Smart Urban Freight Transport: Assessing the Opportunity Offered by Automated Vehicles

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1 Introduction

Urban freight transport plays a key-role in ensuring timely deliveries to households, businesses, and retailers. However, its integration within congested urban areas generates significant externalities [1, 2]. One of the most persistent issues is the lack of adequate parking infrastructure for delivery vehicles. In many cities, delivery bays are undersized, poorly located, or entirely absent, forcing drivers to double-park, stand illegally, or use on-street spaces not intended for loading and unloading. These behaviours reduce road capacity, worsen bottlenecks, slow traffic flow, and increase conflicts with pedestrians and cyclists. Their cumulative impact extends beyond local delays, contributing to broader inefficiencies in the transport network [3–5].

The consequences of inadequate delivery bay management are multidimensional [6]. From a traffic engineering perspective, illegal parking reduces effective lane capacity, disrupts signal coordination, and raises accident risk at intersections or narrow segments. Environmentally, longer delivery times, cruising for parking, and added congestion increase fuel consumption and emissions. For logistics operators, these inefficiencies elevate operational costs and reduce reliability, while city administrations face difficulties balancing mobility, safety, and sustainability objectives [2, 7, 8].

Emerging technologies, particularly automated vehicles, offer new opportunities to address these limitations. When combined with digital parking management, automated vehicles (AVs) can adapt routes in real time, pre-book loading bays, minimise inefficient practices, and support a more efficient and coordinated use of urban delivery infrastructure. This study therefore investigates two key research questions:

- how does the presence of delivery bay management influence the effectiveness of AVs in mitigating inefficiencies in dense urban delivery operations?
- what is the added value of integrating AVs with telematics-based tools for real-time booking, monitoring, and control of delivery bays?

The remainder of the paper is structured as follows. Section 2 briefly presents the current background and points out the advancement proposed by such a study. Then,

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Sect. 3 outlines the methodology proposed and its application to a real case study is given in Sect. 4. Finally, conclusions and the road ahead are drawn in Sect. 5.

2 Background

Urban freight challenges are widely studied, particularly the contribution of delivery operations to road safety risks, congestion, and emissions. A key issue is the persistent lack of suitable loading and unloading areas, which forces operators to adopt practices that compromise traffic efficiency and safety. Cities such as Rome face shortages of dedicated spaces, prompting behaviors like double-parking or occupying inappropriate on-street areas, which reduce road capacity and amplify network inefficiencies [9, 10]. Traditional mitigation measures have relied on regulatory tools, including time-window restrictions, stricter enforcement of illegal parking, and the creation of urban consolidation centers [11, 12]. While these strategies offer partial benefits, they also encounter significant barriers, such as high administrative costs, limited compliance, and operational resistance. Time windows can ease peak-hour congestion but reduce flexibility and may create noise concerns for residents. Enforcement is costly and unevenly implemented across cities. Consolidation centers can reduce truck trips but often struggle financially without long-term public support.

Technological innovations have recently sought to enhance freight coordination. Intelligent Transport Systems provide real-time information, dynamic routing, and parking guidance, yet their integration into freight logistics remains limited, particularly regarding the digital management of loading and unloading bays [13]. While analogous booking and rebalancing problems arise in shared micromobility (e.g., bikes and scooters), urban freight transport differs due to fixed consignee delivery requirements, specific service time-windows, and kerbside safety constraints. Existing reservation initiatives are often experimental and not systematically connected to routing systems, creating a mismatch between infrastructure availability and operational needs [14–17]. AVs offer a transformative potential by enabling more precise, predictable, and flexible delivery operations. When combined with real-time telematics for bay reservation, AVs shift freight management from reactive to proactive, supporting the principles of connected, cooperative, and automated mobility (CCAM). This study introduces and tests an integrated architecture that links automated delivery vehicles with a booking and control platform for loading and unloading bays. Using a simulation-based approach applied to Rome Limited Traffic Zone, it evaluates multiple performance indicators across different scenarios. The contribution is threefold: an integrated AV–telematics framework, a methodology for ex-ante scenario assessment, and insights into how automation can enhance sustainable urban freight.

3 Proposed Methodology

This study employs an agent-based simulation in AnyLogic (vers. 8.9.5) to evaluate urban freight delivery performance, focusing on delivery bay occupancy. Two scenarios are analyzed: a *base case* where automated shuttles operate without reservation tools, and a *smart scenario* where shuttles use a physical digital infrastructure (PDI) system enabling real-time bay monitoring and booking.

The methodology includes designing the simulation environment, defining agents, and setting schedules. *Car agents* represent general traffic and create disruptions, while *SUV agents* represent automated delivery shuttles with identical specifications. Each shuttle follows a schedule involving four or five bays, with a flexible sequence based on real-time bay availability.

In the *base scenario*, AVs depart and proceed sequentially to the next bay on their schedule without any advance knowledge of its occupancy. Upon arrival, if the bay is occupied by another shuttle, the delivery fails and is deferred; the occupied bay is moved to the end of the AV queue and the AV serves the next available location.

The *smart scenario* relies on PDI infrastructure enabling real-time information exchange. A central system (*booking* system) updates bay status and allows shuttles to reserve an available bay before departure, preventing trips to occupied spaces. If no assigned bay is free, shuttles wait in designated lots (*waiting* logic). This approach removes failed parking attempts and replaces chaotic searching with predictable, efficient waiting periods.

The *simulation* uses vary key parameters to assess performance under different conditions: shuttle fleet size (i.e., 3, 4, 5 and 6 Avs), 4- or 5-stop tours, operation times (i.e., randomly between 3 and 40 min), departure intervals (i.e., between 10 and 12 min—uniform distribution), and 30 replications for scenarios for statistical robustness. Disruptions such as delays or illegal parking are included. KPIs measure total service time, bay operation time, waiting time (PDI), failed attempts (*base* scenario only), travel distance, and average performance across replications.

4 Application to a Real Case Study

The proposed methodology was applied to the Tridente limited traffic zone (LTZ) in Rome (Fig. 1). Performance comparisons considered average time, distance, and disruptions. Nine delivery bays were modelled, with eleven additional reserved lots in the *smart* scenario for delayed AVs. A single warehouse acted as the central depot for all tours.

The analysis on travel distance and service disruption shows that shuttles in the base scenario travel longer distances due to failed parking attempts and repeated network reentry (Fig. 2). The smart PDI scenario reduces unnecessary travel by directing shuttles only to available bays or waiting lots. Distance differences are larger in 5-stop destinations, such as 5401 m *vs.* 4150 m for five shuttles. The PDI system also eliminates failed parking attempts entirely. In contrast, failures increase sharply in the base scenario with more shuttles and stops, rising from 9.57 (3 AVs) to 26.27 (6 AVs) in 5-destination tours. This demonstrates that without coordination, scaling operations leads to disproportionate disruptions and inefficiencies.

The total service time (another measure of efficiency used) combines operations time and non-productive waiting or searching. Average operations time remains stable at about 15 min in the analyzed scenarios, meaning that differences in total service time arise mainly from additional travel or waiting. The PDI scenario provides clear benefits under moderate congestion, such as with four to 5 AVs on 4-destination tours. However, in highly saturated conditions, particularly 5-destination tours with 6 Avs, the base scenario can occasionally show slightly lower average service time. This occurs because, under



Fig. 1. The simulation area with delivery bays (blue points) and the depot (red point).

heavy demand, shuttles in the smart scenario experience prolonged predictable waits in reserved lots, reaching more than five minutes on average. This highlights that waiting is not always the most efficient strategy, and further improvements are needed to better manage unexpected disruptions. In contrast, base-scenario shuttles may benefit from opportunistically finding an available bay, sometimes yielding a lower average time despite overall inefficiency (Fig. 3).

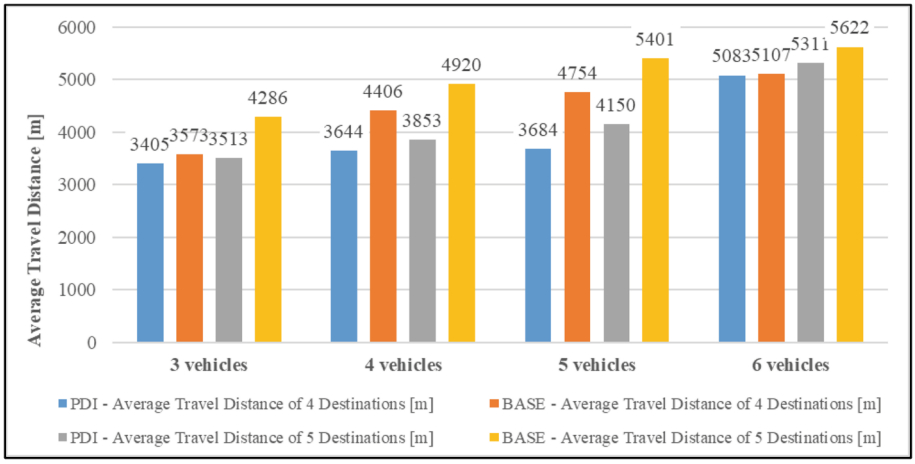


Fig. 2. Comparison of travel distances

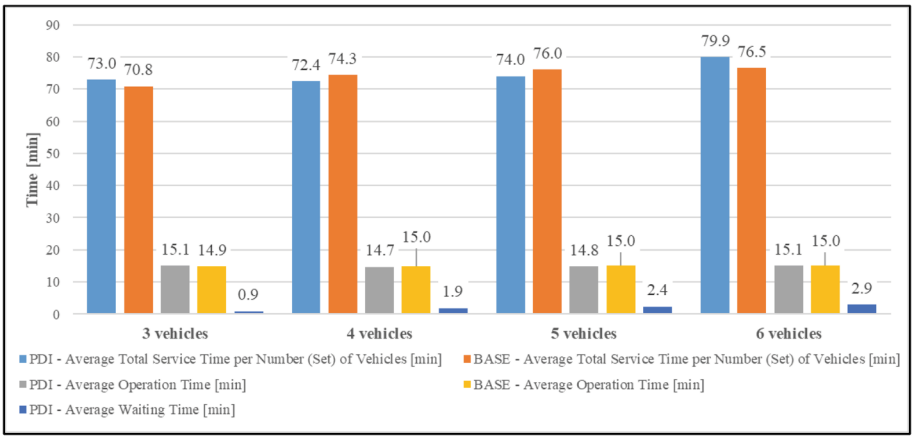


Fig. 3. Time comparison for 4-destination schedules

The base scenario also exhibits high *unpredictability*. The standard deviation of failed parking attempts increases notably with fleet size, exceeding eight failures for six shuttles in five-destination schedules. Distance variability is similarly extreme, surpassing 3000 m for a 5-vehicle fleet, making planning difficult. The PDI scenario offers far greater consistency: service-time variability remains stable, distance variability is low and waiting-time variability increases only under high congestion. Overall, the PDI system converts chaotic delays into predictable waiting, substantially improving operational stability.

5 Conclusions

This paper presented a simulation-based assessment of an integrated physical digital infrastructure (PDI) solution for managing urban freight deliveries using a fleet of automated vehicles operating within the Tridente LTZ in Rome. The proposed system is compared with a base scenario lacking real-time information and booking capabilities. The findings lead to several key conclusions.

First, the PDI-enabled scenario demonstrates clear superiority in terms of operational efficiency and predictability, although the current disruption-management mechanisms (e.g., delays caused by delayed vehicles occupying bays) remain suboptimal. Providing vehicles with real-time bay availability and reservation functionality eliminates stochastic and inefficient parking searches. This results in substantial reductions in average travel distance per tour and fully removes failed parking attempts, offering notable sustainability benefits. The large variability in distance travel and service disruptions observed in the base scenario is replaced by highly stable routing and predictable outcomes, as indicated by significantly lower standard deviations.

Second, analysis of total service time reveals a trade-off between average efficiency and temporal reliability under conditions of high congestion. While the PDI solution consistently improves performance for moderate fleet sizes, in saturated conditions the base scenario may occasionally yield slightly shorter average service times. This counterintuitive effect arises from differences in delay mechanisms: while the base scenario

reactive process is inefficient, it allows non-systematic access to free bay; by contrast, the structured PDI logic transforms failures into predictable waiting periods, which increase as demand grows.

Overall, the study highlights the substantial potential of integrating automated vehicles with intelligent infrastructure. The PDI approach transforms a highly variable and unreliable system into one that is predictable and manageable. Its primary benefit lies not only in reducing service time or distance, but in dramatically improving operational consistency, i.e. a critical aspect for planning and ensuring the economic viability of sustainable urban freight systems.

The findings confirm the value of real-time data integration and reservation mechanisms for automated delivery fleets, while also indicating directions for future research. The current analysis relies on predefined delivery schedules and departure intervals, which, although useful for comparison, do not reflect an optimized operational plan. Congestion and waiting times observed even in the smart scenario suggest overlapping shuttle trajectories and timing.

A key direction for future development is the creation of an integrated simulation-optimization framework. The simulation model could serve as an evaluation engine within a metaheuristic optimization loop (e.g., genetic algorithms or simulated annealing). Decision variables would include both the sequence of delivery stops (a vehicle routing problem) and vehicle departure times. The objective function could minimize a weighted combination of performance indicators such as total service time, travel distance, and waiting time. Iterative generation and simulation of candidate solutions would enable the identification of near-optimal, deconflicted operational plans.

Future research could enhance model realism by incorporating dynamic rerouting based on real-time traffic and advanced control strategies to mitigate service delays. Introducing stochastic travel times and heterogeneous fleets would better capture the complexities of urban congestion and diverse vehicle specifications. Finally, integrating an economic assessment of operational and capital costs would enable a more comprehensive cost-benefit analysis.

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