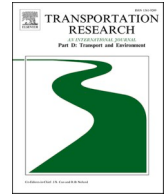




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Navigating the future of urban logistics: Conceptual framework for Dynamic Freight Management[☆]

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ABSTRACT

Sustainable management of urban logistics (UL) is crucial for reducing congestion, enhancing environmental quality, and improving liveability in cities. Traditional approaches are increasingly inadequate due to intensified urbanisation and e-commerce growth. This paper proposes a novel Dynamic Freight Management (DFM) conceptual framework that employs real-time data analytics and comprehensive traffic information to optimise urban freight operations. Reviewing the existing literature and integrating diverse methodologies, we developed a holistic strategy that aligns freight activities with urban traffic patterns to minimise disruptions and environmental impacts. The framework advocates for multi-stakeholder collaboration and supports policy recommendations for its implementation. Through theoretical analysis and case studies, this research study illustrates the potential of DFM to transform UL by reducing congestion and emissions, thus contributing to more sustainable urban environments.

1. Introduction

Sustainable urban logistics (UL) has become a growing concern as urban freight volumes rise globally. With e-commerce sales projected to surpass \$7.4 trillion by 2025 (Invesp, 2025), the demand for last-mile deliveries continues to surge, putting immense pressure on urban infrastructure. Urban freight transport (UFT) already accounts for 30–50 % of urban road congestion and contributes to up to 40 % of city emissions (Quak et al., 2016). Despite various policies and technological advancements aimed at improving efficiency, UL remains hindered by persistent challenges, including traffic congestion (Davidich et al., 2018), environmental impacts, regulatory constraints, and last-mile inefficiencies (Mohri et al., 2024). Addressing these issues requires a shift from static logistics

Abbreviations: UL, urban logistics; DFM, Dynamic Freight Management; UFT, Urban Freight Transport; ABM, agent-based modelling; FR, freight rate; CAS, complex adaptive system; FDM, Freight Demand-Management; STT, Socio-Technical Transition; HGVs, heavy goods vehicles; LCVs, light commercial vehicles; LEZs, low-emission zones; PBZs, parking buffer zones; FCD, floating car data; ULD, urban logistics decision; DFASA, Dynamic Freight Access and Scheduling Algorithm; FVs, freight vehicles; CCTV, Closed Circuit Television; LOS, Level of Service; SUMP, Sustainable Urban Mobility Plan; SULP, Sustainable Urban Logistics Plan; UTN, Urban Transportation Network; PVs, private vehicles.

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planning to dynamic, data-driven freight management solutions that can respond to real-time urban conditions (Nadi, et al., 2022).

Urban freight systems constitute a complex adaptive system (CAS) in which heterogeneous actors—carriers, shippers, receivers, regulators—interact under conditions of pronounced demand volatility and infrastructural constraint (Oughton et al., 2018). Within this milieu, three conceptual lenses frame the present inquiry. First, Freight Demand-Management (FDM) theory posits that congestion and emission externalities can be attenuated by demand-side measures such as access windows, dynamic curb pricing, and slot-booking (Holguín-Veras et al., 2018). Second, Socio-Technical Transition (STT) theory elucidates the co-evolution of technological niches, market incentives, and regulatory regimes that condition the diffusion of innovations such as electric trucks and AI-supported routing (Bjørngen & Ryghaug, 2022). Third, Agent-Based Modelling (ABM) offers an epistemological apparatus for simulating bottom-up interactions among freight agents who adapt to real-time information and policy stimuli (Crainic et al., 2021). Synthesised, these perspectives motivate a Dynamic Freight Management (DFM) paradigm that privileges continuous sensing, predictive analytics, and adaptive regulation over the static heuristics that dominate extant practice.

Traffic congestion remains one of the most pressing issues in UFT, with delivery vehicles often operating at less than 50 % capacity utilisation (Hoekstra and Wegman, 2011; Crainic et al., 2018). UFT makes up 10–15 % of city traffic, yet its impact is disproportionately large due to frequent stops, parking and unloading bays constraints (Alho et al., 2022; Iwan et al., 2018), and route inefficiencies (Comi and Savchenko, 2021). In cities like London and New York, freight vehicles (FVs) spend 28–40 % of their time idling due to congestion and delivery restrictions, leading to annual economic losses exceeding \$100 billion globally (Conway et al., 2017; Allen et al., 2012). Attempts to mitigate congestion through low-emission zones, restricted delivery hours, and urban consolidation centres have produced mixed results, as they often fail to adapt to daily fluctuations in traffic patterns dynamically (Kijewska et al., 2022; Eom & Kim, 2020).

The environmental impact of UFT is another critical challenge. Heavy goods vehicles (HGVs) and light commercial vehicles (LCVs) account for 20–25 % of total urban CO₂ emissions and a significant share of NO_x and PM_{2.5}, which negatively impact air quality and public health (de Bok et al., 2021). In the EU, freight transport emissions are expected to increase by 22 % by 2050 if no significant interventions are implemented (R Core Team 2021). Although electric and hybrid FVs are being introduced, adoption remains slow, with less than 2 % of urban delivery fleets being fully electric as of 2022 (International Energy Agency, 2023). High costs, insufficient charging infrastructure, and limited vehicle range continue to hinder a widespread transition to green freight solutions (Figliozzi et al., 2020).

Regulatory constraints further complicate efforts to improve UFT sustainability (Cruz-Daraviña & Suescún, 2021). Cities implement fragmented and often inconsistent policies that create operational challenges for logistics providers (Brozovsky et al., 2021). For example, 45 % of European cities have adopted low-emission zones (LEZs), yet the criteria for vehicle access vary widely, causing confusion among freight operators and reducing the efficiency (Dablanc & Montanon, 2015; Ma et al., 2021). Additionally, 50 % of urban freight operators report that restrictive delivery time windows increase their costs and inefficiencies (Holguín-Veras et al., 2018). The lack of harmonised freight regulations makes it challenging to coordinate sustainable logistics policies at regional and national levels.

Last-mile delivery inefficiencies pose a significant challenge, with 53 % of total logistics costs being attributed to the last-mile segment (Astarita et al., 2019). The rising demand for same-day and next-day deliveries has increased vehicle miles travelled in urban areas, worsening the congestion and emissions. Studies indicate that in cities where home delivery demand has surged, last-mile emissions have grown by 30–50 % over the past decade (OECD, 2023). Alternative last-mile solutions, such as micro-hubs, cargo bikes (Galkin, et al., 2025), drones (Lemardelé et al., 2021) and autonomous delivery vehicles (De Maio et al., 2024; Kapsner, & Abdelrahman, 2020), have been tested in pilot programs, but their large-scale adoption remains constrained by infrastructure limitations, high operational costs, and regulatory uncertainties (Chen et al., 2021).

Technological advancements have enabled the integration of real-time traffic monitoring, IoT-based fleet management, and AI-driven route optimisation. AI-powered logistics platforms have improved delivery efficiency by 15–30 % in cities that have adopted dynamic scheduling and real-time routing systems (Davidich et al., 2021; van den Haak et al., 2018). Predictive analytics allows logistics operators to anticipate congestion patterns and adjust delivery schedules accordingly, leading to significant reductions in resources consumption and delivery delays (Crainic, et al., 2023). However, despite these innovations, most logistics operations still lack full integration between smart mobility infrastructure and freight transport systems, limiting their effectiveness in real-world applications. Some works related to that have been done under GRASS-NEXT project. The researchers implemented the concept of drone greed to collect data chosen from cameras and AI algorithms to identify the urban FVs (Kujawski and Dudek, 2021). The major idea was to use this approach for vehicle routes analysis.

This paper presents a novel DFM framework, representing a significant departure from static, pre-computed routing and regulation approaches. The framework is designed to optimise urban freight operations by leveraging real-time data analytics, predictive modelling, and stakeholder collaboration to address these pressing challenges.

The primary objectives of this study are: (1) to develop a conceptual framework for DFM, integrating real-time traffic monitoring and adaptive scheduling algorithms for enhanced urban freight efficiency, and (2) to conduct an experimental evaluation in Pardubice, Czech Republic, validating the practical application and impact of the framework. Unlike static models, DFM dynamically adjusts delivery schedules based on evolving urban traffic conditions. By bridging the gap between real-time logistics data and adaptive traffic policies, this research study contributes to the growing body of knowledge and practice in sustainable UFT (Holguín-Veras et al., 2023).

Furthermore, this study addresses a critical gap in transportation research by integrating real-time analytics with regulatory considerations and offering actionable policy recommendations for optimising last-mile delivery networks. The findings have significant implications for urban planners, logistics providers, and policymakers, aiding in the development of sustainable UL strategies

aligned with broader environmental and economic goals (McKinnon, 2023; Dablanc and Montanon, 2015).

The remainder of this paper is structured as follows: Section 2 outlines the methodological approach, including the agent-based modelling (ABM) framework, threshold-based freight access control mechanisms, and emissions assessment techniques. Section 3 presents the empirical results of the simulation-based evaluation completed in Pardubice, focusing on network performance under varying freight rate (FR) thresholds, congestion mitigation strategies, and environmental outcomes. Section 4 discusses the implications of the findings, policy recommendations, and potential refinements for freight management strategies. Finally, the Conclusions summarise the key findings and identify areas for future research in dynamic freight regulation and sustainable UL.

2. Literature review

UL is undergoing a transformation driven by the rapid expansion of e-commerce, increasing consumer expectations, and the imperative to reduce environmental impacts. Yet, the introduction of innovative regulatory measures is not merely a technical challenge; it also demands strong political will and consensus among municipal authorities and stakeholders, as such policies often face resistance and require a rebalancing of urban priorities. Traditional freight management approaches struggle to keep pace, resulting in inefficiencies, congestion, and elevated emissions (Holguín-Veras et al., 2020).

Despite advancements in sustainable logistics practices, a critical issue remains in integrating real-time traffic data and predictive analytics into urban freight planning. Most existing models rely on predefined traffic assumptions and static delivery schedules, failing to adjust dynamically to urban congestion patterns, weather conditions, and fluctuating demand (Comi & Polimeni, 2021; Holguín-Veras et al., 2018).

In-depth analysis in the topic of UFT data acquisition were realized under GRASS-NEXT project (Weir et al. 2022). The Authors analysed several data acquisition technologies in the context of real-time data purchasing, considering the vehicles categorization. The work was focused on chosen UFT characteristics, like number of deliveries time of day delivery/pickup, empty running, time to carry out deliveries/collections, type and quantity of goods delivered/collected, number of vehicles and size/type, loading/unloading activities, environment-friendly distribution, journey speed, journey length. The objective of the analysis was to identify usability of analysed technologies in the context of these characteristics.

This study seeks to contribute to the growing field of dynamic urban freight management by empirically evaluating the impact of threshold-based freight regulations, adaptive parking buffer zones (PBZs), and slot-booking mechanisms on congestion and emissions. By integrating ABM, real-time data analytics, and municipal telematics infrastructure, this research study provides a more comprehensive approach to sustainable freight regulation that bridges the gap between theoretical optimisation models and real-world implementation.

The concept of DFM offers a promising alternative to conventional approaches. DFM integrates real-time data collection, AI-driven predictive analytics, and adaptive freight scheduling to create a responsive and intelligent UL system (Pan, et al., 2021). Unlike traditional static models, DFM adjusts freight routes and delivery schedules based on live traffic data (Li, et al., 2024), reducing congestion and improving operational efficiency (Kahalimoghadam, et al., 2024). Studies suggest that cities adopting AI-powered freight management systems experience lower delivery times, reduced vehicle idling, and decreased energy consumption (Astarita et al., 2019).

A key component of DFM is its ability to integrate floating car data (FCD), GPS tracking, and intelligent transportation systems to provide real-time congestion monitoring and dynamic route optimisation (Nigro et al., 2022; Van den Haak et al., 2018). Logistics operators can: i) Anticipate traffic bottlenecks and reroute deliveries accordingly; ii) Identify alternative delivery routes to minimise delays; iii) Optimise energy consumption, reducing both costs and environmental impact. These capabilities enhance delivery reliability while contributing to more sustainable UL by decreasing congestion and lowering emissions.

One of the key innovations in UL is the integration of real-time monitoring systems (Gao, et al., 2019). Traffic sensors, GPS tracking, and AI-based predictive analytics now allow logistics operators to adjust routes, improving the efficiency and reducing the congestion dynamically (Akhtar and Moridpour, 2021). The adoption of the Physical Internet framework has facilitated sustainable and resilient approaches to production-routing problems by leveraging modular capacity (Peng et al., 2024). The increasing adoption of FCD and smart infrastructure facilitates real-time freight adjustments, significantly enhancing delivery reliability (Van den Haak et al., 2018).

However, the full potential of DFM has yet to be realised, as implementation remains limited and empirical studies are scarce. Many cities still rely on fragmented freight policies and outdated traffic management systems, preventing widespread adoption of real-time, adaptive logistics solutions. Additionally, while some pilot projects have demonstrated the feasibility of DFM, long-term sustainability assessments and large-scale case studies are still lacking (Chen et al., 2021).

While the adoption of smart logistics technologies and AI-driven traffic management has improved certain aspects of smart cities

Table 1

The identification of analytical focus.

5C filters	Description	Analytical focus
Condensation	Data can be combined into a more concise form.	Operational Integration
Correction	Errors contained in the data are eliminated.	Empirical Validation
Contextualization	The purpose for which the data was collected is clear.	Scalability & Context
Categorization	Data can be assigned to specific categories or key components	Technology Integration
Calculate	Data can be analysed using mathematical methods (particularly statistical methods).	Urban Spatial Management

(Crainic et al., 2021; Naganawa et al., 2024), the prevailing body of research focuses on isolated case studies or theoretical models rather than real-world, large-scale implementation. Many of the proposed solutions fail to fully integrate multiple stakeholders, including policymakers, logistics operators, and urban planners, leading to a lack of coordinated freight governance (Storani et al., 2021). Additionally, most current studies overlook the scalability and cost-effectiveness of dynamic freight systems, raising concerns about the practical feasibility of implementing AI-powered logistics solutions in diverse urban environments.

Despite ongoing efforts in both traditional UL and environmental planning, significant gaps persist in the ability to address the complex, dynamic challenges of urban freight. The basis of the analysis was the identification of 5 analytical focus areas, related to the 5C filters of data-to-information transformation process, proposed by Davenport and Prusak (Davenport and Prusak, 1998) – Table 1. The identified gaps are mentioned in the Table 2.

Traditional approaches are largely limited by their reliance on static or semi-dynamic routing and scheduling models, offering only theoretical or simulation-based validation and rarely accounting for real-world variability or scalability beyond major metropolitan areas (Ehmke et al., 2016; Chen et al., 2021; Storani et al., 2021). Similarly, environmental and urban planning strategies tend to focus on static zoning and infrastructure-centric policies, often neglecting operational integration, real-time responsiveness, and the specific needs of medium-sized cities (Björge & Ryghaug, 2022; Holguín-Veras et al., 2023). Both approaches commonly marginalise the role of emerging technologies and fail to integrate operational data with adaptive regulatory frameworks, limited effectiveness in managing spatial and environmental complexities (Allen et al., 2012; Ceulemans et al., 2025; Peng et al., 2024). These shortcomings underscore the need for DFM, which blends real-time analytics, adaptive routing, stakeholder coordination and environmental criteria.

The importance of filling these research gaps extends beyond operational efficiency. Integrated, DFM frameworks are crucial for helping cities achieve their climate targets, improve public health, and strengthen economic resilience in the context of rapid urbanisation and shifting consumer demands. Without such frameworks, urban areas risk continued congestion, emissions, and unsustainable logistics growth, undermining the vision of smart, sustainable cities.

This study aims to address these gaps by evaluating the impact of a DFM framework in an empirical case study conducted in Pardubice, Czech Republic. By integrating real-time data analytics, adaptive routing algorithms, and urban freight policy considerations, this research seeks to develop a scalable and practical ULs solution. The findings will contribute to the broader discourse on sustainable urban freight, providing insights into how cities can transition from static freight models to dynamic, AI-driven logistics frameworks.

Building on the preceding review, Fig. 1 presents the DFM conceptual framework, broadens the lens to the strategic architecture. Drawing on multi-layer smart-mobility and city-logistics perspectives (Crainic et al., 2021), on data-to-knowledge transformation principles emphasised by Davenport & Prusak's 5C filters (Davenport and Prusak, 1998), and on governance-centred urban freight research (Holguín-Veras et al., 2020), the framework organises DFM into four interdependent layers that link long-range policy intent to day-to-day logistics execution. A Governance & Policy layer anchors sustainability goals, freight access rules, and stakeholder agreements articulated in strategic planning instruments such as SUMPs and SULPs. Beneath it, a Data & Sensing layer aggregates continuous observations from Closed Circuit Television (CCTV), floating-car-data (FCD), IoT roadside units, and platform-shared logistics feeds to quantify freight-ratio (FR) and level-of-service (LOS) in real time (Comi & Polimeni, 2021; Astarita et al., 2019). These streaming data drive an Analytical & Decision layer in which the Dynamic Freight Access & Scheduling Algorithm (DFASA), predictive analytics, and agent-based modelling tools evaluate alternative interventions under prevailing and forecast conditions (Nadi et al., 2022). Recommended actions cascade to an Execution & Feedback layer, where logistics operators and drivers enact buffer-zone metering, slot-booking compliance, adaptive routing, or dynamic pricing signals in the field (Björge & Ryghaug, 2022).

Critically, the framework is cyclical rather than linear. Observed operational outcomes, changes in traffic speeds, emissions, schedule adherence, and stakeholder compliance, flow upward from the execution layer and are re-ingested by the sensing and analytical layers, enabling the governance tier to recalibrate policy thresholds (X_1 for LOS, X_2 for FR) and refine regulatory strategies over time. In this way DFM links demand-management measures, adaptive behavioural modelling and real-time optimisation within a single governance-to-operations continuum that is especially well suited to the volatility of medium-sized urban freight markets. The layered construct in Fig. 1 therefore provides the conceptual scaffold that underpins the operational logic detailed in Fig. 2 and elaborated methodologically in Section 3.

3. Methodology

The operational flowchart presented earlier (Fig. 2) shows, step by step, how real-time traffic metrics (FR, LOS) trigger specific operational responses such as freight diversion to buffer zones or delivery rescheduling.

Drawing on an ecosystem perspective, the methodology integrates multiple stakeholders (municipal authorities, logistics operators, technology providers, and end consumers) and leverages real-time data sources (e.g. CCTV, FCD) to optimise urban freight activities. The approach combines ABM, DFASA and scenario-based simulations to capture the complexity of UL under varying congestion conditions and freight traffic shares.

3.1. Overall ecosystem design

Urban freight transport is a complex system, involving different stakeholder groups, infrastructures, and data flows, all of which must be strategically coordinated to achieve efficient deliveries and minimise traffic disruption. To capture this complexity, the proposed DFM framework is conceptualised as an ecosystem comprising five interdependent components:

Table 2
Comparative framework of urban freight strategies and dynamic freight management.

Analytical focus	Traditional urban logistics	Environmental & urban planning	Dynamic Freight Management (DFM)
Operational Integration	Vehicle routing and scheduling optimisation; primarily static or semi-dynamic models (Ehmke et al., 2016; Perboli & Rosano, 2019).	Environmental zoning, static emission standards, infrastructure-centric policies (Björge & Ryghaug, 2022).	Real-time adaptive management integrating dynamic routing, regulatory responsiveness, and environmental criteria.
Empirical Validation	Theoretical constructs, simulation-based validations, and limited real-world longitudinal evidence (Chen et al., 2021).	Policy impact studies focusing on isolated environmental effects, lacking robust operational insights (Muñoz-Villamizar et al., 2024).	Empirical longitudinal validation through algorithmic route optimisations and real operational deployments
Scalability & Context	Metropolitan-centric optimisation models; limited insights on medium-sized urban scalability (Storani et al., 2021).	Predominantly large city urban management strategies; limited transferability to smaller urban contexts (Holguín-Veras et al., 2023).	Specifically tailored scalability framework validated within medium-sized cities, addressing broader applicability.
Technology Integration	Primarily technological innovations without comprehensive policy support (Allen et al., 2012; de Bok et al., 2021).	Infrastructure-based solutions, often technologically agnostic, have limited operational technology integration (Ceulemans et al., 2025).	Explicit integration of operational technology (AI, FCD, Big data, machine learning, etc.) within adaptive policy frameworks.
Urban Spatial Management	Freight marginalisation in transit-oriented urban development: static spatial considerations (Cervero et al., 2004; Ibraeva et al., 2020).	Focus on static green zoning and urban consolidation centres, neglecting dynamic spatial logistics interplay (Peng et al., 2024).	Dynamic spatial-logistical integration (e.g., buffer zones, flexible UL hubs, real-time space allocation).

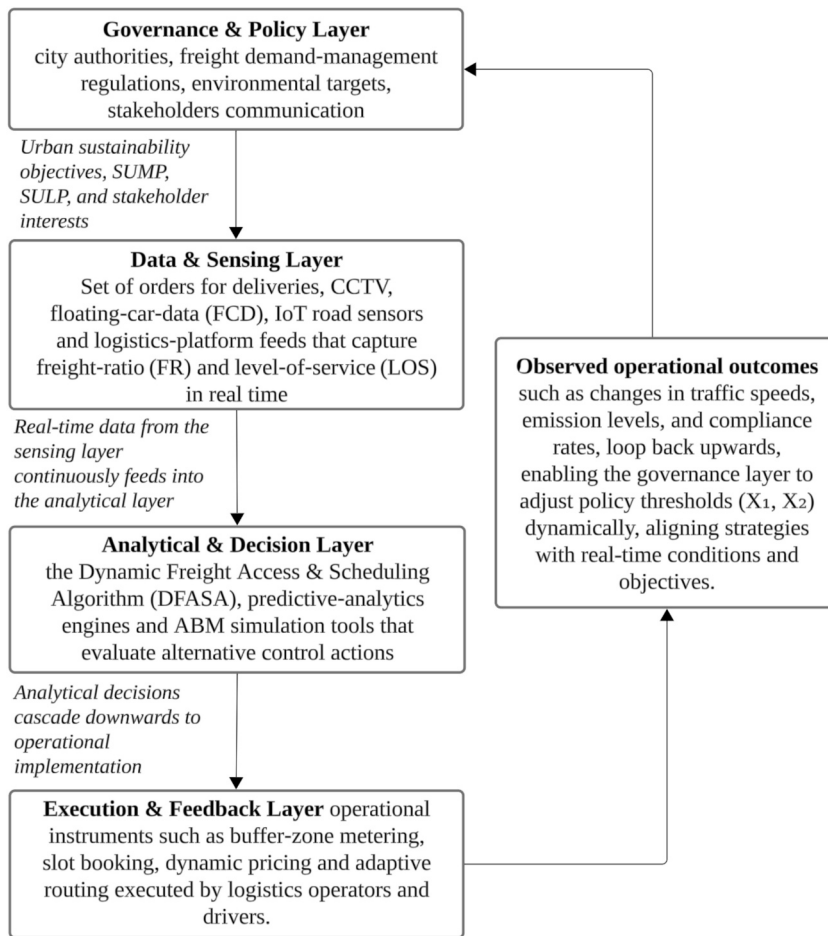


Fig. 1. Dynamic Freight Management (DFM) conceptual framework.

Freight Vehicles (FVs) and Drivers: These constitute the operational core, tasked with transporting goods to and from urban areas. FVs range from small delivery vans to heavy trucks, each influencing traffic flow differently due to their varying size, manoeuvrability, and speed profiles.

Logistics Operators: Representing carriers, courier services, and large retailers, these entities schedule and dispatch multiple vehicles. Their decisions on delivery timing, routing, and vehicle type significantly impact urban congestion, emissions, and final delivery performance.

Municipal Telematic Infrastructure: A network of roadside sensors, CCTV systems, intelligent software (e.g. BriefCam for automated vehicle recognition), and data fusion modules that monitor real-time traffic conditions. This infrastructure generates key indicators such as the FR (K_{fr}) and LOS, triggering automated controls (e.g. restricting incoming FVs) when thresholds are exceeded.

Parking Buffer Zones (PBZs): Strategically located on the periphery or along major arterial roads, these areas temporarily hold FVs if real-time data suggests impending congestion. By metering FV inflows based on dynamic LOS and FR, PBZs prevent critical choke points from forming in the city centre.

Consumers: The demand side of the ecosystem, encompassing businesses (B2B) and households (B2C). Their order placements dictate the flow of deliveries, influencing operators' scheduling decisions and thereby affecting real-time traffic conditions.

These interconnected components form a self-regulating ecosystem in which data-driven policies continuously adapt to prevailing traffic states (Holguín-Veras et al., 2020). Municipal telematics acts as the “central nervous system”, integrating CCTV data, FCD, and vehicle-count analytics to detect congestion trends and issue timely advisories or restrictions on freight movements. In turn, logistics operators and drivers respond to these signals by adjusting routes, rescheduling deliveries, or waiting at PBZs.

From this ecosystem perspective, the urban freight system is not merely shaped by regulatory edicts but is co-created through iterative feedback from all stakeholders. By adopting a dynamic view, where each actor's actions influence and are influenced by the rest, the DFM approach provides a holistic mechanism to optimise deliveries, reduce congestion, and curb emissions in real-world urban contexts.

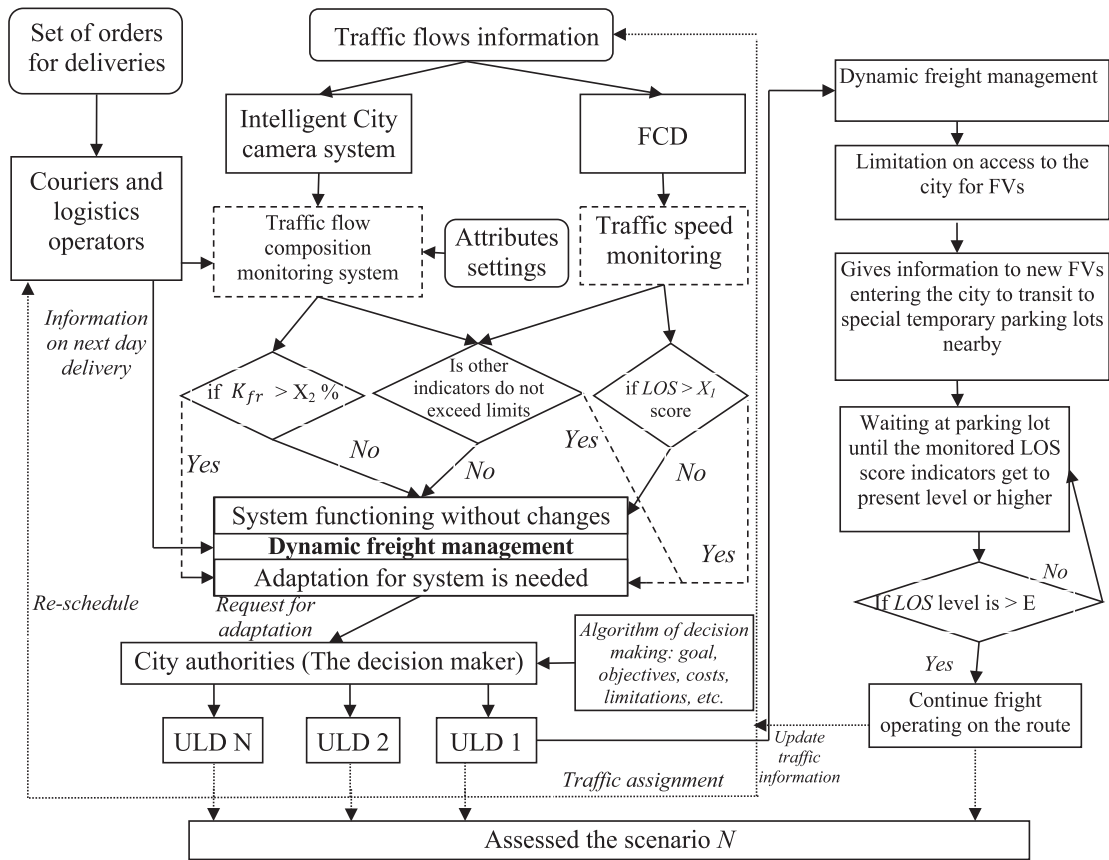


Fig. 2. DFM operational flowchart. K_{fr} – FR in TF, %; X_1 – it’s a preset value of LOS parameter; X_2 – it’s a preset value of K_{fr} parameter; ULD – urban logistics n -th decision.

3.2. Data collection and sources

Data collection for the DFM framework drew on multiple, complementary inputs to ensure comprehensive coverage of both traffic conditions and freight activity. Central to this effort was the integration of continuous, real-time observation methods, historical transport databases, and operational logistics records. By synthesising these diverse data sources, the research team established a robust empirical foundation to calibrate and validate the ABM, the telematic control system, and the DFASA. A detailed breakdown of each dataset, its preprocessing workflow, and its methodological role is provided in Appendix A.

In the first stage, the municipal authority’s CCTV infrastructure provided live video streams at major intersections, arterial roads, and key access points to the city (Liu, & Jian, 2019). These video feeds were processed through BriefCam software, an AI-driven platform capable of recognising and classifying vehicles based on size, shape, and operational characteristics (Wu, et al., 2021). This classification enabled near-instantaneous estimation of the FR – the proportion of FVs among all traffic. Through continuous monitoring, congestion onset could be detected in its early stages, prompting the DFM system to implement proactive measures, such as diverting inbound trucks to PBZs. The accuracy of BriefCam’s classification was periodically audited against manual counts to minimise misclassification of smaller trucks, vans, or passenger cars (Vrba et al., 2024).

Simultaneously, FCD offered a second layer of real-time insight into traffic speeds and flow patterns (Comi, et al., 2024; Dailey et al., 2000). Authors reviewed the submitted article, and they would recommend clarifying how the real-time traffic data was obtained. It is important to proceed carefully due to the licensing terms of the services used – Google, for instance, explicitly prohibits downloading and storing data via its API. By comparing observed speeds against thresholds associated with the Highway Capacity Manual’s LOS scoring, the telematic system inferred congestion levels (e.g. LOS A through F) without requiring physical sensors on every road segment (HCM, 2010). These speed estimates were further validated through occasional short-term manual surveys, ensuring that any positional inaccuracies or data dropouts did not compromise the reliability of the overall dataset.

Beyond real-time data, historical sources and official transport documents such as Sustainable Urban Mobility Plans (SUMP) or Sustainable Urban Logistics Plans (SULP), underpinned the project’s demand modelling and scenario design. However, it must be mentioned that feedback loop is considered in that case. On the one hand the historical data and previous strategical documents influence on the decision process. On the other hand the basis of these documents’ preparing should be the efficient data collection process. In presented work two documents for analysed area were considered: Sustainable Urban Logistics Plan (SULP, 2023) and

Comprehensive Mobility Plan (Pardu-plán, 2024). Both contained detailed information on road geometry, lane capacities, and peak-hour vehicle volumes. This background allowed the research team to identify high-risk corridors prone to congestion, designate probable PBZ locations, and design scenario variations involving changes in freight traffic shares. Stakeholder interviews with city traffic engineers added context to these documents, clarifying local operational constraints, typical bottleneck areas, and ongoing infrastructural projects that might influence freight flows.

To capture the practical dimension of last-mile operations, *logistics operators* (including both high-density parcel carriers and local delivery companies) provided anonymised records of daily orders, vehicle schedules, route assignments, and historical trip times. This information was instrumental in calibrating the ABM's logistics operators. For example, it ensured that the simulated arrival times, vehicle load capacities, and driver behaviours accurately reflected real-world practices, including how operators allocate vehicle capacity and respond to fluctuations in customer demand. Some carriers also detailed peak delivery times, such as early morning restocking for retailers or evening residential e-commerce drops, providing crucial inputs for designing time-window restrictions and pre-booking modules in the DFASA.

Finally, data on *environmental and emissions performance* were integrated to measure how changes in freight access policies influenced air quality. Municipal environmental agencies supplied emissions factors for various vehicle categories –passenger cars, vans under 3.5 tons, and heavy-duty trucks – enabling the research team to estimate pollutants (CO, NO_x, PM_{2.5}) as vehicle flows varied. These estimates were cross-checked against known emission standards and local testing data to account for vehicle age distributions and engine types in the city's fleet mix.

Taken together, the combination of CCTV video analytics, floating car data, municipal road and traffic surveys, logistics operator records, and emissions factors formed an interconnected database on which the DFM framework relied. By merging live and historical datasets, the telematic control system was able to adapt in real time – aligning freight inflows with actual road capacity – and to inform scenario-based simulations that assessed the resilience and sustainability of different policy thresholds for freight traffic. This holistic data strategy ultimately ensured the fidelity of the DFM model's findings, strengthening its applicability to real-world transport policy and city logistics contexts.

3.3. Agent-Based modelling framework

The design and evaluation of the DFM framework rely heavily on ABM approach, chosen for its capacity to capture the discrete, autonomous decisions of diverse stakeholders and the emergent traffic dynamics within urban environments. Table 3 summarises each agent's primary functions.

By representing each major actor – FVs, logistics operators, municipal traffic control, end consumers, and PBZ – as separate, goal-oriented entities, the model can replicate the complexity of real-world interactions and provide insights into how policy interventions affect system-wide outcomes.

3.3.1. Freight vehicle agents

FVs embody the fundamental operational units of the DFM system. They can range from light vans serving small retail deliveries to heavy-duty trucks transporting pallets of goods to distribution centres. Each vehicle enters the urban area under scheduled or ad hoc routes determined by its respective logistics operator. Upon approaching city borders, the vehicle continuously polls real-time congestion metrics –particularly the FR and the LOS – through telematics or driver notifications.

Vehicles receive instructions to hold in designated PBZs when congestion thresholds are exceeded. If conditions permit, they proceed to their assigned destinations. Throughout this process, vehicle agents adapt dynamically, recalculating estimated arrival times and re-sequencing stops if wait times in a PBZ jeopardise certain deliveries. By iterating through multiple simulated days, vehicle agents can “learn” traffic patterns or test alternative entry times, converging on efficient behaviour that reduces travel delays while still meeting time-window requirements.

3.3.2. Logistics operator agents

Logistics operators represent the organisational layer behind fleets of FVs. They allocate vehicles to daily delivery tasks, define routing plans, and negotiate time windows with both city authorities and end consumers. In the ABM, each operator maintains its own objectives, such as minimising total route distance, meeting promised delivery times, and controlling operational costs. These goals may conflict with municipal congestion objectives, leading to strategic decisions regarding off-peak scheduling or slot-booking to avoid PBZ delays.

Operators rely on standard planning methods (e.g. solving the Capacitated Vehicle Routing Problem) but must also incorporate

Table 3
Agent primary functions.

Agent	Functions
FVs	Attempt entry, wait in buffer zones if congestion is high.
Logistics Operators	Adjust schedules, pre-book entry slots, re-route deliveries.
Consumers	Generate demand for urban delivery
City Control Systems	Collect real-time data, trigger DFM responses, manage traffic.
PBZ	Temporary waiting areas for FVs until congestion improves.

dynamic elements of the DFM system. For instance, if repeated traffic alerts indicate that *FR* is approaching the threshold (X_2), operators may proactively reschedule certain shipments to off-peak periods or adjust departure times from distribution hubs. This autonomy captures the real-world interplay between municipal control systems, which seek to mitigate congestion, and private actors, which balance regulatory compliance with service quality and cost containment.

3.3.3. Municipal telematic control agent

The municipal telematic control agent, functioning through a network of roadside sensors and AI-based software, forms the coordinating mechanism for real-time congestion management. By analysing CCTV streams, floating car data, and historical traffic patterns, it computes the freight share and traffic speeds across critical corridors. If *FR* rises above the preset threshold (X_2) or if LOS falls below an acceptable limit (X_1), the system triggers restrictions on new FV entries.

Building on these alerts, the agent uses the DFASA to update the operating environment for all vehicles. This can mean instructing inbound trucks to shift to PBZs, adjusting time-window allowances for previously booked slots, or expanding release intervals to clear existing queues. Over the course of multiple simulation cycles, the agent may fine-tune its parameters – raising or lowering X_2 , for example – based on observed bottlenecks and operator compliance, thereby embodying an adaptive policy framework aligned with the city's broader traffic management goals.

3.3.4. Consumer agents

End consumers drive freight demand through orders placed for personal or business reasons. These agents can represent retail stores awaiting stock replenishment or households receiving e-commerce deliveries. Demand fluctuates according to numerous factors: the time of day, local economic cycles, and consumer preferences for expedited or flexible deliveries. Although consumer agents do not directly interface with municipal controls, their aggregated requests shape the arrival patterns of FVs.

In the ABM, each consumer agent inputs a delivery request with a specified time constraint – such as same-day or next-day – thereby influencing how logistics operators schedule routes. When overall consumer demand surges (e.g. holiday seasons), agent-level interactions reflect the resulting increase in urban congestion and illustrate whether the DFM system's threshold-based regulations can smooth or re-time deliveries.

3.3.5. Parking buffer zone agents

PBZs serve as holding areas that temporarily accommodate excess FVs whenever the city's real-time indicators project unsafe congestion levels. Each PBZ is an autonomous agent controlling the rate (μ) at which vehicles are reintroduced into the urban grid, typically once *FR* and LOS revert to stable conditions. The ABM tracks queue lengths, waiting durations, and vehicle release scheduling to evaluate whether PBZ capacity is adequate and whether waiting times remain manageable.

Operating under constraints set by the municipal telematic control system, PBZ agents may offer premium or prioritised waiting tiers (for instance, to eco-friendly vehicles or those with critical deliveries) or implement first-in-first-out policies. The presence of multiple PBZ sites around major arterial roads can distribute vehicles more equitably, mitigating the risk of localised backlogs near a single access point.

3.4. Dynamic freight access and scheduling algorithm

A central element of the proposed DFM system is the DFASA. While the ABM captures the autonomy of stakeholders, the DFASA serves as the regulatory and optimisation engine. It continuously evaluates *FR* and LOS to decide whether FVs can enter the city or must be diverted to a PBZ. The decision thresholds are presented in Table 4.

At its core, the DFASA relies on two principal metrics: the freight-ratio (*FR*)—the proportion of FVs within the overall traffic stream—and the level-of-service (LOS), which converts observed mean traffic speeds into six standard quality-of-flow classes, A (free flow) through F (breakdown). The speed thresholds for each LOS class are listed in Table 5. The telematic control system computes these metrics in real-time, drawing on inputs from CCTV vehicle classification and FCD. When either the *FR* exceeds the preset maximum (X_2) or the LOS drops below the minimum threshold (X_1), the algorithm triggers regulatory actions. Newly arriving FVs receive digital or visual signals advising them to divert to PBZs, where they await improved traffic conditions before proceeding to their final destinations.

This threshold-based mechanism is augmented by a dynamic queue management process, which determines the volume and timing of releasing vehicles from PBZs. In relatively stable traffic conditions – indicated by *FR* below the X_2 threshold and LOS above X_1 – no action is taken; incoming freight continues unimpeded. Should conditions become critical, the DFASA reduces inflows to a controlled trickle or suspends them entirely, preventing saturation in areas already near gridlock. Once sensor data confirms that average speeds

Table 4
Decision Thresholds.

Condition	Action
$K_{fr} \leq X_2 \ \& \ LOS \geq X_1$	Normal operation (no restrictions)
$K_{fr} > X_2 \ \& \ LOS \geq X_1$	Limit freight entries to buffer zones, reschedule deliveries
$K_{fr} \leq X_2 \ \& \ LOS < X_1$	Restrict new entries to buffer zones, reschedule deliveries
$K_{fr} > X_2 \ \& \ LOS < X_1$	Full freight access suspension

Table 5

Average speed and corresponding LOS values for the urban roads (Prassas & Roess, 2020).

LOS	A	B	C	D	E	F
Travel Speed Intervals for speed limits of 50 km/hr	> 42.5	33.5 < V < 42.5	25 < V < 33.5	20 < V < 25	15 < V < 20	<15

have rebounded and the FR has fallen to acceptable levels, the system authorises queued vehicles to rejoin city traffic in carefully managed batches. This incremental release helps avoid abrupt surges that might spawn new congestion hotspots and acts as a safeguard against the cyclical “stop-and-go” disruptions sometimes seen in static traffic control systems.

Beyond real-time diversion decisions, the DFASA supports a slot-booking system, allowing logistics operators to schedule city access during off-peak windows. This feature addresses the problem of delivery bunching that can occur when multiple operators converge at the same high-demand intervals. By incentivising pre-booked slots, whether through reduced waiting times or regulatory compliance benefits, the algorithm encourages a smoother, more predictable freight arrival profile across the day. In turn, operators benefit from decreased dwell times in PBZs, while municipal authorities see fewer congestion peaks and lower overall emissions. Iterative feedback helps refine this booking logic, as historical data indicates which hours pose the highest risk of congestion, prompting the system to adjust the availability or cost of certain time slots.

To maintain adaptability, the DFASA also includes a short-term predictive module that incorporates machine-learning methods. This module regularly analyses fluctuations in FR and LOS over preceding days or weeks, as well as learning patterns that can guide near-future interventions. If holiday shopping surges or frequent morning backups become apparent, the algorithm may pre-emptively adjust the X_1 or X_2 values upward or downward, or alter the number of vehicles released from PBZs per time interval. Over time, these micro-adjustments reduce the incidence of threshold violations, stabilise last-mile delivery timelines, and create a more resilient Urban Transportation Network (UTN).

By linking threshold-based controls, queue management at PBZs, and slot-based scheduling, the DFASA stands out from traditional static approaches to urban freight regulation. Instead of responding only after congestion or when delays become severe, it constantly monitors traffic health and applies subtle real-time corrections, aiming to forestall costly breakdowns of flow. When paired with an ABM-ing environment, the DFASA can be systematically tested under different freight traffic intensities, infrastructure constraints, and policy goals, yielding evidence-based recommendations for managing complex city logistics systems.

3.5. Simulation scenarios and experimental design

We developed a comprehensive suite of simulation scenarios in PTV VISUM, systematically stress-testing the model by varying freight-ratio thresholds, LOS triggers and buffer-zone capacities. The modelling of the transport supply involves the construction of the UTN and transport zones. The UTN graph encompasses a collection of directed segments and nodes, effectively depicting the UTN’s geometry. In this graph, nodes correspond to points of intersection of transportation routes (such as roads, railways, and others) intended for a modelled representation of intersections. The segments represent sections of the UTN.

The manual construction of the UTN graph is a rather labour-intensive process, prone to potential errors in assigning attribute information to UTN elements. One approach to address this issue involves obtaining digitised databases from Geographic Information Systems (GIS) for the UTN, utilising cartographic services. Within the scope of this article, an open service known as BBBIKE was employed to obtain the GIS database, which is based on the cartographic service called OpenStreetMap (Fig. 3).

The transportation supply model included a range of modes, such as private vehicles (PVs) and FVs, all of which were incorporated into a digitised UTN. The network was constructed using Geographic Information System (GIS) data from OpenStreetMap, allowing for a precise representation of transport zones, road geometry and capacities, and traffic restrictions. Within the scope of this article, an open service known as BBBIKE was employed to obtain the GIS database, which is based on the OpenStreetMap cartographic service.

A consolidated overview of all scenario groups, their parameter settings (FR levels, LOS trigger X_1 , freight-ratio trigger X_2 , PBZ capacities, slot-booking adoption rates) and the performance indicators recorded in each experiment is provided in Appendix A (Table A.2). Each scenario systematically manipulates key parameters – such as the allowable FR, LOS thresholds, and capacity of PBZs

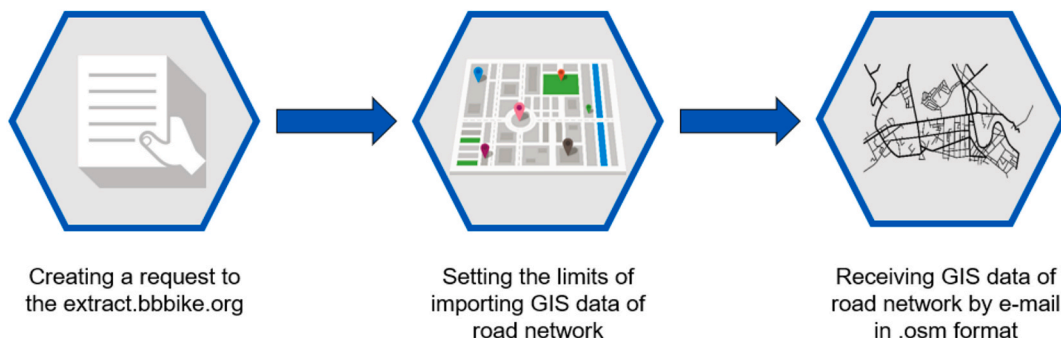


Fig. 3. Sequence of actions for unloading the GIS database.

– to reveal how the DFASA performs under both typical and extreme traffic conditions. This approach not only quantifies potential benefits (e.g. shorter delays and decreased emissions), but also exposes the trade-offs that arise when restricting freight access to protect broader urban mobility.

To begin, a *Baseline Scenario* was established by collecting average traffic volumes, fleet compositions, and typical arrival schedules from historical data in Pardubice, Czech Republic. These baseline parameters, approximating “business-as-usual” conditions, provided the reference point for subsequent comparisons. In the baseline runs, FVs moved freely unless congestion spontaneously emerged from normal fluctuations in traffic. This setup reflected current municipal practices, with only minimal telematic oversight or formal scheduling incentives for operators.

Once the baseline was set, the research team tested multiple *FR Variation Scenarios* to understand how different proportions of trucks and delivery vans in the traffic flow affect system stability. For instance, a Reduced FR scenario (–50 % of baseline) allowed the model to simulate the impact of off-peak incentives or robust consolidation strategies that substantially cut FV trips. Conversely, Elevated FR scenarios (+50 % or + 100 % of baseline) stress-tested the network, representing conditions such as sudden e-commerce surges during holidays or severe road closures that concentrate more trucks into fewer corridors. By comparing results across these experiments, it became possible to identify thresholds beyond which traffic flow deteriorates rapidly and to analyse the DFASA’s capacity to prevent complete breakdowns.

Simultaneously, *Threshold Sensitivity Scenarios* varied the LOS and FR trigger values (X_1 and X_2 , respectively). For example, the system might be configured to preserve LOS D (around 20 km/h) at a minimum, effectively placing tighter controls on freight entries. Alternatively, more lenient thresholds – such as LOS E (below 20 km/h) – could reduce waiting times in PBZs while accepting a moderate dip in traffic speed. Adjusting X_2 similarly influenced how frequently and aggressively trucks were diverted. In scenarios with a low X_2 (e.g. 5 % freight share), the system intervened more often, aiming to keep truck volumes from dominating urban roads. Higher X_2 thresholds (e.g. 20 %) limited interventions to near-peak conditions, minimising disruptions to the logistics sector but risking heavier congestion once the threshold was breached.

Finally, *Slot-Booking Adoption Scenarios* captured the range of responses that logistics operators could exhibit when offered time-window scheduling. In a low-adoption variant, only a small fraction of operators cooperated, continuing mostly with on-demand deliveries. In contrast, high-adoption scenarios assumed that nearly all delivery companies booked slots in advance, distributing traffic more evenly throughout the day. In tandem, differing incentive structures were explored, such as reduced PBZ waiting for pre-booked arrivals or penalty fees for peak-time entries without a slot. Observing how these measures altered traffic patterns provided insight into the policy levers that most effectively shift logistics behaviour and mitigate congestion.

By iterating through these multidimensional experiments, the research team was able to collect granular data on average speeds, LOS, total emissions, waiting times, and UTN reliability. These outcomes were then benchmarked against the baseline scenario to evaluate which interventions (e.g. tighter thresholds, larger buffer zones, higher slot-booking compliance) produced the greatest net benefits. The findings offer a practical guide for city officials, logistics managers, and policymakers seeking to balance economic imperatives with sustainable transport objectives, demonstrating how the DFASA can be fine-tuned for a wide spectrum of urban freight environments.

3.6. Performance indicators

The dynamic and interdependent nature of urban freight systems necessitates multifaceted evaluation criteria to assess whether the proposed DFM framework achieves its core objectives – namely, reducing congestion, optimising delivery efficiency, and lowering environmental impact. This section details the performance indicators used to measure system outcomes in the simulation environment and outlines the validation employed to ensure that the ABM and the DFASA capture real-world conditions accurately. Main Key Performance Indicators applied were as follows:

Average Network Speed (km/h): A central proxy for overall traffic flow quality, calculated by aggregating real-time or simulated speeds across principal corridors and collector roads. A network average speed significantly lower than 20 km/h typically corresponds to LOS E or F, signifying congested conditions.

FR: The real-time ratio of FVs to total traffic. Although this metric guides the DFASA’s threshold-based controls (e.g. X_2 value), it also serves as a post-hoc measure of how effectively the system balanced freight inflows with acceptable traffic conditions.

Queue Lengths and Waiting Times at PBZs: Tracking how many FVs are held in PBZs, and for how long, illuminates the direct impact of DFM policies on last-mile delivery.

Emissions Estimates: Using standard emission factors for different vehicle classes, the system computes the total or average per-vehicle release of pollutants (e.g. CO₂, NO_x, PM_{2.5}). This metric is especially pertinent to municipal authorities concerned with environmental regulations and air quality goals.

Slot-Booking Utilisation: In scenarios that include time-window reservations, logging how many operators voluntarily schedule arrivals (and how many adhere to their slots) indicates whether slot booking meaningfully shifts traffic away from peaks.

Before testing new scenarios, the *baseline* simulation output is compared against recorded metrics from municipal surveys, Google-based FCD and historical speed profiles. This ensures that ABM faithfully replicates real-world congestion patterns, average travel times, and freight shares.

By employing multiple validation layers – from direct data comparisons to stakeholder reviews – the research team ensures that simulation outcomes both reflect genuine urban freight challenges and highlight credible solutions. Consequently, the performance

metrics generated in experimental scenarios can meaningfully inform policymakers and practitioners on how to refine threshold policies, PBZ configurations, and slot-booking mechanisms for maximum benefit to city traffic and last-mile delivery.

4. Results

4.1. Overview of empirical data and model calibration

Speed measurements anchored empirical observations in Pardubice on nine principal routes (labelled 1–9 in Fig. 4 and mirrored by the same IDs in Table 6), each monitored at 15-minute intervals from 6 a.m. to 11 a.m. for a one-week period.

The dataset holds 1760 records. Measured averages ranged from roughly 17 km/h on heavily travelled corridors to about 28 km/h on less congested links, with the highest variability observed in routes serving both through traffic and local deliveries. FV traffic represented approximately 12 % of the total flow under normal conditions, with peak-hour congestion reflecting drops in speed below 20 km/h around major arterial junctions. These outcomes confirm that specific city-centre and highway-exit segments remain particularly vulnerable to freight-induced slowdowns even without full gridlock.

The DFM platform is used to regulate traffic entering the city. It is planned to install two PBZs (Fig. 5): 1) the Globus district and 2) the Main Railway Station. These PBZs will also be equipped with parking lots for temporary waiting transport. Temporary parking will increase the dwell time for carriers and extend the delivery schedule. This temporary parking will stop the flow of new FVs into the city until the LOS score becomes acceptable (e.g. $LOS > E$). Consumers' locations are presented in Fig. 6.

The empirical baseline scenario was established by integrating real-world measurements from Floating Car Data (FCD) and BriefCam video analytics (Fig. 7), providing a robust representation of Pardubice's urban traffic dynamics. Fig. 8 illustrates the hourly trajectories of mean traffic speed and freight rate, derived directly from sensor observations, for both (a) a representative weekday and (b) a typical weekend.

The weekday profile demonstrates pronounced temporal heterogeneity, with distinct morning and afternoon congestion peaks corresponding to periods of intensified travel demand. During these intervals, average traffic speeds drop below 20 km/h, resulting in a concomitant elevation of the freight rate. In contrast, off-peak periods are characterized by noticeably higher speeds and reduced freight rates, reflecting the alleviation of network congestion and improved operational efficiency for freight deliveries.

The weekend profile, by comparison, is markedly uniform, with both average speed and freight rate exhibiting minimal fluctuation over the course of the day. This attenuation of diurnal variability reflects the substantial reduction in traffic volumes and the absence of pronounced commuter surges. Consequently, the operational environment is considerably more stable, with consistently favorable conditions for freight movements.

As a result, further analyses of freight management interventions could reliably isolate the impact of threshold-based controls and buffer zone usage rather than artefacts of an imprecise model setup (Fig. 9).

A Pearson test substantiates the strong inverse relationship illustrated in Fig. 9 between freight rate and average traffic speed ($r = -0.98$, $p < 0.001$), and complementary spatial congestion maps with hour-by-hour flow profiles confirm that the baseline parameters faithfully reproduce the city's temporal traffic rhythm, providing a robust reference for subsequent scenario analyses.

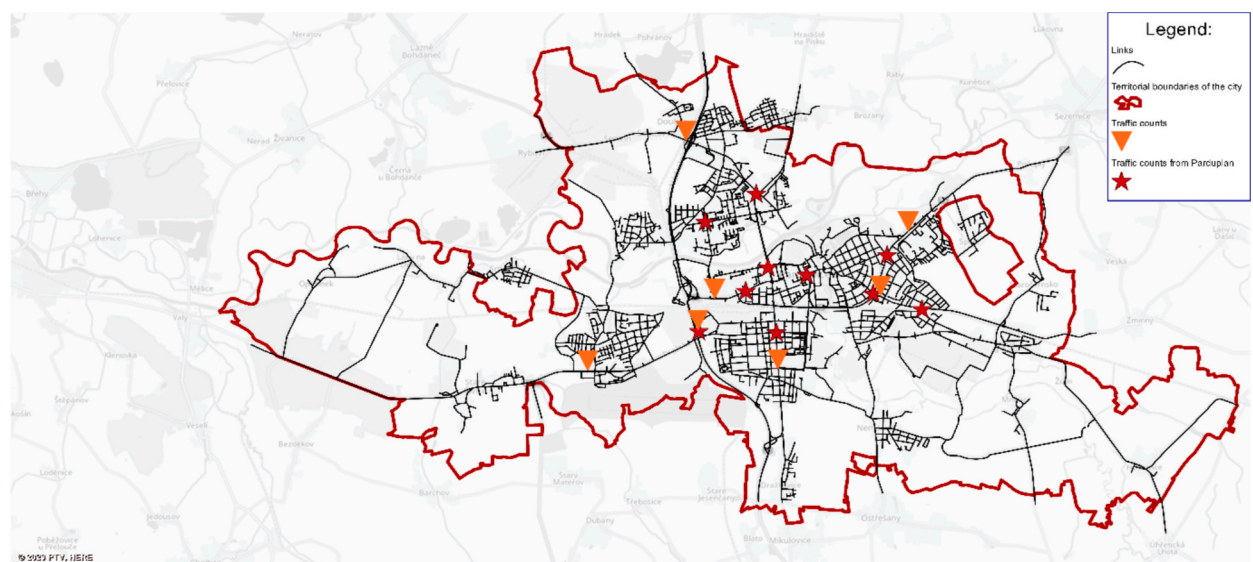
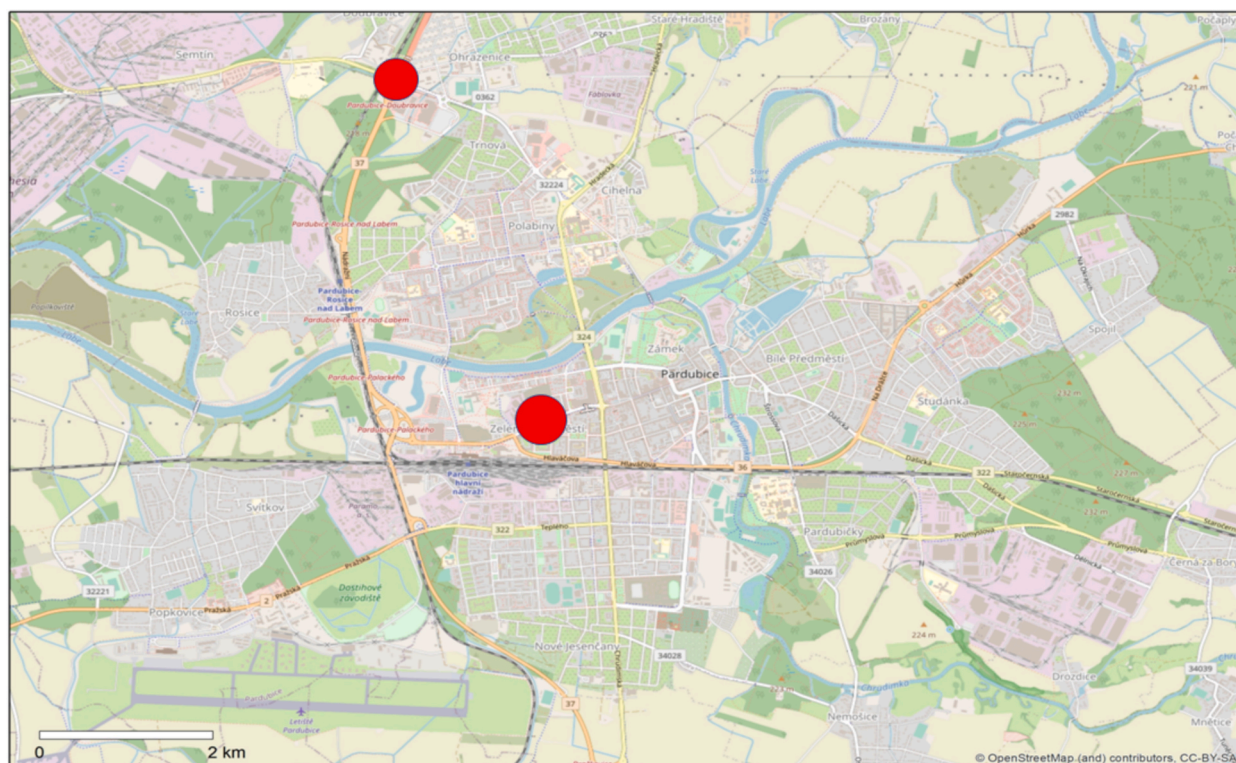


Fig. 4. Traffic count locations visualization in Pardubice.

Table 6

Statistical characteristics of transportation speed on the nine routes marked 1–9 in Fig. 4.

Route	Origin	Destination	Number of observations, records	The minimum value of speed, km/h	The maximum value of speed, km/h	The average value of speed, km/h
1	Palackého tř. 2882, 530 02 Pardubice I	Komenského nám. 120, 530 02 Pardubice	280	9.60	22.15	17.44
2	Doubravická 363, 533 53 Pardubice VII	I-Staré Město	280	15.5	34.3	27.7
3	Hradecká 587, 533 52 Pardubice II		40	20.47	34.80	27.2
4	Bílé Předměstí 1039, 530 02 Pardubice III		280	16	32	23.94
5	Staročernská, 530 03 Pardubice III		280	12.9	31.64	22.60
6	Chrudimská 1142, 530 02 Pardubice V		280	10	21.75	17.1
7	Pražská, 530 02 Pardubice V		20	16	24	19.8
8	Pod Kopečkem, 530 03 Pardubice IV	Chrudimská 1142, Pardubice	20	17.8	30	25.27
9	Pražská, 530 02 Pardubice V	Staročernská, 53,003 Pardubice	20	17.14	31.6	23.67

**Fig. 5.** The micro-hub location (proposed).

4.2. Baseline scenario findings

In the *baseline* scenario, freight traffic constitutes approximately 12 % of total vehicle flow in Pardubice, with no restrictions on inbound deliveries (Fig. 10). Traffic data collected across nine principal routes shows average speeds between roughly 17 and 28 km/h, reflecting moderate but manageable congestion on most corridors. When aggregated network-wide in the simulation, passenger cars and light vans achieve an average travel speed of about 24.3 km/h, requiring just over 19 min per trip. Heavy-goods vehicles follow a similar pattern, but tend to experience slightly longer travel times due to their size and load constraints. These baseline conditions yield a combined daily output of around 3.0 million g NO_x and 7,400 kg CO, underscoring the emissions burden tied to routine urban freight activity.

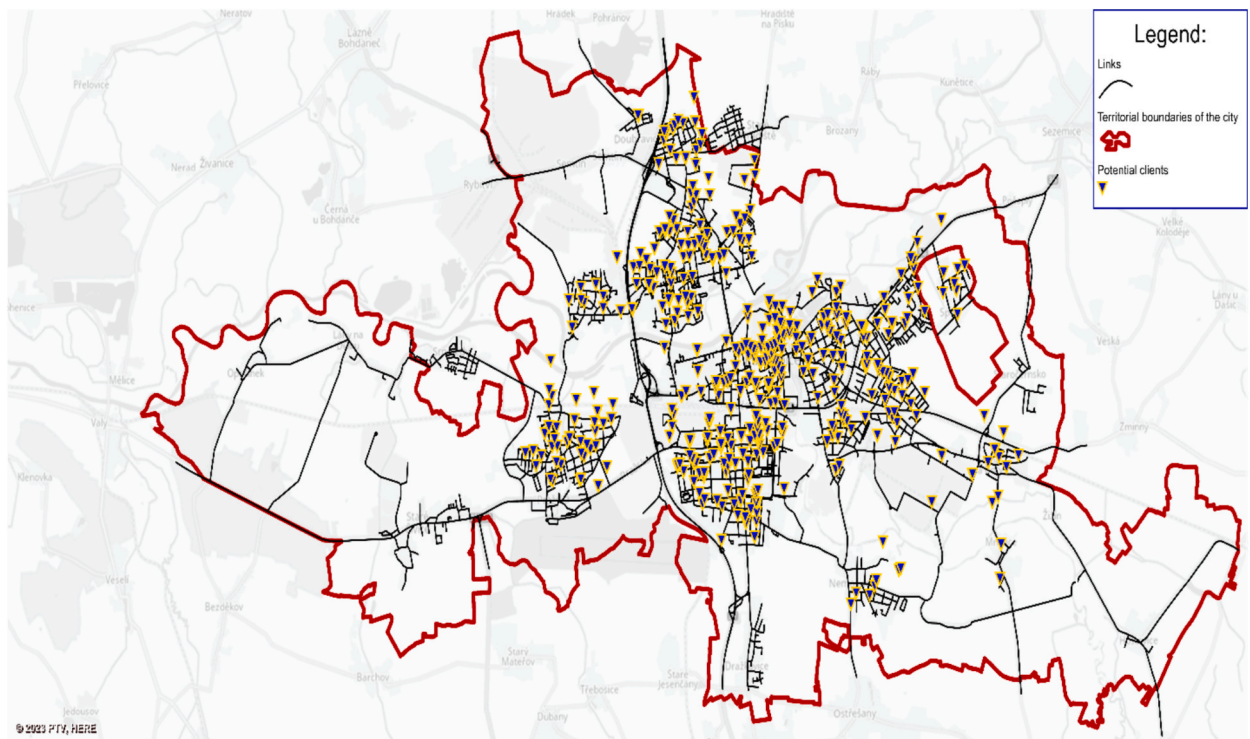


Fig. 6. Clients' locations.

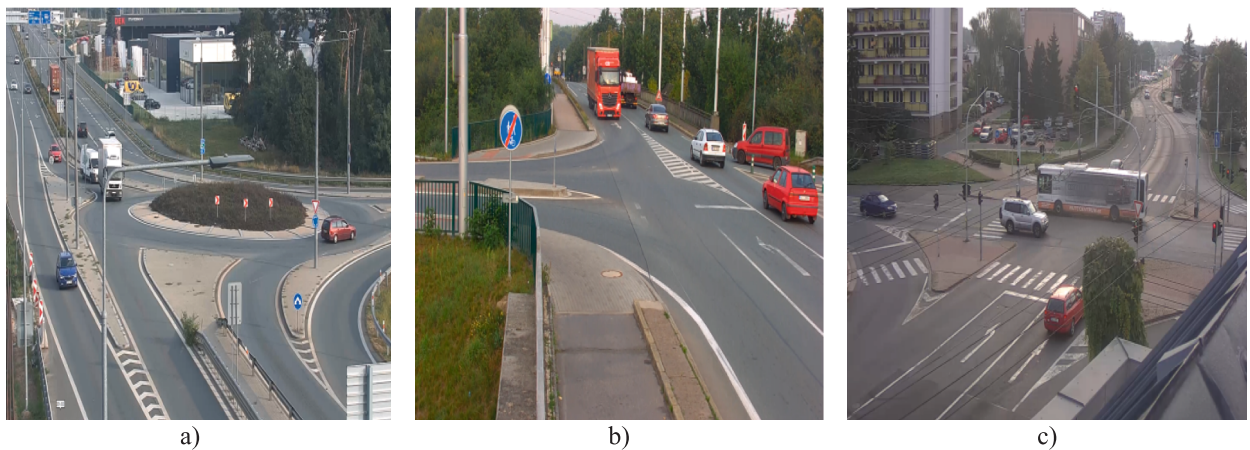
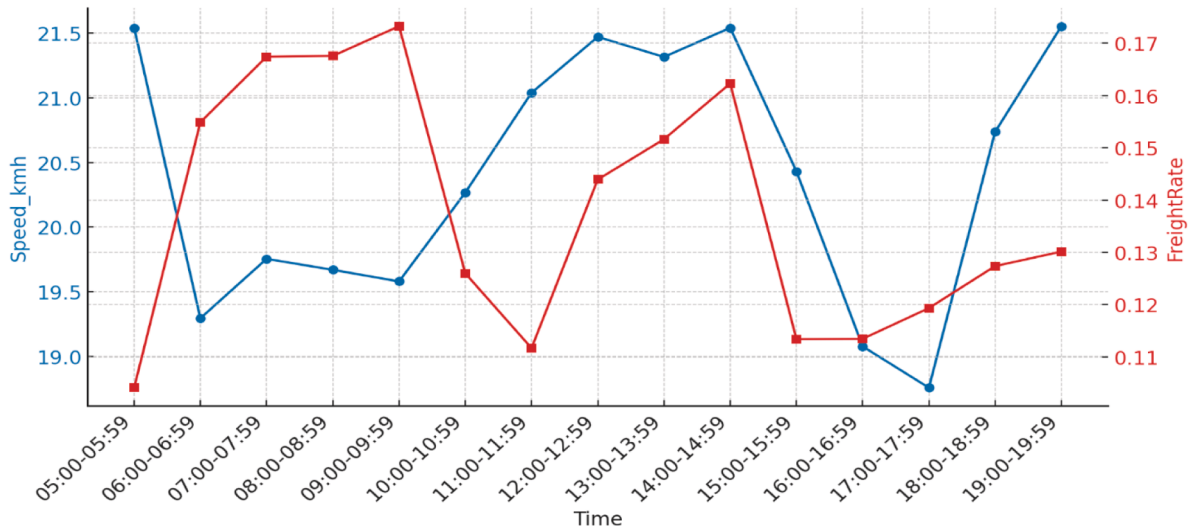


Fig. 7. Examples of camera monitoring system in Pardubice.

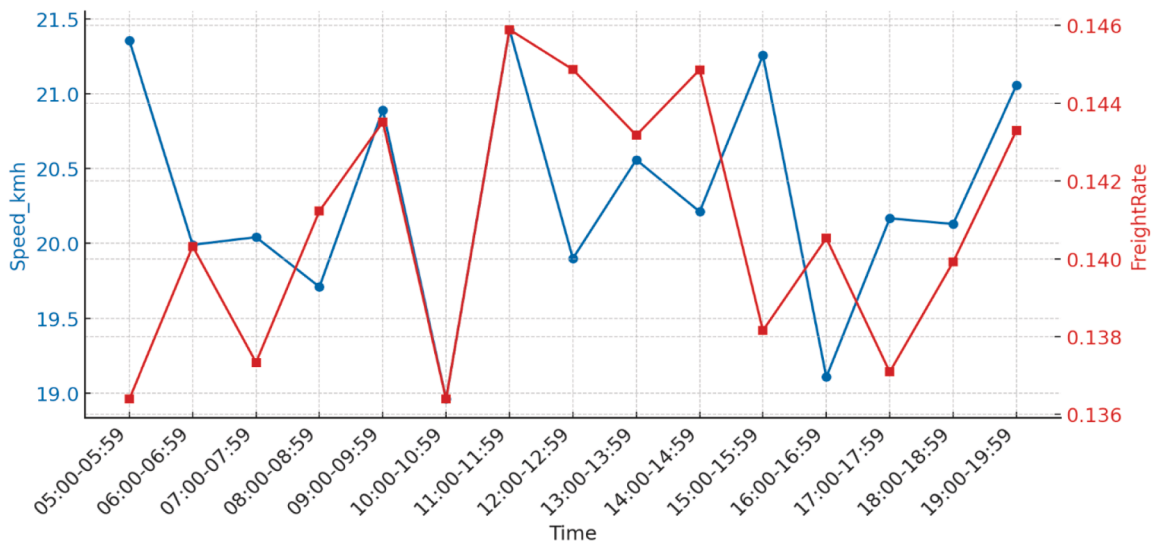
Throughout peak morning hours, certain arterial junctions show local speed drops below 20 km/h, though traffic does not devolve into a widespread gridlock. Because no buffer zones or scheduling interventions are active in this baseline, FVs simply merge into the general traffic stream. As a result, operators face occasional slowdowns around busy retail clusters, but do not incur persistent queuing delays. Observations from the city CCTV system confirm that most freight trips are completed within typical delivery windows, although congestion is more pronounced near the city centre and at highway exits leading into central districts.

4.3. Impact of FR variation

The calibrated baseline model, reflecting approximately 12 % freight share in daily traffic, served as the reference point for evaluating different FR levels. Table 7 compares outcomes for the baseline case alongside three alternative scenarios: a 50 % reduction in Freight Share (−50 % FR), a moderate increase (+50 % FR), and a doubling of freight influx (+100 % FR), Table 7.



a) weekday



b) weekend

Fig. 8. Empirical hourly profiles of average traffic speed and freight rate in Pardubice (FCD and BriefCam data).

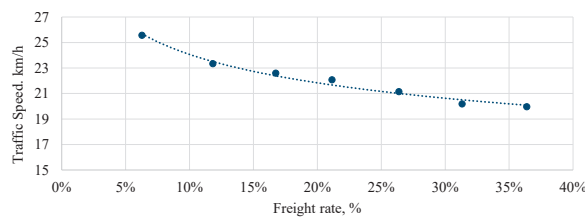


Fig. 9. Dependence of Traffic Speed on Fright Rate in the city after VISIM simulation of scenarios.

The – 50 % FR scenario produced a noticeable improvement in average speed, rising from around 24.3 km/h in the baseline to over 25 km/h. Overall travel times dropped correspondingly, suggesting that lighter freight volumes alleviated localised congestion around known bottleneck intersections, particularly during the morning peak. Emissions estimates (e.g. NO_x and CO) showed proportional

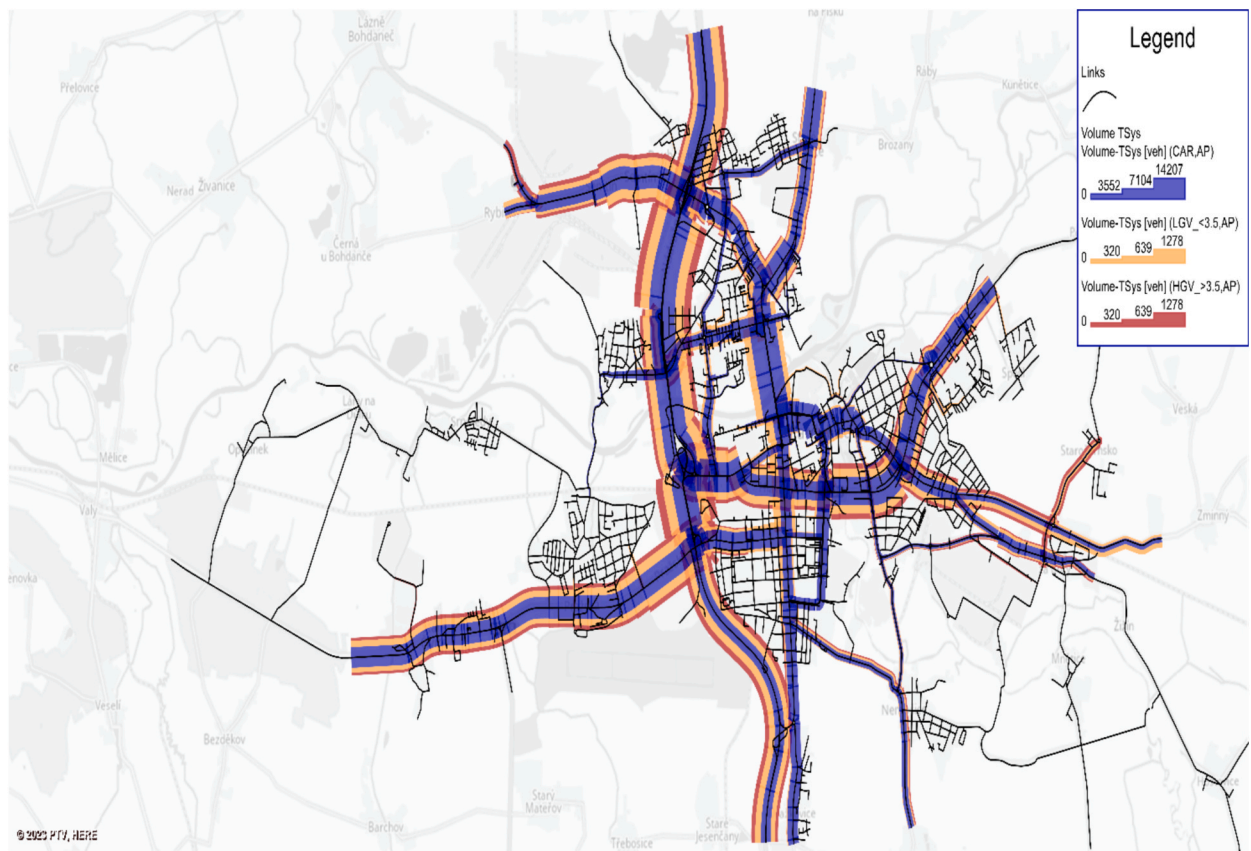


Fig. 10. Baseline scenario (data from Transport Company of Pardubice).

Table 7

Scenario simulation results.

Scenario	Total Trips (Vehicles)	Freight Share (%)	Average Speed (km/h)	Total Time (min)	Total Distance (km)	NO _x (g)	SO ₂ (g)	CO (kg)	HC (g)
Baseline	122778.71	11.82	24.33	141,004,588	969,957	3015823.82	388162.57	7393.15	1451046.86
-50 % FR	115520.82	6.28	25.26	128,358,366	917,007	2150678.94	304572.2	6588.54	1075820.54
+50 % FR	130036.59	16.74	23.4	154,755,644	1,023,206	3838244.28	468655.6	8204.88	1813687.25
+100 % FR	137294.47	21.15	22.47	169,847,542	1,076,778	4697134.86	553440.59	9079.79	2206164.91

decreases because vehicles spent less time in low-speed conditions or idling at intersections.

Conversely, boosting the freight share by 50 % led to an approximate reduction of 1 km/h in average speed. Total daily travel times increased by over 13 million minutes compared to the baseline, primarily due to the higher mixing of passenger and FVs on arterial roads. This congestion manifested most acutely during peak windows, when queue build-ups at critical junctions extended beyond typical waiting times observed in the baseline scenario. More frequent stop-and-go conditions raised emissions of NO_x and CO, reinforcing the direct link between diminished average speeds and rising pollutant output.

Doubling the freight share to + 100 % FR exacerbated these trends: average speeds fell below 23 km/h, trip durations grew significantly, and total emissions peaked at nearly 4.70 million g NO_x and over 9,000 kg CO. Under these conditions, a localised gridlock emerged in select corridors with limited alternative routing. Although the simulation enforced no buffer zone constraints in this comparison, it revealed how quickly unregulated freight surges strain capacity and produce cascading delays.

4.4. Determination of parking buffer zone capacity

The estimation of required PBZ capacity is based on an analysis of freight inflows, traffic congestion levels, and the effectiveness of threshold-based freight regulations. The dynamic management of PBZs plays a crucial role in mitigating peak-hour congestion while ensuring that freight deliveries remain efficient.

Empirical traffic data and simulation results indicate that the demand for parking spaces fluctuates significantly throughout the day, depending on traffic intensity and the level of freight access restrictions imposed. The validated FR threshold of 15 % provides an optimal balance between limiting congestion and maintaining delivery reliability. However, even under this configuration, PBZ demand exhibits considerable variation across different time intervals.

The peak-hour requirement for PBZs reaches approximately 100 parking spaces, while during non-peak hours, the demand drops significantly to an average of 18 spaces. Under the 15 % FR scenario, the calculated average hourly need for PBZ spaces is 55, which ensures smooth freight inflows without excessive queue formation or unnecessary delays for logistics operators (Fig. 11).

Fig. 9 illustrates the fluctuations in PBZ demand across different time intervals under varying freight access scenarios, which underscores the importance of adaptive freight regulation strategies, ensuring that UL operations remain efficient, environmentally sustainable, and responsive to fluctuating traffic conditions.

4.5. Slot booking and scheduling results

In addition to using buffer zones, the DFM framework introduced a slot-booking system that lets logistics operators reserve city-entry windows during off-peak hours. This mechanism aimed to reduce the risk of reaching critical freight-share thresholds (X_2) and incurring extended PBZ holds. Simulation analyses compared two principal conditions: low adoption (fewer than 30 % of freight operators using slot booking) and high adoption (most operators pre-booking their arrival times).

Under the *low-adoption* condition, morning traffic retained a pronounced spike in inbound freight between 8:00 and 10:00 AM. Because so few deliveries were rescheduled, PBZ queues continued to form at similar levels to scenarios without slot booking, and the overall average speed in these peak windows showed only modest gains relative to the baseline. Operators who adopted slot booking consistently reported shorter waiting times at the city boundary, yet the broader network still endured notable slowdowns due to uncoordinated arrivals.

By contrast, high adoption of time-window reservations yielded more uniform inbound traffic patterns. Freight arrivals became noticeably flatter over the day, with a reduced morning peak and an uptick in midday/late-afternoon deliveries. This spread led to a measurable improvement in average travel speeds, particularly on corridors that had previously borne the brunt of early-morning congestion. PBZ usage also decreased – FVs holding only when absolutely necessary – since many operators targeted entry slots below the critical FR threshold. Queue lengths at PBZs shrank by up to 40 % in peak hours compared with the *low-adoption* scenario, reflecting the system's ability to match freight inflows with available road capacity.

Fig. 5 depicts the hour-by-hour distribution of inbound freight arrivals for the high-adoption setting, illustrating how off-peak slots around midday rose from under 10 % in the baseline to nearly 25 %. This migration proved instrumental in stabilising network speeds above 20 km/h for longer durations, particularly in the late morning. From an emissions standpoint, time-window scheduling generated modest but significant decreases (roughly 5–10 %) in daily totals.

4.6. Validation of FR thresholds

The primary metric used for validation is the FR, which determines the proportion of FVs in the total traffic flow. The empirical data from 1760 recorded observations in the data collection stage (Section 4.1) serve as the benchmark to evaluate whether the pre-set FR thresholds (5 %, 10 %, 15 %, and 20 %) effectively mitigate congestion and maintain acceptable levels of service.

Table 8 compares the empirical traffic data with the corresponding effects of varying FR thresholds on the average urban transportation speed (V) and the number of records where traffic speeds exceed LOS D (20 km/h).

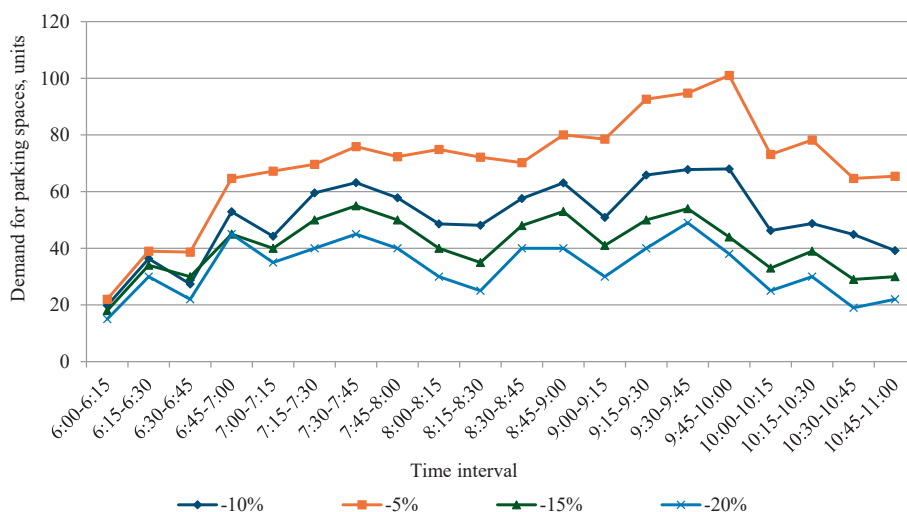


Fig. 11. Demand for PBZs over time.

Table 8
Validation of Scenarios Based on Empirical Data (1760 records).

Pre-set FR Threshold (X_2 , %)	Records with FR > X_2	Records with LOS > 20 km/h	Total Records	Original Avg. Speed (km/h)	Modified Avg. Speed (km/h)	Change in Speed (km/h)	Impact on Network Performance
5 %	1724	350	1760	16.39	27.68	+11.23	Significant improvement but high PBZ queueing
10 %	880	280	1760	16.39	23.07	+6.68	Balanced congestion control with moderate PBZ demand
15 %	793	154	1760	16.39	21.14	+4.75	Optimal balance between speed and freight flow
20 %	550	115	1760	16.39	19.49	+3.10	Minimal PBZ intervention but lower average speed

When X_2 was set at 5 % (meaning freight traffic above that share triggered a redirection), about 1,724 records breached the threshold, sending more vehicles to PBZs and yielding a higher overall travel speed of nearly 28 km/h. Though this stringent control notably improved UTN throughput, it also meant frequent PBZ usage: operators reported extended queue times, given that many trucks arrived during morning peaks. By contrast, a more lenient threshold of 20 % reduced the frequency of PBZ intervention to 550 records but allowed average speeds to fall below 20 km/h at some critical corridors.

A moderate threshold of 15 % freight share emerged as a practical compromise. Under this setting, around 793 records exceeded the limit, leading to selective PBZ holds but still maintaining an acceptable Level of Service (LOS \geq D) for the majority of the day. Simulation outputs showed that typical waiting times at PBZs peaked during the morning rush, yet were short enough (under an hour for most vehicles) to avoid major disruptions to operators' schedules. Additionally, the citywide average speed in this scenario rose to around 21 km/h, marking a noticeable gain over the baseline without imposing overly frequent diversions.

While Table 7 verifies that the four pre-set freight-rate thresholds ($X_2 = 5\%$, 10 %, 15 %, 20 %) keep network speeds within acceptable bounds, Table 9 drills down to the loading-bay scale, reporting how each threshold affects parking-buffer zone (PBZ) performance.

With X_2 tightened to 5 %, virtually all trucks depart the PBZ within 25 min, but the low threshold inflates demand to an average of only 15 vehicles per hour, leaving bays underutilised during off-peak periods. At the opposite end, an X_2 of 20 % pushes the 90th-percentile delay close to an hour and creates mean queues of 55 vehicles, exceeding the 55-bay design envelope and risking kerbside spill-back.

The 15 % setting again strikes the most workable balance. Median delay is 27 min, and even the 90th-percentile vehicle clears the zone at *exactly* the 45-minute policy ceiling, while average occupancy (\approx 42 vehicles) remains within capacity.

Fig. 12 visualises this result by plotting the *cumulative distribution* of PBZ waits for the $X_2 = 15\%$ scenario. The curve shows a sharp inflexion at 45 min, where 90 % of departures have already occurred, confirming that the recommended ceiling coincides with the natural tail of the delay distribution and prevents queue build-up beyond LOS D conditions.

Together, Table 9 and Fig. 12 demonstrate that the proposed PBZ rule set maintains reliable turnaround times without introducing the queue spill-back observed under laxer (20 %) or more restrictive (5 %) freight-rate caps.

5. Discussion

This study closes four long-standing gaps identified in FDM, STT and ABM scholarship. First, by carrying out a year-long field simulation in Pardubice, it delivers the medium-sized-city evidence that has been missing from freight research dominated by megacity cases (Holguín-Veras et al., 2018; Chen et al., 2021). Second, it is the first empirical test of a truly coupled intervention—threshold-triggered access rules plus AI-supported slot-booking—thereby operationalising the theoretical call for joint curb-policy/route-optimisation frameworks (Crainic et al., 2021; Nadi et al., 2022). Third, the twelve-month observation window provides a long-horizon assessment of behavioural adaptation and policy durability that short pilot studies have lacked (Bjørngen & Ryghaug, 2022). Finally, the project documents how formalised data-sharing protocols between carriers and municipal telematics raise compliance, answering recent governance critiques in the urban-logistics literature (McKinnon, 2023). Collectively, these contributions advance DFM from conceptual promise to practice-ready guidance, demonstrating measurable gains in network speed, emissions and stakeholder coordination that earlier theoretical models only posited (Reis, 2019).

The empirical findings confirm that managing urban freight via threshold-based controls, PBZs, and time-slot scheduling can significantly alleviate congestion while reducing emissions, aligning with prior research that highlights the importance of real-time policies in ULs (Holguín-Veras et al., 2020; Comi & Polimeni, 2021). By fine-tuning the FR and LOS thresholds, municipal authorities in mid-sized cities like Pardubice can prevent daily surges in freight traffic from overwhelming key arterial corridors. The simulations illustrate that implementing a moderate threshold, where traffic is partially curbed without forcing undue delays, effectively stabilises UTN speed around 20 km/h or higher. This finding aligns with earlier theoretical work suggesting that relatively small changes in allowable freight influx can generate disproportionate improvements in overall traffic flow (Keyvan-Ekbatani et al., 2012).

From a theoretical standpoint, the study extends agent-based urban freight models by integrating adaptive feedback loops into a DFASA. Existing literature often treats traffic thresholds as fixed parameters, but the iterative approach adopted here demonstrates that thresholds can and should evolve in response to real-time performance metrics (Nadi et al., 2022). This flexibility not only

Table 9
PBZ waiting-time statistics by FR scenario (n = 800 truck arrivals).

FR threshold	Median wait, min	75th-percentile, min	90th-percentile, min	Mean queue length, veh	Departures \leq 45, min
0.05	12	18	24	15	100 %
0.10	20	30	40	30	99 %
0.15	27	37	45	42	95 %
0.20	35	48	58	55	83 %

Note: A 45-minute cap aligns with the 90th-percentile delay at FR = 15 %, maintaining queue lengths within the 55-bay design envelope and preserving LOS D network speeds.

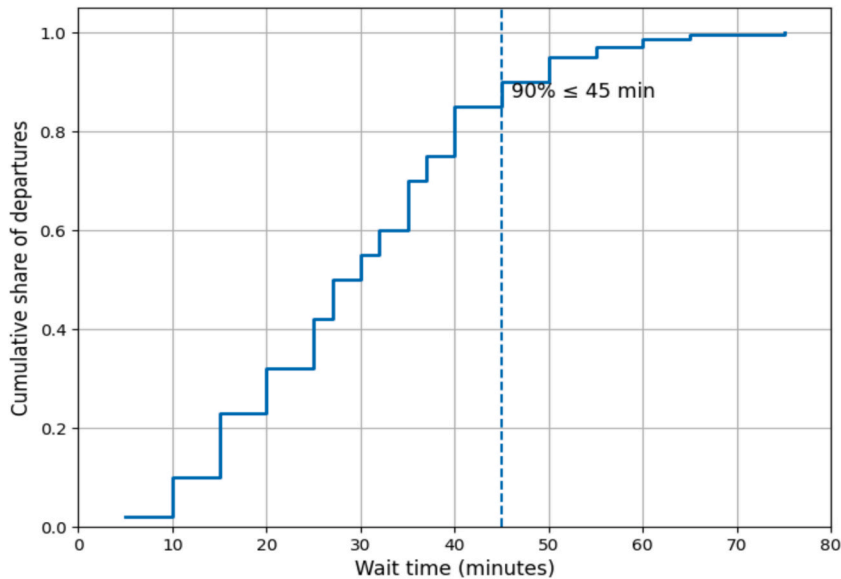


Fig. 12. Cumulative distribution of PBZ waits (FR = 15 %).

enhances the realism of modelling outcomes but also contributes new insights to congestion management theory by demonstrating how threshold-based regulation, buffer queue control, and slot-booking can be interwoven to balance efficiency and environmental concerns. In doing so, the work enriches the theoretical foundation of multi-agent logistics systems, suggesting novel ways for municipalities to align network capacity with evolving patterns of last-mile deliveries.

Practically, the results imply that well-calibrated interventions, such as moderate freight caps and proactive PBZ usage, can yield tangible speed gains for both freight and passenger vehicles, improving daily travel reliability and reducing emissions. Cities may also incentivise high operator participation in off-peak time-slot programs by offering nominal fee reductions or priority handling at PBZs. The success of such programs depends on stakeholder coordination and robust data-sharing platforms that encourage logistics operators to adopt more flexible delivery timings. In this respect, the framework provides a blueprint for municipalities to orchestrate dynamic freight scheduling without imposing rigid bans or narrowly defined traffic windows. Based on the findings, the following policy measures are recommended for cities aiming to balance freight efficiency with environmental sustainability:

Municipal Authorities: Municipal authorities should implement an adaptive freight regulation framework with a FR cap (X_2) of 10–15 % to maintain manageable freight flows while preventing congestion. The (LOS) threshold (X_1) should be set at 20 km/h (LOS D) to ensure that road saturation does not critically impact urban mobility. Expanding low-emission freight zones and incentivising electric vehicle adoption can contribute to achieving a 10–20 % reduction in NO_x/CO emissions. These controls should be integrated with urban telematics infrastructure to automate enforcement and streamline compliance tracking. Nevertheless, implementing such restrictive measures is ultimately a political choice, and success depends on the willingness of local decision-makers to adopt and sustain them despite potential resistance.

Logistics Operators: To improve slot-booking utilisation, logistics operators should aim for a > 70 % adoption rate of scheduled delivery windows. Operators should be required to pre-book time slots for urban entry, prioritising off-peak hours to smooth traffic flow and reduce peak-hour congestion. Additionally, penalties should be imposed for non-compliance, while incentives such as 30–50 % lower waiting times at PBZs should be provided to encourage participation. Predictive scheduling models should be integrated to adjust slot availability dynamically based on freight demand forecasts.

PBZ Management: Based on the modelled 90th-percentile PBZ delay under the validated FR = 15 % scenario (\approx 43–46 min), a 45-minute cap is adopted to guarantee that the vast majority of freight movements clear the buffer without jeopardising scheduled

deliveries. Dynamic allocation of buffer slots should be based on congestion indicators, with priority given to low-emission and pre-booked freight movements. A minimum of two PBZs per high-congestion district should be implemented, equipped with digital signage to provide real-time availability updates. Regular monitoring should be conducted to maintain optimal queue lengths and prevent PBZ overflows.

Consumers play a crucial role in optimising urban freight flows by adjusting delivery preferences to off-peak hours. A shift of at least 30 % of home deliveries to scheduled evening or non-peak times can significantly reduce congestion and emissions. Retailers and e-commerce platforms should incentivise flexible delivery options (Beckers et al., 2023) by offering discounts or loyalty rewards for choosing less congested time slots. Additionally, promoting consolidated deliveries – where multiple orders from different retailers are combined into a single drop-off – can help lower overall freight traffic volume by 10 – 15 %, easing the pressure on urban road networks. Enhanced consumer awareness campaigns should be conducted to highlight the environmental benefits of optimised delivery choices.

6. Conclusions

This study demonstrates that applying moderate, dynamic thresholds, such as LOS D (20 km/h) and freight caps around 10–15 %, is effective in reducing congestion and emissions in urban freight systems. Simulation results show that these measures, particularly when combined with high adoption of off-peak slot-booking and well-scaled parking buffer zones, can cut daily NO_x and CO emissions by up to 20 % compared to baseline, while maintaining reliable delivery performance for operators. Network resilience is enhanced by balancing access restrictions with flexible, data-driven policies, allowing cities to respond effectively to fluctuating demand.

Policy implications are clear: municipal authorities in medium-sized cities should implement adaptive regulatory frameworks, investing in real-time surveillance (e.g., CCTV, FCD, telematics), formalising threshold values in urban codes, and engaging logistics stakeholders through outreach and pilot programs. These strategies can help cities meet climate targets, reduce congestion, and support sustainable last-mile logistics.

Implementing the proposed DFM framework will inevitably confront several real-world challenges. Chief among them are the up-front investment costs for city-wide sensing infrastructure, the need for robust data-sharing agreements that satisfy privacy regulations, and potential resistance from freight operators who may face schedule disruptions or additional compliance costs. Successful roll-out therefore requires phased pilot programmes, clear incentive structures and sustained stakeholder engagement to secure political support and operational buy-in. Limitations of the study include its focus on a single mid-sized city (Pardubice), the reliance on simulation-based findings that may not capture all real-world behavioural responses, and the exclusion of electric or autonomous vehicle fleets, which could alter congestion dynamics. The adaptability of the DFM framework to larger or more complex urban contexts remains to be fully tested.

Recommendations for future research include: (i) multi-city, longitudinal evaluations of DFM strategies; (ii) integration of emerging vehicle technologies and smart infrastructure; and (iii) advanced machine learning for real-time prediction of demand surges and network bottlenecks. By building on the adaptive, stakeholder-centered framework presented here, future studies can help ensure urban freight remains efficient, resilient, and sustainable amid growing logistical demands.

CRedit authorship contribution statement

Andrii Galkin: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Libor Švadlenka:** Writing – review & editing, Supervision, Project administration. **Radek Vrba:** Validation, Software, Data curation. **Kinga Kijewska:** Writing – review & editing, Validation, Resources, Funding acquisition, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Data Integration Pipeline and Scenario Configuration for DFM Simulation

Table A1

Data-pipeline overview for the DFM methodology.

Source	Raw data type (temporal resolution)	Pre-processing / aggregation	Derived indicator or variable	Model component(s) using the data
CCTV + BriefCam analytics	Vehicle detections, class labels (≈ 3 s)	Object tracking & 5-min aggregation	Freight-ratio (FR) per link, vehicle counts	DFASA thresholds; ABM vehicle generation
Floating-Car-Data (FCD)	GPS probe speeds (≈ 1 min)	Map-matching; 5-min speed average	Link speed; Level-of-Service (LOS) classification	DFASA LOS trigger; VISUM network calibration
Logistics-operator manifests	Stop lists, vehicle type, promised time windows (daily)	Anonymisation; temporal binning	Shipment demand profile; delivery time-window constraints	ABM demand layer; slot-booking scenarios
Municipal traffic counts & SUMPs/SULPs	24 h directional volumes; road geometry (periodic)	Harmonisation into VISUM format	Static base network, capacity & lane attributes	VISUM network; ABM road graph
Environmental-agency emission factors	Pollutant coefficients by vehicle class (static)	Direct lookup	NOx, CO, PM2.5 factors	Post-processing of scenario outputs

Table A2

Summary of simulation scenarios and evaluation indicators.

Scenario group	Scenario label	Main parameters varied	Purpose of test	Key performance indicators recorded
Baseline	–	Existing FR ≈ 12 %; LOS observed in field; no PBZ or slot controls	Provide real-world reference point	Avg. network speed; total travel time; emissions (NOx, CO); observed FR
FR-variation	FR – 50 %	Freight-ratio cut to ~ 6 %	Evaluate benefits of aggressive demand reduction	Same as baseline, plus PBZ demand (if triggered)
	FR + 50 %	Freight-ratio raised to ~ 18 %	Stress-test network under moderate surge	As above
Threshold-sensitivity	FR + 100 %	Freight-ratio doubled to ~ 24 %	Worst-case surge scenario	As above
	LOS strict ($X_1 = D$)	Minimum LOS set to 20 km h^{-1}	Gauge impact of tighter speed threshold	Avg. PBZ queue length; waiting time; speed; emissions
	LOS lenient ($X_1 = E$)	Minimum LOS set to 15 km h^{-1}	Assess trade-off of looser speed target	Same KPIs
Slot-booking adoption	FR caps 5 %, 10 %, 15 %, 20 %	Successively higher X_2 values	Identify balanced FR threshold	Same KPIs
	Low adoption (< 30 %)	Few operators pre-book slots	Baseline for behavioural shift	Avg. slot utilisation; peak FR; PBZ demand
PBZ-capacity test	High adoption (≈ 80 %)	Most operators pre-book slots	Test efficacy of widespread slot use	Same KPIs
	25, 40, 55 bays	Holding capacity varied	Dimension buffer zones	Peak queue; 90th-pct waiting time; spill-back incidents

Data availability

The authors do not have permission to share data.

References

- Akhtar, M., Moridpour, S., 2021. A review of traffic congestion prediction using artificial intelligence. *J. Adv. Trans.* 2021 (1), 8878011.
- Alho, A., Oh, S., Seshadri, R., Dalla Chiara, G., Chong, W.H., Sakai, T., Ben-Akiva, M., 2022. An agent-based simulation assessment of freight parking demand management strategies for large urban freight generators. *Res. Transp. Bus. Manag.* 43, 100804.
- Allen, J., Browne, M., Cherrett, T., 2012. Investigating relationships between road freight transport, facility location, logistics management and urban form. *J. Transp. Geogr.* 24, 45–57.
- Astarita, V., Giofrè, V.P., Guido, G., Vitale, A., Festa, D.C., 2019. Floating car data adaptive traffic signals. In: *Proceedings of the 23rd IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications*, pp. 320–321.
- Beckers, J., Cardenas, I., Le Pira, M., Zhang, J., 2023. Exploring Logistics-as-a-Service to integrate the consumer into urban freight. *Res. Transp. Econ.* 101, 101354.
- Bjorgen, A., Ryghaug, M., 2022. Integration of urban freight transport in city planning: Lesson learned. *Transp. Res. Part D: Transp. Environ.* 107, 103310.
- Brozovsky, J., Gustavsen, A., Gaitani, N., 2021. Zero emission neighbourhoods and positive energy districts – A state-of-the-art review. *Sustain. Cities Soc.* 72, 103013.
- Chen, Y., Chen, C., Wu, Q., Ma, J., Zhang, G., Milton, J., 2021. Spatial-temporal traffic congestion identification and correlation extraction using floating car data. *J. Intell. Transp. Syst.* 25 (3), 263–280.
- Ceulemans, E., Cardenas, I., van Hassel, E., Vanelslander, T., 2025. Synchronodal transport vs. conventional hinterland transport: a stakeholder theory analysis. *Transp. Rev.* 45 (1), 1–25.
- Cervero, R., et al., 2004. *Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects*. TCRP Report 102.
- Conway, A., Cheng, J., Kamga, C., Wan, D., 2017. Cargo cycles for local delivery in New York City: Performance and impacts. *Res. Transp. Bus. Manag.* 24, 90–100.
- Comi, A., Polimeni, A., 2021. Forecasting delivery pattern through floating car data: Empirical evidence. *Future Transportation* 1 (3), 707–719.

- Comi, A., Crisalli, U., Sportiello, S., 2024. Forecasting the vehicle energy potential to support the needs of electricity grid: A floating car data-based methodology. *Front. Future Transp.* 5, 1500224.
- Comi, A., Savchenko, L., 2021. Last-mile delivering: Analysis of environment-friendly transport. *Sustain. Cities Soc.* 74, 103213.
- Crainic, T.G., Perboli, G., Rosano, M., 2018. Simulation of intermodal freight transportation systems: a taxonomy. *Eur. J. Oper. Res.* 270 (2), 401–418.
- Crainic, T.G., Perboli, G., Ricciardi, N., 2021. *City logistics*. Springer International Publishing, pp. 507–537.
- Crainic, T.G., Feliu, J.G., Ricciardi, N., Semet, F., Van Woensel, T., 2023. Operations research for planning and managing city logistics systems. In: *Handbook on city logistics and urban freight*. Edward Elgar Publishing, pp. 190–223.
- Cruz-Daraviña, P.A., Suescún, J.P.B., 2021. Freight operations in city centers: A land use conflict in urban planning. *Land Use Policy* 108, 105575.
- Dablanc, L., Montanon, A., 2015. Impacts of environmental access restrictions on freight delivery activities: Example of low emissions zones in Europe. *Transp. Res. Rec.* 2478 (1), 12–18.
- Dailey, D.J., Cathey, F.W., Pumrin, S., 2000. An algorithm to estimate mean traffic speed using uncalibrated cameras. *IEEE Trans. Intell. Transp. Syst.* 1 (2), 98–107.
- Davenport, T.H., Prusak, L., 1998. *Working Knowledge: How Organizations Manage What They Know*. Harvard Business School Press.
- Davidich, N., Galkin, A., Iwan, S., Kijewska, K., Chumachenko, I., Davidich, Y., 2021. Monitoring of urban freight flows distribution considering the human factor. *Sustain. Cities Soc.* 75, 103168.
- Davidich, N., Melenchuk, T., Kush, Y., Davidich, Y., Lobashov, O., Galkin, A., 2018. Modelling truck's transportation speed on the route considering driver's state. *Transp. Res. Procedia* 30, 207–215.
- de Bok, M., Tavasszy, L., Kourounioti, I., Thoen, S., Eggers, L., Nielsen, V.M., Streng, J., 2021. Simulation of the impacts of a zero-emission zone on freight delivery patterns in Rotterdam. *Transp. Res. Rec.* 2675 (10), 776–785.
- Eom, M., Kim, B.-I., 2020. The traffic signal control problem for intersections: A review. *Eur. Transp. Res. Rev.* 12, 50.
- Ehmke, J.F., Campbell, A.M., Thomas, B.W., 2016. Vehicle routing to minimize time-dependent emissions in urban areas. *Eur. J. Oper. Res.* 251 (2), 478–494.
- Figliozzi, M., Saenz, J., Faulin, J., 2020. Minimization of urban freight distribution lifecycle CO₂e emissions: Results from an optimization model and a real-world case study. *Transp. Policy* 86, 60–68.
- Gao, K., Han, F., Wen, M., Du, R., Li, S., Zhou, F., 2019. Coordinated control method of intersection traffic light in one-way road based on V2X. *J. Cent. South Univ.* 26, 2516–2527.
- Galkin, A., Svadlenka, L., Vrba, R., de Oliveira, L.K., 2025. Evaluation of cargo bike program for parcel deliveries in a medium-sized city. *Transp. Res. Part D: Transp. Environ.* 140, 104609.
- De Maio, A., Ghiani, G., Laganà, D., Manni, E., 2024. Sustainable last-mile distribution with autonomous delivery robots and public transportation. *Transp. Res. Part C Emerging Technol.* 163, 104615.
- HCM (2010). *Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, DC, 1207.
- Hoekstra, T., Wegman, F., 2011. Improving the effectiveness of road safety campaigns: Current and new practices. *IATSS Res.* 34 (2), 80–86.
- Holguín-Veras, J., Leal, J.A., Sánchez-Díaz, I., Browne, M., Wojtowicz, J., 2020. State of the art and practice of urban freight management: Part I: Infrastructure, vehicle-related, and traffic operations. *Transp. Res. A Policy Pract.* 137, 360–382.
- Holguín-Veras, J., Rivera-González, C., Caron, B., Amaral, J.C., Ismael, A., 2023. Integrated transportation and land-use program to improve metropolitan freight system performance. In: *Handbook on City Logistics and Urban Freight*. Edward Elgar Publishing, pp. 35–58.
- Ibraeva, A., de Almeida Correia, G.H., Silva, C., Antunes, A.P., 2020. Transit-oriented development: A review of research achievements and challenges. *Transp. Res. A Policy Pract.* 132, 110–130.
- Kapser, S., Abdelrahman, M., 2020. Acceptance of autonomous delivery vehicles for last-mile delivery in Germany—Extending UTAUT2 with risk perceptions. *Transp. Res. Part C Emerging Technol.* 111, 210–225.
- Keyvan-Ekbatani, M., Kouvelas, A., Papamichail, I., Papageorgiou, M., 2012. Exploiting the fundamental diagram of urban networks for feedback-based gating. *Transp. Res. Part B: Methodol.* 46 (10), 1393–1403. <https://doi.org/10.1016/j.trb.2012.06.008>.
- Kijewska, K., França, J.G.C.B., de Oliveira, L.K., Iwan, S., 2022. Evaluation of urban mobility problems and freight solutions from residents' perspectives: A comparison of Belo Horizonte (Brazil) and Szczecin (Poland). *Energies* 15 (3), 710.
- International Energy Agency, 2023. *Global EV Outlook 2023: Catching up with climate ambitions*. IEA, Paris. <https://www.iea.org/reports/global-ev-outlook-2023>.
- Invesp, (2025, April 6). Global online retail statistics and trends for 2025: \$7.4 trillion projected. Retrieved August 2025, from Invesp website: <https://www.invespro.com/blog/online-retail-statistics-and-trends/>.
- Iwan, S., Kijewska, K., Johansen, B.G., Eidhammer, O., Malecki, K., Konicki, W., Thompson, R.G., 2018. Analysis of the environmental impacts of unloading bays based on cellular automata simulation. *Transp. Res. Part D: Trans. Environ.* 61, 104–117. <https://doi.org/10.1016/j.trd.2017.03.020>.
- Kahalimoghadam, A., Thompson, R.G., Rajabifard, A., 2024. Self-adaptive metaheuristic-based emissions reduction in a collaborative vehicle routing problem. *Sustain. Cities Soc.* 110, 105577.
- Kujawski, A., Dudek, T., 2021. Analysis and visualization of data obtained from camera mounted on unmanned aerial vehicle used in areas of urban transport. In: *Sustainable Cities and Society*. Elsevier. <https://doi.org/10.1016/j.scs.2021.103004>.
- Lemardel, C., Estrada, M., Pages, L., Bachofner, M., 2021. Potentialities of drones and ground autonomous delivery devices for last-mile logistics. *Transportation Research Part E: Logistics and Transportation Review* 149, 102325.
- Liu, Z., Jian, M., 2019. Traffic impacts analysis of bus stops near signalised intersections based on an optimal velocity model. *Adv. Mech. Eng.* 11 (5).
- Li, Y., Guan, Q., Gu, J., Jiang, X., 2024. A deep reinforcement learning with dynamic spatio-temporal graph model for solving urban logistics delivery planning problems. *Int. J. Digital Earth* 17 (1), 2376273.
- Ma, L., Graham, D.J., Stettler, M.E., 2021. Has the ultra low emission zone in London improved air quality? *Environ. Res. Lett.* 16 (12), 124001.
- McKinnon, A., 2023. Environmentally sustainable city logistics: minimising urban freight emissions. In: *Handbook on City Logistics and Urban Freight*. Edward Elgar Publishing, pp. 463–482.
- Mohri, S.S., Ghaderi, H., Van Woensel, T., Mohammadi, M., Nassir, N., Thompson, R.G., 2024. Contextualizing alternative delivery points in last mile delivery. *Transportation Research Part E: Logistics and Transportation Review* 192, 103787.
- Muñoz-Villamizar, A., Velazquez-Martínez, J.C., Caballero-Caballero, S., 2024. A large-scale last-mile consolidation model for e-commerce home delivery. *Expert Syst. Appl.* 235, 121200.
- Nadi, A., Sharma, S., van Lint, J.W.C., Tavasszy, L., Snelder, M., 2022. A data-driven traffic modeling for analyzing the impacts of a freight departure time shift policy. *Transp. Res. A Policy Pract.* 161, 130–150.
- Naganawa, H., Hirata, E., Firdausiyah, N., Thompson, R.G., 2024. Logistics Hub and Route Optimization in the Physical Internet Paradigm. *Logistics* 8 (2), 37.
- Nigro, M., Castiglione, M., Colasanti, F.M., De Vincentis, R., Valenti, G., Liberto, C., Comi, A., 2022. Exploiting floating car data to derive the shifting potential to electric micromobility. *Transp. Res. A Policy Pract.* 157, 78–93.
- OECD, 2023. *OECD iLibrary | Trade in goods and services [WWW Document]*. OECD. URL https://www.oecd-ilibrary.org/trade/trade-in-goods-and-services/indicator/en_glish_0fe445d9-en. Accessed 9 July 21.
- Oughton, E.J., Usher, W., Tyler, P., Hall, J.W., 2018. Infrastructure as a complex adaptive system. *Complexity* 2018 (1), 3427826.
- Pan, S., Zhou, W., Piramuthu, S., Giannikas, V., Chen, C., 2021. Smart city for sustainable urban freight logistics. *Int. J. Prod. Res.* 59 (7), 2079–2089.
- Pardu-plán: <https://parduplan.cz/>.
- Peng, X., Ji, S., Zhang, L., Thompson, R.G., Wang, K., 2024. Physical internet enabled sustainable and resilient production-routing problem with modular capacity. *Kybernetes*.
- Perboli, G., Rosano, M., 2019. Parcel delivery in urban areas: Opportunities and threats for the mix of traditional and green business models. *Transp. Res. C* 99, 19–36.
- Prassas, E.S., Roess, P.R., 2020. *The Highway Capacity Manual: A Conceptual and Research History, Volume 2*. Springer International Publishing.
- R Core Team. (2021). *European environment agency*. 2020.
- Reis, V., 2019. A new theoretical framework for integration in freight transport chains. *Trans. Rev.* 39 (5), 589–610.

- Storani, F., Di Pace, R., Bruno, F., Fiori, C., 2021. Analysis and comparison of traffic flow models: a new hybrid traffic flow model vs benchmark models. *Eur. Transp. Res. Rev.* 13, 1–16.
- SULP (2023) Validation of the SULP methodology (application in the city of Pardubice). <https://www.isvavai.cz/riv?ss=detail&h=RIV%2F00216275%3A25510%2F23%3A39921154>.
- van den Haak, P., Bakri, T., Van Katwijk, R., Emde, M., Snelder, M., 2018. Validation of Google floating car data for applications in traffic management. *Proceedings of the Transportation Research Board Annual Meeting*.
- Vrba, R., Švadlenka, L., & Galkin, A. 2024. Monitoring Traffic Flow Using Breifcam Software to Improve Sustainable Urban Logistics. In *Systems, Decision and Control in Energy VI: Volume I: Energy Informatics and Transport* (pp. 377-387). Cham: Springer Nature Switzerland.
- Quak, H., de Koster, M., van Duin, J.H.R., 2016. A city logistics living lab for efficient urban distribution using electric vehicles. *European Journal of Transport and Infrastructure Research* 16, 112–137. <https://doi.org/10.18757/ejtir.2016.16.2.3141>.
- Weir IV, H.T., Andersen, J., Caspersen, E., Iwan, S., Jedliński, M., Kujawski, A., Dudek, T., Nürnberg, M., Osypchuk, O., Sosik-Filipiak, K., Żuchora, M., 2022. Description and Comparison of the Methods, Technologies and Tools for Freight Flows at City Area Analysis – Analysis Results. GRASS-NEXT Project Deliverable 2 (3), 1.
- Wu, L., Zhang, R., Zhou, R., Wu, D., 2021. An edge computing based data detection scheme for traffic light at intersections. *Comput. Commun.* 176, 91–98.

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