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PREDICTIVE COORDINATION OF THIRD-PARTY LOGISTICS FOR SMART URBAN FREIGHT MANAGEMENT: EVIDENCE FROM WARSAW AND WROCLAW

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Urban freight has become a central concern in smart-city governance because rising delivery intensity increases congestion, emissions, and service unreliability in dense metropolitan areas. This study examines whether third-party logistics (3PL) providers can contribute to urban freight management not only through execution, but also through predictive coordination. Using operational data from an international 3PL operator serving Warsaw and Wroclaw, the paper evaluates a forecasting workflow that combines warehouse management system (WMS) and transport management system (TMS) data to predict delivery intensity at both city and postcode levels. The dataset covers four months of daily operations and contains approximately 200,000 records. The predictive engine dynamically selects among `auto.arima()`, `nnetar()`, *and* `ets()` *on the basis of weighted forecast-error testing. Results show high forecast accuracy for palletized flows and weaker but still decision-useful performance for parcel flows. At city level, mean absolute percentage error (MAPE) is 0.36% for Warsaw pallets, 17.47% for Warsaw parcels, 3.78% for Wroclaw pallets, and 4.03% for Wroclaw parcels. Postcode-level error profiles further show that pallet forecasts remain comparatively stable, whereas parcel deliveries exhibit materially greater volatility. The delivery network is also highly irregular: most destination postcodes in both cities are served on no more than 25% of working days. On that basis, the paper proposes a practical smart-city coordination model in which 3PL forecasts are integrated with intelligent transport system (ITS) traffic data and postcode priorities to support delivery-slot prioritization. The study demonstrates that predictive 3PL capabilities can form a viable operational interface between logistics providers and urban traffic governance.*

Index Terms — smart city; urban freight; third-party logistics; last-mile delivery; delivery forecasting; smart mobility; urban traffic management

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INTRODUCTION

Rapid urbanization has intensified freight flows into metropolitan areas, increasing pressure on road space, curb access, and delivery reliability. In smart-city settings, this creates a dual challenge: cities must preserve accessibility and economic vitality while limiting congestion, emissions, and service disruption. Although urban mobility debates often focus on passenger transport, freight movement is equally consequential for city performance because last-mile distribution directly affects traffic conditions, environmental quality, and the functioning of commercial districts.

Third-party logistics (3PL) providers occupy a particularly important position in this environment. They aggregate demand across many shippers, manage warehouse release patterns, and determine how freight enters urban space. For that reason, 3PL firms are not merely operational contractors; they are potential coordination actors whose forecasting capabilities can influence city-facing freight intensity before vehicles are dispatched. If delivery volumes can be anticipated with sufficient accuracy, warehouse release, transport planning, and time-window assignment can be aligned more effectively with urban traffic conditions.

This study investigates that proposition using evidence from two Polish cities, Warsaw and Wroclaw. It asks whether predictive 3PL activity can support smarter urban freight management by improving the timing and organization of last-mile deliveries. The contribution is twofold. First, it presents a structured empirical analysis of delivery forecasting performance using real operational data from a 3PL environment. Second, it translates those results into a policy-relevant coordination concept in which logistics forecasts can be combined with city traffic information to support delivery prioritization.

The paper is organized as follows. Section 2 positions the study within smart-city and urban freight research. Section 3 describes the case setting, data, and forecasting workflow. Section 4 presents the empirical results. Section 5 discusses implications for urban development and smart-city operations. Section 6 concludes with limitations and future research directions.

SMART-CITY LOGISTICS AND THE STRATEGIC ROLE OF 3PL

The smart-city concept emphasizes the use of data, digital systems, and inter-organizational coordination to improve urban efficiency, sustainability, and quality of life. Within this agenda, mobility is typically treated as a core domain of intervention. Yet the practical functioning of cities depends not only on passenger movement but also on the steady circulation of goods. Retail replenishment, parcel distribution, and service deliveries shape congestion patterns throughout the day, especially in dense commercial zones.

Last-mile logistics is particularly difficult because it is costly, time-sensitive, spatially fragmented, and exposed to rapidly changing urban traffic conditions. Traditional operational responses include consolidation centers, route optimization, delivery window management, and freight-supportive intelligent transport systems. However, a persistent governance gap remains: city authorities often manage traffic reactively, while logistics operators manage freight flows internally. The absence of predictive coordination between these domains limits the effectiveness of smart-city transport strategies.

3PL providers are well positioned to narrow this gap. Because they control large volumes of operational data and actively schedule warehouse and transport processes, they can forecast delivery intensity and potentially moderate the temporal distribution of freight entering the city. This shifts the discussion from logistics execution alone toward predictive urban freight governance, where operational planning by private logistics actors becomes relevant to public transport management.

MATERIALS AND METHODS

Case Setting and Data Source

The empirical setting consists of the distribution operations of an international 3PL operator serving two Polish cities: Warsaw and Wroclaw. Data were obtained from the operator's WMS and TMS environments and relate to daily distribution activity over a four-month period. The exported dataset contains approximately 200,000 records.

Each record includes the following fields:

- shipping date,
- pallet quantity,
- parcel quantity,
- delivery postcode,
- delivery city,
- country code.

The source data structure allows the analysis of delivery intensity at both aggregate city level and disaggregated postcode level. A sample observation consists of a shipment date paired with pallet and parcel quantities and linked to a specific destination postcode in either Warsaw or Wroclaw.

Table 1: Summary of the empirical dataset and analytical scope.

Element	**Specification**
Study setting	International 3PL operator
Cities analyzed	Warsaw; Wroclaw
Observation period	4 months
Temporal granularity	Daily
Approximate raw records	200,000
Data systems	WMS and TMS
Core variables	Shipping date, pallet quantity, parcel quantity, postcode, city, country code
Analytical levels	City-level forecasts; postcode-level forecasts
Forecast horizon	2 weeks per update
Evaluation window	24 days (two forecast updates)

Delivery Network Structure

A key feature of the distribution network is the large number of destination points and the irregularity of service frequency across postcodes. In the four-month period, the operator delivered to 2,611 distinct postcodes in Warsaw and 862 in Wroclaw. Most of these locations were supplied infrequently, indicating a sparse and highly dispersed last-mile structure.

The volume moved during the study period was substantial:

Table 2: Number of destination postcodes by delivery frequency class.

Percentage of delivery days in total work days	**Warsaw**	**Wroclaw**
0.00–25.00%	2,513	771
25.00–50.00%	69	69
50.00–75.00%	21	21
75.00–100.00%	8	1
Total	**2,611**	**862**

- **Warsaw:** 27,691 pallets and 174,600 parcels;
- **Wroclaw:** 11,328 pallets and 84,898 parcels.

Given a five-day operating week, this corresponds to an average daily requirement of approximately 346 pallet spaces for Warsaw and 141 pallet spaces for Wroclaw. Using a standard semi-trailer capacity of 33 EUR pallets, this implies roughly 10 outbound shipments per day to Warsaw and 4 to Wroclaw, before accounting for smaller vehicle types and excluding e-commerce-specific flows.

Forecasting Workflow

The forecasting tool uses three functions from the `forecast` package in R:

- `auto.arima()` for automated ARIMA selection,
- `nnetar()` for neural network autoregression,
- `ets()` for exponential smoothing state-space models.

The workflow follows four principal stages:

1. Data extraction from WMS and TMS systems;
2. Automatic split into training and testing subsets;
3. Model estimation using all three candidate forecasting engines;
4. Model selection based on weighted forecast accuracy.

The training set comprises 95% of each time series and the test set the remaining 5%. Forecast performance is evaluated using mean absolute error (MAE), root mean square error (RMSE), and mean absolute percentage error (MAPE). Each metric receives equal weight (0.33), and the model with the strongest combined test performance is selected for operational forecasting.

Forecasts are produced with a two-week horizon and then refreshed after two weeks. The evaluation period for inferring predictive performance spans 24 days, corresponding to two forecast updates.

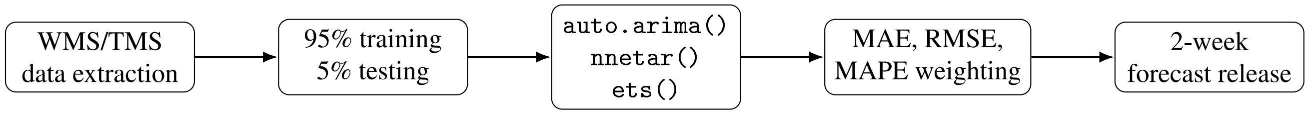

Figure 1: Operational forecasting workflow used for delivery-intensity prediction.

Smart-City Delivery Prioritization Logic

Beyond forecasting, the study advances a practical coordination concept for smart-city application. In this concept, 3PL forecasts from one or more logistics providers are integrated with traffic information from ITS environments and used to prioritize deliveries across destination postcodes. The goal is not to eliminate freight flows, but to sequence them more intelligently.

The proposed prioritization tool is built around four decision inputs:

1. an objective of minimizing congestion in the city,
2. current traffic-volume data obtained from ITS systems,
3. forecasted delivery volumes generated by 3PL operators,
4. postcode-level weights reflecting delivery priority and route structure.

Algorithm 1. Conceptual delivery-prioritization routine

1. Collect forecasted delivery volumes by postcode from participating 3PL operators.
2. Import current or near-real-time traffic conditions from city ITS systems.
3. Assign priority weights to destination postcodes based on service requirements and route structure.
4. Rank delivery tasks by predicted load, urgency, and expected traffic exposure.
5. Allocate dispatch windows to reduce congestion pressure while preserving service continuity.
6. Update priorities as new forecast or traffic data become available.

This design is intentionally operational: it translates logistics forecasting into a coordination mechanism that can interface with urban traffic governance without requiring cities to manage freight flows blindly or in purely reactive fashion.

RESULTS

City-Level Forecast Accuracy

The forecasting system achieved strong performance for palletized flows and lower accuracy for parcel flows, especially in Warsaw. The dynamically selected model varied by city, shipment type, and update cycle, demonstrating the value of adaptive model choice rather than relying on a single forecasting method.

Three findings are especially important. First, pallet forecasting is highly accurate in both cities, and especially in Warsaw, where error is below 1%. Second, parcel forecasting is less stable, with Warsaw parcels producing

Table 3: City-level forecast performance and selected algorithms.

City	Prediction type	MAPE	First update	Second update
Warsaw	Pallets	0.36%	`nnetar()`	`nnetar()`
Warsaw	Parcels	17.47%	`nnetar()`	`nnetar()`
Wroclaw	Pallets	3.78%	`auto.arima()`	`nnetar()`
Wroclaw	Parcels	4.03%	`nnetar()`	`auto.arima()`

the highest observed aggregate error. Third, `nnetar()` is the most frequently selected model, although dynamic switching to `auto.arima()` occurs in Wroclaw, confirming that forecast performance depends on local series behavior.

Postcode-Level Error Profile

Because urban freight operations are ultimately executed at destination level, postcode-level performance is operationally more informative than city aggregates alone. The study therefore compares real delivered volumes with forecast volumes across individual postcodes using average difference and the spread around that average.

Table 4: Differences between real and forecast values at postcode level.

City	Prediction type	Average difference	Av + SD	Av - SD
Warsaw	Pallets	−0.09	2.52	−2.69
Warsaw	Parcels	−0.30	16.25	−16.86
Wroclaw	Pallets	0.15	1.85	−1.56
Wroclaw	Parcels	0.02	14.80	−14.77

The postcode-level results reinforce the city-level pattern. Pallet forecasts remain comparatively stable in both cities, with narrow dispersion around the average error. Parcel forecasts, by contrast, show much wider variation. In Warsaw, the parcel standard deviation is particularly large, indicating sharp local swings that are difficult to capture with a purely historical forecasting workflow. Wroclaw parcel forecasts are slightly more balanced on average, but they remain substantially more volatile than pallet predictions.

These differences matter for operational control. In palletized retail replenishment, predictable flows make it easier to plan loading and dispatch. In parcel distribution, the greater variability introduces higher uncertainty into route design, resource assignment, and time-window management.

Daily Forecast Variation

The study also reports daily MAPE patterns across the 24-day evaluation window. Average daily MAPE values are approximately 6.09% for Warsaw pallets, 10.20% for Warsaw parcels, 7.54% for Wroclaw pallets, and 10.69% for Wroclaw parcels. Error spikes occur on specific days:

- Warsaw pallets: maximum error on day 4 (16.06%); low error on day 8 (0.30%);
- Warsaw parcels: higher error on days 1 (16.75%) and 3 (15.66%); very low error on day 15 (0.04%);
- Wroclaw pallets: maximum error on day 22 (33.33%); low error on day 20 (0.96%);

- Wroclaw parcels: maximum error on day 13 (22.98%); zero error on day 16.

This pattern indicates that forecasting performance is not uniformly distributed across time. The existence of occasional high-error days suggests that extraordinary shifts in order behavior or demand timing can materially reduce predictive reliability, particularly in parcel flows.

DISCUSSION

Implications for Urban Development and Smart-City Operations

The empirical evidence supports a clear conclusion: 3PL operators can contribute to smarter urban freight governance through predictive coordination. The strongest evidence lies in palletized flows, where forecasts are sufficiently accurate to support practical scheduling decisions. Even in the parcel segment, where volatility is higher, the forecasts remain informative enough to guide operational attention and identify riskier delivery periods.

From an urban-development perspective, the significance of this result lies in the connection between private logistics data and public transport objectives. If 3PL providers can forecast delivery intensity before dispatch, they can help smooth the temporal concentration of freight entering the city. This creates a basis for more coordinated use of delivery windows, curb access, loading infrastructure, and congestion-management measures.

The postcode-frequency profile is particularly revealing. Because the majority of destination points are served on no more than 25% of working days, the studied network is highly irregular. That means city logistics problems cannot be understood solely through aggregate daily totals; spatial granularity matters. Sparse destination patterns amplify the planning burden on operators and strengthen the case for data-driven prioritization in smart-city logistics policy.

Managerial Relevance

For 3PL managers, the results demonstrate that predictive tools based on existing WMS and TMS data can already support operational decision making without requiring a wholesale change in digital infrastructure. High-accuracy pallet forecasts can improve dock planning, shipment consolidation, and fleet utilization. More volatile parcel forecasts signal where additional data sources or faster forecast updates may be necessary.

For city authorities, the findings suggest that freight should be treated as a governable urban flow rather than an uncontrollable by-product of commerce. A coordination model in which 3PL forecasts are exchanged with city traffic systems would allow municipalities to move from reactive congestion monitoring toward anticipatory freight management. Such an approach is directly relevant to smart mobility strategies, freight-window regulation, and data-sharing frameworks between public and private actors.

LIMITATIONS AND FUTURE RESEARCH

This study is subject to three principal limitations. First, the empirical analysis covers only two cities and one 3PL operator. The results therefore demonstrate feasibility, but they do not establish universal generalizability across all urban freight systems. Second, the evaluation period reflects normal operating conditions and does not explicitly incorporate extraordinary demand peaks associated with holidays, promotions, or abnormal disruptions. Third, the forecasting framework relies primarily on internal operational data; exogenous inputs such as weather, promotional campaigns, and event calendars are not yet included.

These limitations point directly to future research opportunities. A broader multi-city and multi-operator design would strengthen external validity. Additional data layers, including meteorological and promotional signals, could improve parcel forecasting, where variability remains highest. The next practical step is the formal testing of a delivery-prioritization algorithm that combines 3PL forecasts with ITS traffic states to determine the most advantageous delivery times in the city. Further work could also examine how predictive freight coordination interacts with omnichannel retail systems, urban consolidation centers, and digital freight platforms.

CONCLUSION

Efficient and sustainable urban development requires smarter management of freight as well as passenger mobility. This study shows that 3PL providers can play a meaningful role in that process by forecasting delivery intensity and using those forecasts to support better-timed urban distribution. Based on four months of daily WMS and TMS data from Warsaw and Wroclaw, the evidence indicates strong predictive performance for palletized deliveries and lower but still practically relevant performance for parcel flows. The results also show that urban delivery networks are highly irregular at postcode level, reinforcing the need for granular and adaptive planning.

The study's core contribution is to reposition 3PL forecasting as a smart-city coordination tool. When combined with postcode-level prioritization and ITS traffic information, predictive logistics can help cities and operators align freight movement more effectively with urban mobility objectives. In that sense, the operational intelligence of logistics providers is not peripheral to smart-city governance; it is an actionable component of it.

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