trips) and 15.0% (17,718 trips), respectively. Car demand decreases marginally to 53,305 trips ($-1.2\%$). Both scenarios share an identical transit network configuration, enabling direct comparison of system responses to demand redistribution.

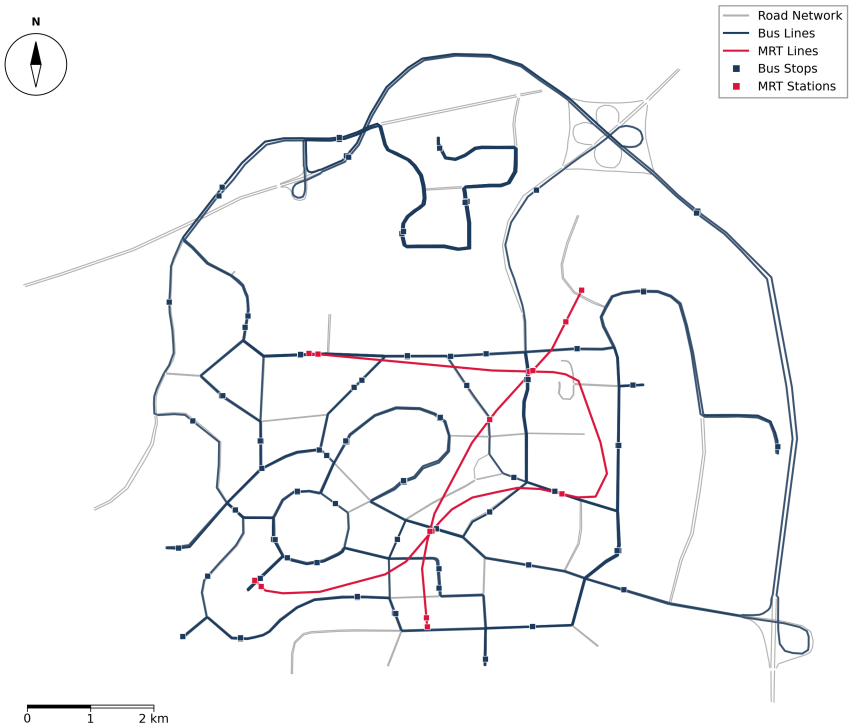



Figure 2: Virtual City transport network.

## 3 RESULTS AND DISCUSSION

***Base-Case Characterization***

The 300-vehicle MoD configuration is adopted as the reference scenario. Across the three modes, the system achieves markedly different service completion rates: MRT attains 99.7%, bus 98.1%, and MoD 74.0%. The contrast reflects the asymmetry between fixed-schedule transit, which serves predetermined routes regardless of localized demand pressure, and MoD, whose performance is tightly coupled to fleet availability and spatial matching efficiency. The small proportion of uncompleted bus and MRT trips is attributable to requests whose departure times fall outside the operating hours of the relevant transit lines.
The temporal dynamics of MoD operations reveal a pronounced bi-modal demand structure (Figure 3). During the morning peak (07:00 to 09:00) and afternoon peak (17:00 to 19:00), fleet utilization exceeds 96% and the unserved waiting pool accumulates over 300 concurrent requests; the 300-vehicle fleet is momentarily saturated and supply falls short of demand. Between the two peaks, utilization drops to 20–50% and the waiting pool remains effectively zero, so incoming requests are assigned near-immediately. This concentrated demand structure directly shapes service quality: requests submitted during the saturation windows inevitably experience longer waits due to fleet scarcity.
Figure 4 shows the per-mode assignment volume over the 24-hour simulation period. Bus and MRT assignment volumes both exhibit strong morning-peak dominance, whereas MoD assignment remains capped at approximately 1,100 to 1,300 requests per hour during both peaks despite substantially higher morning demand. This ceiling effect reflects the fleet capacity constraint: when the 300-vehicle fleet is near-fully utilized, the number of assignments per callback is bounded by vehicle availability rather than demand intensity.
The three modes exhibit distinct service characteristics. For MoD, completed trips have an average wait time of 5.48 min and an average in-vehicle time of 10.12 min, yielding a mean door-to-door trip time of 15.60 min. For public transit, total travel time averages 53.41 min for bus and 51.77 min for MRT. Therefore, MoD offers substantially faster door-to-door service, but is constrained by fleet capacity during peak periods, whereas public transit provides reliable service at the cost of longer journey times.

***Supply-Side Sensitivity: MoD Fleet Scaling***

To evaluate how supply-side provisioning affects MaaS system performance, five MoD fleet sizes are tested under the baseline demand scenario. Table 1 summarizes the resulting performance indicators. MoD service

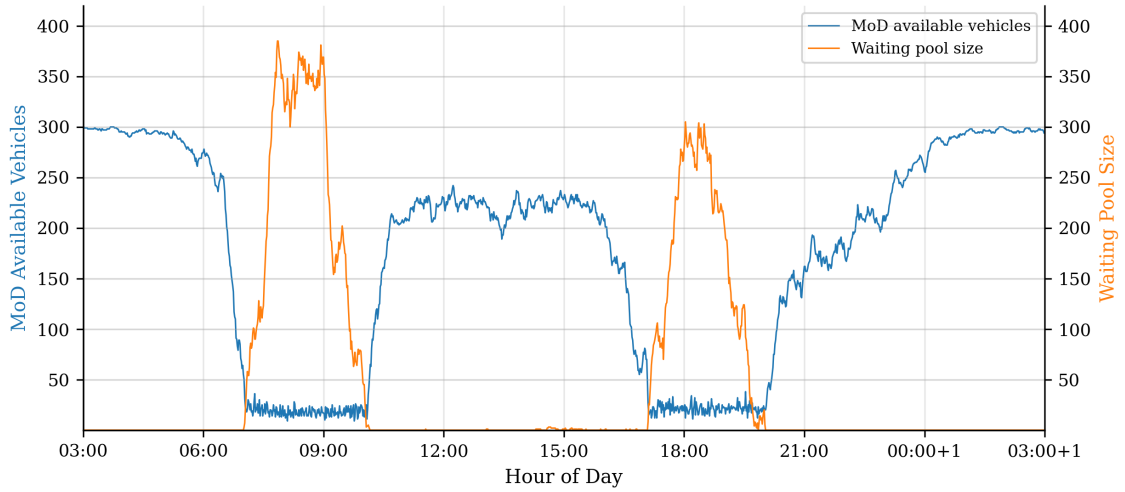



Figure 3: MoD fleet availability and unserved waiting pool over 24 hours.

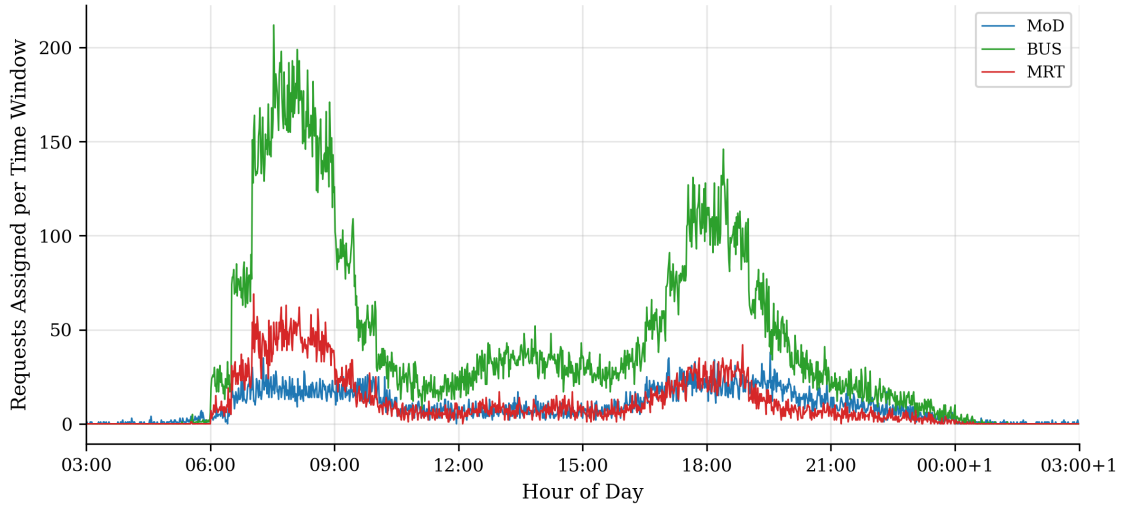



Figure 4: Per-mode assignment volume over 24 hours (300-vehicle MoD baseline).

rate exhibits a strongly nonlinear response to fleet scaling: expanding from 100 to 200 vehicles yields the largest marginal gain of 19.8 percentage points (pp), while successive 100-vehicle increments deliver progressively smaller returns (+12.3, +8.3, and +5.8 pp respectively). This diminishing-returns pattern reflects a transition from a supply-constrained regime, where vehicle scarcity is the binding constraint, to a distribution-constrained regime, where spatially dispersed demand during peak periods limits further improvement. The 300-vehicle configuration represents the efficiency frontier for this network, achieving the minimum average door-to-door MoD travel time (15.60 min) with a favorable balance between per-vehicle productivity (45.3 trips/vehicle) and total road consumption (122,155 km VKT).

Expanding the MoD fleet from 100 to 500 vehicles more than doubles total VKT (from 70,835 to 147,791 km), while per-vehicle productivity drops from 77.1 to 32.4 trips per vehicle, indicating that additional fleet capacity yields diminishing operational returns. Meanwhile, public transit service rates remain stable across all fleet scales (bus $\geq$ 97.9%; MRT $\geq$ 99.6%), confirming that the modular architecture of MaaS controller prevents cross-mode interference. However, a measurable congestion externality emerges on the shared road network: bus end-to-end travel time increases monotonically from 52.90 to 54.30 min (+2.6%) as MoD VKT doubles, reflecting the additional vehicular load placed on road segments shared by buses. This cross-modal feedback, captured because the framework embeds fleet operations within a live mesoscopic traffic simulation, demonstrates the importance of network-realistic evaluation for MaaS system design.

Table 1: System performance metrics across MoD fleet sizes (baseline scenario).

| **Metric** | **100 veh** | **200 veh** | **300 veh** | **400 veh** | **500 veh** |
|---|---|---|---|---|---|
| MoD service rate (%) | 41.9 | 61.7 | 74.0 | 82.3 | 88.1 |
| Avg. wait $D_1$ (min) | 6.85 | 5.82 | 5.48 | 5.36 | 5.21 |
| Avg. in-vehicle $D_2$ (min) | 9.53 | 9.78 | 10.12 | 10.52 | 10.95 |
| Avg. total travel (min) | 16.38 | 15.61 | 15.60 | 15.88 | 16.16 |
| Trips per vehicle | 77.1 | 56.7 | 45.3 | 37.8 | 32.4 |
| Total VKT (km) | 70,835 | 102,075 | 122,155 | 137,150 | 147,791 |
| VKT per vehicle (km) | 708.3 | 510.4 | 407.2 | 342.9 | 295.6 |
| BUS service rate (%) | 98.1 | 98.1 | 98.1 | 97.9 | 97.9 |
| BUS total travel time (min) | 52.90 | 53.35 | 53.41 | 53.66 | 54.30 |
| MRT service rate (%) | 99.7 | 99.7 | 99.7 | 99.7 | 99.6 |
| MRT total travel time (min) | 50.97 | 51.37 | 51.77 | 51.73 | 52.86 |

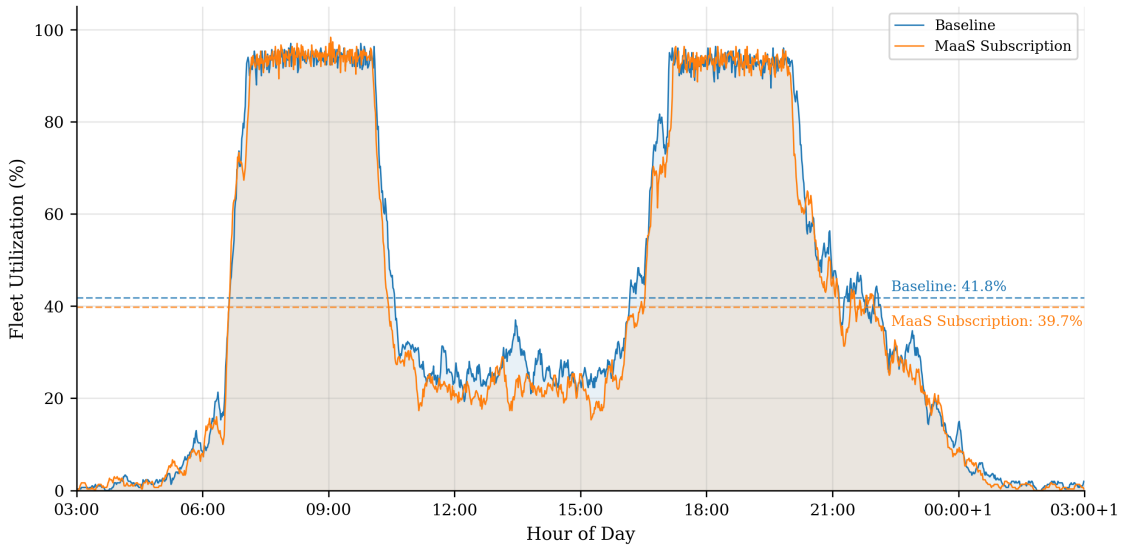



Figure 5: MoD fleet utilization over 24 hours under baseline and MaaS subscription scenarios.

***Demand-Side Sensitivity: Baseline vs. MaaS Subscription***

Under the MaaS subscription scenario, the total MaaS-controlled demand increases by 7.7%, accompanied by a pronounced modal rebalancing: MoD demand contracts by 9.2%, while bus and MRT ridership increase by 11.1% and 15.0% respectively.

Figure 5 compares MoD fleet utilization across the two scenarios. Both scenarios exhibit a bi-modal utilization profile, with peaks exceeding 90% during 07:00–09:00 and 17:00–19:00. During these saturated periods, utilization remains virtually identical between the two scenarios, because the fleet is near-fully committed and any demand reduction is immediately absorbed by previously unserved requests. In contrast, off-peak and evening hours show a substantial utilization drop under the subscription scenario, lowering daily average utilization from 41.8% to 39.7% and total MoD VKT from 122,155 to 113,402 km ($-7.2\%$). MoD service rate improves marginally (75.8% vs. 74.0% baseline) with average wait time effectively unchanged (5.43 vs. 5.48 min).

Regarding public transit, Figure 6 shows that the subscription-induced demand increase is distributed unevenly across time of day and modes. Bus boarding gains are concentrated in the afternoon and evening, while morning-peak boarding is virtually unchanged. MRT displays a different pattern: morning-peak boarding actually declines, while the afternoon and evening periods see substantial increases. This contrasting response suggests that the subscription interacts differently with the catchment areas and scheduling of the two modes. PT service rates remain stable (bus 98.3%; MRT 99.5%), though bus average travel time increases by 1.05 min as higher ridership extending dwell times at stops.

Taken together, the MaaS subscription improves system performance along four dimensions. First, it achieves modal rebalancing, shifting passengers from capacity-constrained flexible services to fixed-route

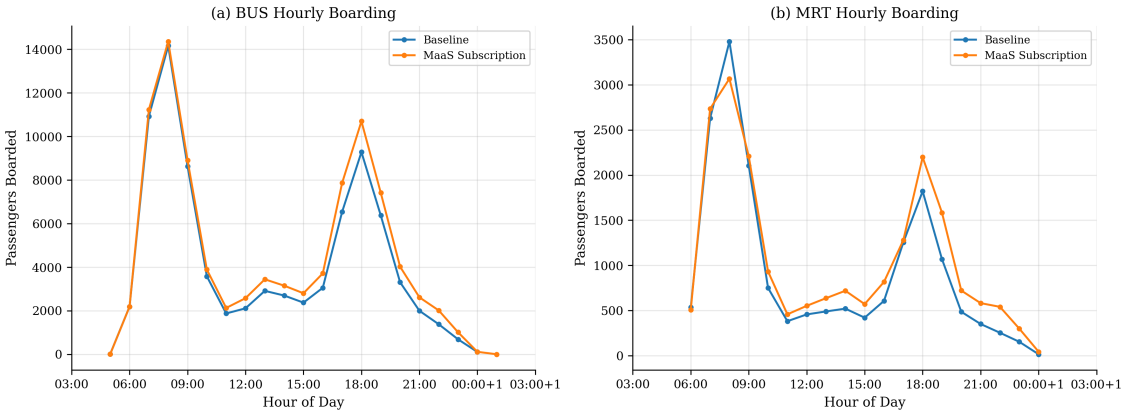



Figure 6: Hourly PT boarding volumes under baseline and MaaS subscription scenarios.

transit. Second, it delivers a road footprint reduction: MoD VKT decreases by 7.2% while PT operates on fixed schedules regardless of ridership, yielding a net reduction in system-wide road consumption. Third, MoD service quality improves: the released peak-hour capacity serves previously failed requests, raising the service rate from 74.0% to 75.8% without increasing wait times. Fourth, PT absorbs the additional demand without degradation, with only a modest increase in bus travel time (+1.05 min).

## 4 Conclusions

This study developed and demonstrated an integrated simulation framework for MaaS policy analysis that couples activity-based travel demand (SimMobility), mesoscopic traffic dynamics (Aimsun), and a novel system-level multimodal MaaS controller operating across MoD, bus, and MRT services. Unlike existing whole-system frameworks that rely on simplified network abstractions or disconnect demand generation from operational simulation, the proposed architecture enables dynamic feedback among travel behavior, fleet decisions, and network congestion.

Three principal findings emerge. On the supply side, MoD service rate exhibits a strongly nonlinear response to fleet scaling, with diminishing marginal gains consistent with a transition from a supply-constrained to a distribution-constrained regime; the 300-vehicle configuration represents the efficiency frontier for this network, while bus travel time rises monotonically with MoD VKT under fleet scaling, revealing a measurable congestion externality on the shared road network. On the demand side, the MaaS subscription scenario demonstrates that MaaS implementation can rebalance the modal split, contracting MoD demand and reducing MoD VKT, while PT absorbs the redirected demand without service degradation and MoD service quality improves as released capacity serves previously failed requests. However, fleet utilization during both peaks remains above 90% under the subscription scenario, indicating that demand-side instruments alone cannot resolve peak-period saturation and that complementary supply-side strategies such as time-varying fleet deployment are needed to further improve service quality.

Despite these findings, several limitations should be noted. The current MoD formulation assigns one vehicle per trip without ride-pooling, which overstates road consumption and understates potential vehicle efficiency at scale. The virtual city, while structurally representative, differs from any real urban network, and replication with an empirical city case is needed to validate the findings. Future work will implement multimodal transport coordination across all service modes and assess day-to-day feedback to capture the dynamic evolution of travel behavior over successive simulation days. Nonetheless, the framework reproduces realistic temporal demand patterns, quantifies cross-modal interactions, and captures system-level responses to MaaS subscription, supporting its use as an operational tool for MaaS planning and policy analysis.

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