

Article

A Pigouvian Policy Framework for Urban Logistics: Decision-Maker Alignment and Integrated Pricing-Incentive Design

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Abstract

Urban logistics supports retail, public services, healthcare, construction, and household consumption, but delivery decisions often fail to account for the social costs imposed on congested roads, curbside space, air quality, noise exposure, safety, and public-space use. This study addresses the decision-maker mismatch that arises when the vehicle operator physically generates an externality while receivers, shippers, platforms, building managers, or consumers control delivery timing, shipment fragmentation, service level, fleet choice, and receiving conditions. It develops a Pigouvian policy framework that integrates dynamic road-user charging, curbside pricing, emission-based instruments, off-hour delivery incentives, clean-vehicle support, consolidation incentives, and revenue recycling. The study combines a structured narrative synthesis, decision-maker mapping, an illustrative Korean urban logistics scenario, cost–benefit comparison, and deterministic sensitivity screening. Under the stated scenario assumptions, a carrier-only peak charge reduces monetized daily external costs by only 1.3%, whereas a combined road-and-curbside package reduces them by 12.5%, and an integrated Pigouvian package reduces them by 23.6%. Sensitivity results preserve this ranking. The paper contributes a transferable policy design architecture for internalizing urban logistics externalities while maintaining freight functionality and stakeholder acceptability.

Keywords: urban logistics; Pigouvian tax; external costs; road pricing; curbside management; off-hour delivery; sustainable freight

1. Introduction

1.1. Research Background and Existing Problems

Urban logistics is an essential infrastructure of contemporary urban life. Retail stores, restaurants, hospitals, schools, construction sites, public agencies, and households depend on continuous goods movements into, within, and out of cities. The expansion of e-commerce, quick commerce, and on-demand distribution has increased the spatial and temporal intensity of last-mile delivery systems [1]. Urban freight activities are indispensable for the urban economy, but they also generate negative impacts that require public policy attention [2]. City logistics therefore cannot be treated only as a private operational problem; it is also a sustainability issue involving scarce road space, air quality, climate policy, neighborhood livability, and equitable access to public space.

The policy challenge arises because the private cost of a delivery does not normally include the full social cost of the activity. A carrier may pay for labor, fuel, vehicles, insurance, and warehousing, but delivery-related congestion delays, local air pollution,



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greenhouse gas emissions, noise, crash risk, and curbside occupation are often borne by society. When these costs remain external to market prices, delivery demand, timing, vehicle choice, and curbside use may deviate from socially desirable levels. This gap is especially acute in dense urban areas, where road capacity and loading space are limited and where emissions and noise are concentrated among residents, workers, pedestrians, and vulnerable road users.

The Korean context illustrates why this problem has become urgent. Korea combines very high platform and mobile commerce penetration with dense residential morphology. Official statistics reported KRW 24.2904 trillion in online shopping transactions in December 2025, of which mobile shopping accounted for 77.4% [3]. The National Logistics Information Center reported that annual parcel volume reached 6.41 billion items in 2025, up 7.75% from 2024 [4]. At the same time, the 2024 register-based census reported that 53.9% of general households resided in apartments and that one-person households accounted for 36.1% of all households [5]. These conditions intensify apartment-complex deliveries, parcel-room congestion, elevator and access conflicts, repeated small-batch deliveries, and curbside friction in mixed-use districts.

Korean cities also show why urban logistics externalities cannot be addressed only through conventional vehicle regulation. Seoul has implemented low-emission traffic restrictions and continues to expand clean-vehicle measures, including support for electric freight vehicles and electric motorcycles [6]. The national Grade-5 vehicle restriction system is also applied during fine-dust management periods in the capital region and major metropolitan cities [7], while Seoul's Green Transport Zone provides a local implementation example of Grade-5 vehicle restrictions [8]. These policies are relevant to air-quality externalities, but they do not automatically solve peak-hour delivery concentration, curbside dwell time, double parking, apartment receiving constraints, or platform-driven delivery frequency. A policy framework is therefore needed to connect environmental regulation with logistics pricing, receiving-site incentives, and freight-space management.

1.2. Mainstream Policy Solutions and Remaining Gaps

Urban freight research has long recognized this tension. City logistics aims to coordinate freight flows while considering congestion, safety, service quality, and environmental performance [9]. Dablanc argued that urban goods movements are difficult to organize through conventional public policy because freight is embedded in dispersed private supply chains and because city authorities often lack detailed knowledge of freight operations [10]. Comparative studies of urban freight policies also show that freight measures must balance economic efficiency, environmental improvement, and stakeholder acceptability [11]. Quak similarly framed urban freight as both necessary and unsustainable when local regulations do not address the operational incentives faced by private actors [12].

Pigouvian taxation offers a clear economic starting point for this problem. If a delivery activity generates marginal external cost, then a charge equal to that external cost can, in theory, induce the decision-maker to internalize the social cost of the activity [13,14]. Applied to urban logistics, this logic supports freight road pricing, freight parking pricing, emission-based charges, and other differentiated user charges. However, urban logistics differs from passenger travel in a crucial respect: the actor operating the vehicle is not always the actor controlling the delivery decision. The carrier may drive the truck or van, but the receiver, shipper, retailer, platform, or consumer may determine the delivery time, service level, shipment fragmentation, and receiving conditions. If the price signal reaches only the carrier, the behavioral effect may be weak.

1.3. Advantages and Innovations of the Proposed Framework

Prior urban freight pricing research emphasizes that pricing instruments and incentives are effective only when they are aligned with the actors who can modify delivery timing, routing, vehicle choice, receiving conditions, or ordering patterns [2,15,16]. This insight motivates the present framework, which extends Pigouvian cost internalization from a vehicle-based charging logic to a supply chain-based governance logic. A Pigouvian policy for urban logistics must not merely impose a fee on a vehicle; it must identify the supply chain decision that produces the external cost and design a price or incentive that can influence that decision.

The proposed framework is innovative because it treats Pigouvian internalization as a supply chain governance problem rather than as a stand-alone vehicle fee. It first decomposes external costs by mechanism, time, space, vehicle type, and stopping behavior; it then maps each cost mechanism to the actor that can realistically alter the underlying decision. This enables charges and incentives to be designed as a coordinated package rather than as isolated congestion, emission, or parking measures.

1.4. Research Objectives, Contributions, and Article Structure

This article develops a Pigouvian policy framework for urban logistics externalities. The framework integrates four ideas: external costs should be identified by mechanism, location, time, and vehicle type; policy instruments should be mapped to the decision-maker who controls the relevant behavior; pricing should be combined with incentives and revenue recycling to improve acceptability and operational feasibility; and conceptual policy design should be complemented by transparent scenario analysis before city-specific empirical calibration is attempted. The study addresses four research questions: (1) What external costs are generated by urban logistics, and how can they be expressed through a Pigouvian logic? (2) Why do carrier-only road-pricing measures have limited effectiveness in some freight markets? (3) How can road pricing, curbside pricing, vehicle taxation, and incentive mechanisms be combined? (4) What design principles can guide cities seeking to internalize urban logistics externalities while maintaining freight functionality?

The contribution of the study is conceptual, policy-oriented, and partially simulation-based. It does not estimate a definitive Pigouvian tax for a specific Korean city. Instead, it offers a transferable policy design architecture and uses an illustrative Korean district simulation to compare alternative policy packages. This approach is appropriate because cities face similar externality categories but differ in logistics structure, regulatory capacity, technology infrastructure, and political acceptability. Section 3 explains the research design, analytical framework, and simulation assumptions. Section 4 presents the framework components, the Korean scenario application, and stakeholder analysis. Section 5 discusses implementation issues, limitations, and implications for dense urban and port–airport hinterland regions. Section 6 concludes.

2. Related Works and Literature Synthesis

Urban logistics research has developed along several partially connected streams. City logistics studies emphasize freight coordination, sustainability, and stakeholder complexity; transport economics studies provide the Pigouvian logic of marginal-cost pricing; freight demand management research explains carrier–receiver interactions; curbside and last-meter research highlights stopping-space scarcity; and low-emission-zone and consolidation studies address specific environmental or operational instruments. The gap is that these streams are rarely integrated into a single design architecture that links each externality mechanism to the actor who can change the relevant behavior.

Table 1 positions the proposed framework against these streams. The comparison shows that the contribution of this paper is not the invention of a new isolated instrument, but the integration of pricing, incentives, operational alternatives, and revenue recycling through decision-maker alignment.

Table 1. Comparative positioning of the proposed framework in relation to prior urban freight policy approaches.

Prior Approach	Representative Contribution	Remaining Limitation for Pigouvian Urban Logistics	Added Value of This Study
City logistics and urban freight sustainability [9–12]	Frames freight as essential but environmentally and socially costly.	Often emphasizes coordination or regulation without a full marginal–external-cost design.	Links sustainability problems to specific Pigouvian cost mechanisms.
Road pricing and transport economics [13,14,17–19]	Establishes marginal social cost and congestion-pricing logic.	Primarily developed for road use and passenger-like decision structures.	Extends pricing logic to freight-specific supply chain decision control.
Freight pricing, OHD, and demand management [15,16,20–23]	Shows that receiver and carrier interactions shape delivery timing response.	Often evaluates individual instruments or pilot programs.	Combines charges, receiver incentives, and revenue recycling in one architecture.
Low-emission and clean-vehicle policy [6–8,24]	Targets tailpipe emissions and fleet composition.	Does not solve congestion, curb dwell time, or public-space conflict.	Treats emissions as one component of the total external-cost bundle.
Curbside and last-meters management [25,26]	Highlights loading-space scarcity and dwell-time externalities.	Often separated from road pricing and broader supply chain incentives.	Internalizes stopping-related costs alongside movement-related costs.
Acceptability and stakeholder governance [27,28]	Explains why pricing succeeds only when users see legitimacy and benefits.	Less frequently tied to instrument calibration and pass-through logic.	Embeds equity safeguards, stakeholder roles, and reinvestment into the framework.

3. Materials and Methods

3.1. Research Design

This study uses a conceptual policy design method combined with an illustrative scenario simulation. Rather than testing a single empirical intervention, it synthesizes established theory and urban freight policy evidence to construct a design framework for future empirical application. The method is organized around four steps: literature-based problem definition, Pigouvian cost internalization modeling, decision-maker-based policy mapping, and Korean urban logistics scenario analysis. The study applies a structured narrative synthesis rather than a systematic review. The purpose is not to exhaustively enumerate all urban freight studies, but to integrate theoretical and policy evidence relevant to the design of pricing and incentive instruments. Figure 1 presents the overall research process and methodological framework used in this study.

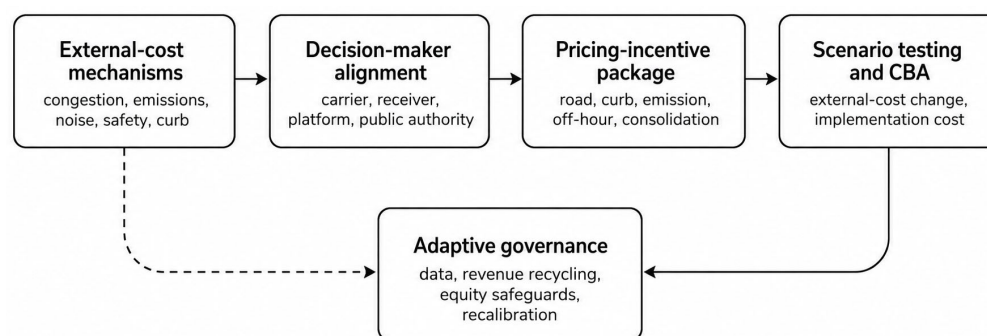


Figure 1. Conceptual framework for Pigouvian urban logistics policy design. CBA denotes cost–benefit analysis. Solid arrows indicate the main analytical sequence, whereas the dashed arrow indicates feedback and recalibration loops.

The literature synthesis focused on five streams. The first stream concerns the role of urban logistics in urban economies and sustainability challenges [1,2,9–12]. The second stream concerns the economic theory of road pricing and the Pigouvian internalization of external costs [13,14,17–19]. The third stream concerns freight road pricing, off-hour delivery, and carrier–receiver interactions in competitive markets [15,16,20–23]. The fourth stream concerns policy acceptability and stakeholder reactions to urban freight and congestion-pricing measures [27,28]. The fifth stream concerns curbside management, freight parking, low-emission zones, consolidation centers, and complementary urban freight interventions [24–26,29,30].

The literature was identified through targeted searches in Scopus, Web of Science, Google Scholar, and major transport-policy repositories using combinations of the terms “urban freight”, “city logistics”, “road pricing”, “Pigouvian tax”, “curbside management”, “off-hour delivery”, and “freight externalities”. Priority was given to peer-reviewed articles, seminal theoretical works, and policy reports directly relevant to pricing, incentives, and urban freight governance. Sources were included when they contributed to at least one of the three analytical dimensions of the framework: external-cost mechanisms, decision-maker control, or policy–instrument alignment. Sources that addressed only general logistics efficiency without an explicit externality, pricing, curbside, or governance were excluded from the core synthesis.

The conceptual model is constructed as a design framework rather than as a statistical model. The synthesis was used to derive three analytical dimensions: external-cost mechanisms, decision-maker control, and policy–instrument alignment. These dimensions were combined into a framework that identifies variables required for empirical calibration. The scenario simulation then demonstrates how the framework can be translated into a transparent ex ante comparison of alternative policy packages. This structure addresses a common limitation of purely conceptual urban freight policy studies: the absence of quantified implications for policy alternatives.

For transparency, the synthesis was conducted as a four-step screening process: (i) identification of candidate sources from Scopus, Web of Science, Google Scholar, OECD/ITF, European Commission, and municipal policy repositories; (ii) screening for explicit relevance to urban freight externalities, pricing, curbside management, off-hour delivery, low-emission logistics, or stakeholder acceptability; (iii) exclusion of sources concerned only with general logistics efficiency or unrelated intercity freight operations; and (iv) synthesis of the retained evidence into three analytical dimensions: external-cost mechanism, decision-maker control, and policy–instrument alignment. The targeted search primarily covered studies published between 2010 and 2026. Earlier seminal theoretical works on Pigouvian taxation and marginal-cost road pricing were additionally retained,

where they provided foundational concepts for the framework. The retained core corpus consists of the 30 cited sources, including peer-reviewed articles, major policy reports, and official statistical sources, and was used for framework construction rather than for a PRISMA-style meta-analysis.

3.2. Analytical Boundary

The analytical boundary of the study is urban road-based freight and last-mile delivery. The framework covers vans, light goods vehicles, heavy goods vehicles, parcel delivery vehicles, service vehicles, and other freight vehicles using urban roads and curbside space. It also addresses stopping-related impacts associated with loading, unloading, dwell time, and the final meters of delivery [26]. The framework does not directly model maritime, rail, or air freight operations, although the policy logic can be relevant to port and airport hinterland cities where drayage, consolidation, and urban distribution overlap.

The boundary can be interpreted as a corridor–district and last-mile policy scope. Included elements are urban road movement, loading and unloading, curbside dwell time, apartment and building receiving interfaces, and policy instruments controlled by local or metropolitan authorities. Excluded elements are maritime, rail, and air operations as transport modes, long-haul intercity logistics, and firm-level inventory optimization, except where these systems directly create urban road or curbside externalities. This distinction prevents the scenario from being misread as a full metropolitan freight model.

The study distinguishes three types of actors. The first is the physical operator, usually the carrier or logistics service provider. The second is the controlling decision-maker, such as the receiver, shipper, retailer, platform, or consumer, who determines ordering patterns, delivery windows, service speed, shipment fragmentation, and receiving conditions. The third is the public authority, which sets rules, prices, incentives, data requirements, and enforcement mechanisms. This distinction is necessary because Pigouvian charges influence behavior only when the price signal reaches the actor capable of changing the relevant decision.

3.3. Pigouvian Cost Framework

The basic Pigouvian formulation begins with the difference between marginal private cost and marginal social cost. In road transport, Walters showed that a congestion charge equal to the difference between private and social cost can reduce traffic toward an efficient level [14]. The same logic applies to freight movements, but the social cost must be decomposed into multiple urban externalities and linked to spatial, temporal, vehicle-specific, and stopping-related conditions. Existing external-cost methods provide a basis for monetizing several of these components, although local calibration remains necessary [19].

$$MSC_{i,t,z,v} = MPC_{i,t,z,v} + MEC_{i,t,z,v} \quad (1)$$

where MSC is marginal social cost, MPC is marginal private cost, MEC is marginal external cost, i denotes a delivery or vehicle movement, t denotes time period, z denotes spatial zone, and v denotes vehicle type.

$$MEC_{i,t,z,v} = EC_{cong} + EC_{emis} + EC_{noise} + EC_{safety} + EC_{curb} + EC_{space} \quad (2)$$

Equation (2) expresses the external cost of an urban freight activity as the sum of congestion, emissions, noise, safety, curbside occupancy, and broader public-space costs. The components can be monetized through existing external-cost methods or approximated through relative policy weights when direct monetization is not feasible. In either case, the

purpose of the equation is to clarify the cost mechanisms that should inform instrument design rather than to prescribe a universal tax rate.

$$\text{Net Charge}_{i,t,z,v} = \alpha \text{MEC}_{i,t,z,v} - \text{Incentive}_{i,t,z,v} \quad (3)$$

Equation (3) represents the policy package proposed in this study. The net charge is not necessarily a pure tax. It combines a Pigouvian charge, represented by the calibration parameter alpha, with incentives for behaviors that reduce external costs. In practical terms, a city may impose a higher charge for peak-hour diesel deliveries in congested zones while providing incentives for off-hour, consolidated, low-noise, or zero-emission deliveries. When the incentive exceeds the calibrated charge, the instrument becomes a net subsidy. Cities should therefore specify whether the net charge is bounded below by zero or whether negative values are intentionally used as targeted support for low-externality logistics behavior.

3.4. Evaluation Criteria

Five criteria are used to assess policy instruments. Efficiency refers to whether the instrument can reduce external costs relative to administrative and compliance costs. Behavioral reach refers to whether the instrument reaches the decision-maker who can change delivery behavior. Acceptability refers to stakeholder and political feasibility. Equity refers to distributional impacts among carriers, small retailers, consumers, and residents. Enforceability refers to whether the city can monitor and administer the instrument with available technology and governance capacity. Table 2 summarizes the main externality categories and their corresponding Pigouvian internalization logic.

Table 2. Urban logistics externalities and Pigouvian internalization logic.

Externality	Mechanism	Potential Metric	Policy Internalization Logic
Congestion	Freight vehicles add delay to other vehicles, buses, cyclists, and pedestrians, particularly during peak periods.	Vehicle kilometers by time and zone; delay minutes; speed loss.	Dynamic road-user charge or time-distance fee calibrated by congestion level.
Emissions	Combustion vehicles produce CO ₂ , NOx, PM, and other pollutants in dense population areas.	Vehicle type; fuel; emission factor; distance; idling time.	Emission-based access fee, low-emission-zone surcharge, or differentiated vehicle tax.
Noise	Engine, braking, reversing alarms, loading, and unloading create nuisance, especially in residential areas.	Delivery time; noise level; exposed population; receiving-site characteristics.	Noise-sensitive delivery windows, low-noise equipment standards, and off-hour incentives conditioned on quiet delivery.
Safety risk	Large and frequent freight movements increase conflict with pedestrians, cyclists, and passenger vehicles.	Crash risk by road type; vehicle size; vulnerable road-user exposure.	Safety surcharge in high-risk zones; vehicle-safety requirements; preferential access for safer vehicles.
Curbside occupancy	Loading, unloading, double parking, cruising for loading space, and illegal stops reduce road and sidewalk capacity.	Dwell time; loading-zone occupancy; violations; cruising time.	Freight parking pricing, loading-zone reservation, enforcement, and priority rules.
Public-space conflict	Freight activity competes with transit, active mobility, public realm, and local economic functions.	Street-space allocation; land-use intensity; local exposure.	Spatial zoning, logistics microhubs, consolidation incentives, and revenue recycling.

Table 2 shows that the relevant tax base for urban logistics is not limited to vehicle entry. Road movement, emissions, dwell time, and public-space conflicts generate different external-cost mechanisms and therefore require differentiated instruments.

3.5. Illustrative Korean Scenario and Cost–Benefit Method

To strengthen the empirical relevance of the conceptual framework, this study adds an illustrative scenario analysis for a dense Korean urban delivery district. The simulation is not intended to estimate the actual external costs of Seoul, Busan, or any other specific city. Instead, it provides an ex ante policy laboratory that translates the framework into comparable numerical outcomes. This approach is appropriate for early-stage policy design where a city lacks full freight trajectory data, delivery-contract data, curbside sensor data, and receiver response data.

The illustrative district is defined as a high-density mixed residential-commercial area with apartment complexes, retail streets, parcel delivery concentration, and constrained curbside space. The baseline is set at 10,000 freight delivery tours per weekday, an average within-district distance of 8 km per tour, a peak-period delivery share of 42%, an internal combustion freight-vehicle share of 80%, an average loading dwell time of 10 min, and a flat residual noise/safety/public-space cost of KRW 800 per tour. These parameters are not city estimates; rather, they are representative hypothetical values selected for a policy design demonstration showing how a local government could structure a preliminary cost–benefit comparison before collecting detailed city data.

The scenario model decomposes daily external cost into four components: congestion, emissions, curbside dwell time, and residual noise-safety-public-space impacts. Congestion costs are differentiated between peak-period and off-peak freight kilometers. Emission costs are differentiated between internal combustion and zero-emission vehicles. Curbside costs are based on dwell minutes. Residual costs are assigned per tour to reflect externalities that are harder to monetize at the pilot stage. The total daily external cost is expressed as follows:

$$TEC_s = N_s \left[D \left(P_s c_{peak} + (1 - P_s) c_{offpeak} \right) + D (ICE_s e_{ice} + ZEV_s e_{zev}) + W_s c_{curb} + r_s \right] \quad (4)$$

where TEC_s is total external cost under scenario s , N_s is daily freight tours, D is average within-district distance, P_s is peak-period share, ICE_s and ZEV_s are vehicle shares, W_s is average curbside dwell time, and r_s is residual noise–safety–public-space cost per tour.

The net social benefit of each scenario is calculated as the reduction in external costs relative to the baseline minus additional administrative, compliance, and incentive costs. Pricing revenue is treated primarily as a transfer if it is recycled into the freight system; therefore, the comparison focuses on external-cost reductions and real implementation costs rather than gross fee revenue.

$$NSB_s = (TEC_0 - TEC_s) - AC_s \quad (5)$$

where NSB_s is net social benefit, TEC_0 is baseline total external cost, TEC_s is scenario external cost, and AC_s is additional administrative, technology, enforcement, and incentive cost. The model also reports the charge-incentive logic for each scenario to show whether the policy reaches only carriers or also reaches receivers, platforms, building managers, and fleet owners.

To address the robustness of the illustrative scenario without claiming city-specific calibration, the model also includes a deterministic sensitivity test. The peak congestion-cost coefficient is varied by $\pm 20\%$, and the peak-period delivery share is varied by $\pm 15\%$. These two variables were selected because they strongly influence the monetized congestion

component and are likely to differ across Korean metropolitan cores, apartment districts, traditional markets, port corridors, and logistics–industrial interfaces. The sensitivity test preserves the behavioral assumptions of each policy scenario and recalculates external costs and net social benefits relative to the baseline under the same sensitivity condition. It is therefore a robustness screen for policy ranking, not a substitute for empirical calibration using observed traffic speeds, vehicle trajectories, curbside occupancy, or delivery contract data.

The behavioral parameters used in Table 3 are scenario assumptions informed by the directional evidence reported in prior urban freight pricing, carrier–receiver interaction, off-hour delivery, and consolidation studies [15,16,20–22,29]. They should not be interpreted as direct econometric estimates transferred from those studies. For S1, the conservative 5% reduction in peak-period share reflects evidence that cordon-only or carrier-only tolls have limited behavioral reach when receivers control delivery timing [15,16]. For S2 and S3, larger reductions in tours, peak shares, and dwell time reflect the combined logic of dynamic pricing, curbside management, off-hour delivery incentives, consolidation, and self-supported freight demand management [20–22,29].

Table 3. Scenario assumptions and illustrative cost–benefit comparison.

Scenario	Policy Package	Behavioral Assumptions	External Cost and Net Benefit
S0 Baseline	No additional freight-specific pricing, curbside pricing, or receiver incentive.	10,000 tours/day; 42.0% peak share; 80% ICE share; 10.0 min dwell time.	External cost: KRW 101.84 million/day. Net benefit: reference case.
S1 Carrier-only peak charge	Peak-period cordon or area charge imposed mainly on vehicle operator.	Peak share falls by 5% relative to baseline, from 42.0% to 39.9%; no change in tours, dwell time, or fleet composition. Conservative response informed by limited behavioral reach of carrier-only pricing [15,16].	External cost: KRW 100.50 million/day, a 1.3% reduction from baseline. With KRW 2.0 million/day implementation cost, net benefit is about KRW 0.66 million/day.
S2 Dynamic road + curbside pricing	Time-zone differentiated freight charge plus loading-zone price, enforcement, and reservation.	Tours fall by 5%, from 10,000 to 9500 tours/day; peak share falls by 15% relative to baseline, from 42.0% to 35.7%; dwell time falls by 20%, from 10.0 to 8.0 min; ICE share falls slightly.	External cost: KRW 89.15 million/day, a 12.5% reduction from baseline. With KRW 7.0 million/day implementation cost, net benefit is about KRW 5.69 million/day.
S3 Integrated Pigouvian package	Dynamic road pricing, curbside pricing, receiver off-hour incentives, clean-vehicle support, consolidation incentives, and revenue recycling.	Tours fall by 10%, from 10,000 to 9000 tours/day; peak share falls by 25% relative to baseline, from 42.0% to 31.5%; dwell time falls by 30%, from 10.0 to 7.0 min; ZEV share rises to 35%; residual noise/safety cost falls.	External cost: KRW 77.80 million/day, a 23.6% reduction from baseline. With KRW 12.0 million/day implementation and incentive cost, net benefit is about KRW 12.04 million/day.

Table 4 clarifies why a Korean application should include both vehicle-side and receiver-side instruments. The same delivery vehicle can be affected by emissions regulation, apartment receiving constraints, platform promises, and curbside scarcity at the same time.

Table 4. Korean context variables motivating the scenario application.

Context Variable	Observed Korean Condition	Policy Relevance
Mobile commerce intensity	Online shopping transactions reached KRW 24.2904 trillion in December 2025; mobile shopping accounted for 77.4% [3].	High mobile ordering and quick-service expectations increase delivery frequency and time-window pressure.
Parcel volume growth	Annual parcel volume reached 6.41 billion items in 2025, up 7.75% from 2024 [4].	Rising parcel traffic intensifies last-mile vehicle movements, sorting pressure, and curbside demand.
Apartment-based receiving	Apartments housed 53.9% of general households in 2024 [5].	Apartment parcel rooms, elevators, access rules, and concentrated delivery stops make receiver-side policy important.
One-person households	One-person households accounted for 36.1% of all households in 2024 [5].	Unattended receiving, parcel lockers, and flexible delivery windows become important for reducing repeated delivery attempts.
Existing air-quality regulation	Seoul and national policies restrict high-emission vehicles and support clean vehicles [6,7].	Emission-based rules can be integrated with road pricing, curbside management, and receiver incentives.

Table 5 is deliberately transparent: each assumption can be replaced by locally observed data when traffic speeds, vehicle trajectories, emission factors, loading-zone occupancy, and receiver response data become available.

Table 5. Baseline parameters for the illustrative Korean urban logistics scenario.

Parameter	Baseline Value	Interpretation
Daily freight delivery tours	10,000 tours/day	Illustrative size of a dense residential-commercial delivery district.
Average within-district distance	8 km/tour	Distance exposed to the urban external-cost zone.
Peak-period delivery share	42%	Share of tours occurring during high-congestion periods.
Internal combustion freight-vehicle share	80%	Share of tours made by diesel/gasoline vehicles.
Zero-emission freight-vehicle share	20%	Share of tours made by electric or other zero-tailpipe-emission vehicles.
Average curbside dwell time	10 min/tour	Loading, unloading, waiting, searching, and access time at the curb or building interface.
Peak congestion cost	KRW 1200/km	Illustrative marginal external congestion cost during peak periods.
Off-peak congestion cost	KRW 400/km	Illustrative marginal external congestion cost during off-peak periods.
ICE emission cost	KRW 250/km	Illustrative local air-pollution and carbon-related external cost.
ZEV residual emission cost	KRW 60/km	Illustrative upstream and non-tailpipe residual external cost.
Curbside dwell cost	KRW 180/min	Illustrative opportunity cost of scarce loading and stopping space.
Residual noise/safety/public-space cost	KRW 800/tour	Illustrative residual cost not otherwise itemized.

4. Results

4.1. External-Cost Structure of Urban Logistics

The first component of the framework is an external-cost structure that separates movement-related costs from stopping-related costs. Conventional road pricing focuses mainly on vehicle movement. In urban logistics, however, the delivery process includes both movement and curbside activity. A parcel vehicle may generate congestion while moving, but it may also generate delay and safety risk while searching for a loading space, double parking, walking goods through sidewalks, or occupying a curb that could otherwise serve transit, passenger loading, cycling, or public-space functions. The final part of the delivery process is increasingly recognized as a distinct operational and planning problem, often described as the last meters or final segment of delivery [25,26].

This distinction has policy consequences. A distance-based charge can internalize part of the congestion and emissions cost of moving through a zone, but it will not necessarily internalize the cost of occupying scarce loading space. Conversely, a curbside parking price may improve loading turnover but may not reduce long-distance circulation or peak-hour entry. Therefore, a Pigouvian urban logistics policy requires more than a single tax base. It requires multiple price points linked to different cost mechanisms: road use, zone entry, emissions, parking dwell time, delivery time window, and delivery fragmentation.

The external-cost structure also explains why uniform charges are inefficient. A zero-emission van operating in a residential street at night may reduce local emissions but still generate noise if loading is not managed. A diesel truck operating on a high-capacity urban arterial at off-peak times may generate emissions but relatively lower congestion costs. A small parcel vehicle may have low per-vehicle emissions but can generate high curbside and circulation costs if it performs many fragmented deliveries. The appropriate charge or incentive should therefore vary by time, place, vehicle, and logistics behavior.

4.2. Limitations of Carrier-Only Charging Mechanisms

The second component identifies a decision-maker mismatch. Passenger road pricing can be effective because the driver is usually the person deciding whether, when, and where to drive [17,18]. In freight, the carrier may be the payer but not the controller of the delivery schedule. Holguín-Veras showed that time-of-day cordon or area tolls may not shift deliveries to off-hours when the toll is absorbed by carriers and not transmitted to receivers [15]. Similar findings in freight pricing and incentive research suggest that instruments should reach the appropriate decision-maker rather than only the vehicle operator [2,16].

This mismatch is structural. Receivers often prefer regular-hour deliveries because staff and building access are already available. Carriers often prefer off-hour deliveries because travel speeds are higher, tour productivity improves, and delivery uncertainty falls. In competitive freight markets, however, receivers may have stronger bargaining power. If receivers do not accept off-hour deliveries, carriers cannot unilaterally reschedule without risking service failure or customer loss [16].

The policy implication is that a Pigouvian tax aimed only at carriers may become a cost of doing business rather than a behavioral signal. The charge may be partially absorbed by carriers, passed on in diffuse contract prices, or offset through operational adjustments that do not reduce external costs. For Pigouvian policy to work in urban logistics, it must identify the supply chain decision that generates the externality. Peak-hour congestion is partly a receiver-scheduling problem; high delivery frequency is partly a shipper or platform-service-level problem; curbside dwell time is partly a building management and receiving process problem; and emissions are partly a fleet investment problem and partly

a regulatory infrastructure problem. Table 6 maps major policy instruments to externality mechanisms and decision-maker reach.

Table 6. Policy instruments, target mechanisms, and decision-maker reach.

Instrument	Primary Externality Addressed	Decision-Maker Reached	Key Limitation
Time-of-day cordon or area toll	Peak-hour congestion and emissions in a defined zone.	Carrier or vehicle operator.	Weak behavior change if receiver controls delivery time and toll cannot be transferred.
Time-distance freight toll	Distance-based road use, congestion exposure, and zone occupation.	Carrier and, if contractually transferable, receiver or shipper.	Requires high enough price signal; may face political resistance.
Freight parking or loading-zone pricing	Curbside occupation, double parking, cruising, and loading-space scarcity.	Carrier, driver, building manager, and receiver.	Needs enforcement, data, and adequate legal loading alternatives.
Emission-based vehicle fee	Local air pollution and greenhouse gas emissions.	Fleet owner, carrier, and shipper through procurement conditions.	May not reduce congestion; risks burdening small carriers without support.
Off-hour delivery incentive	Peak congestion and travel-time unreliability.	Receiver, building manager, retailer, and carrier.	Requires security, labor, noise management, and receiving infrastructure.
Clean-vehicle incentive	Tailpipe emissions and compliance with low-emission zones.	Fleet owner and carrier.	Reduces emissions but not necessarily congestion or curbside conflict.
Consolidation and microhub incentive	Fragmented trips, low load factors, and repeated delivery tours.	Shipper, platform, carrier, and local authority.	Requires land, operational coordination, and financially sustainable business model.

Table 6 demonstrates the central logic of the framework: each instrument has a different behavioral reach. Even a theoretically correct charge may be weak if it does not reach the actor able to change the relevant delivery behavior.

4.3. Integrated Pigouvian Policy Package

The third component proposes an integrated policy package that combines charges and incentives. Although pricing is theoretically efficient, it may face political and stakeholder constraints. Pure incentives may be more acceptable but fiscally limited and potentially insufficient if external costs remain underpriced. A combined model allows cities to charge high-externality activities while using part of the revenue to fund lower-externality alternatives.

The proposed package has four layers. The first layer is dynamic road-user charging for freight vehicles in congested urban zones. The charge should vary by time, zone, vehicle class, and emission profile. The second layer is curbside pricing and loading-space management. Loading zones should be treated as scarce public assets with time limits, reservation options, enforcement, and differentiated access rules. The third layer is receiver-oriented incentives for off-hour or shoulder-hour deliveries. These incentives may include grants for secure unattended receiving, recognition programs, tax credits, access privileges, or subsidies for quiet-delivery equipment. The fourth layer is clean and efficient logistics support, including zero-emission vehicle incentives, charging infrastructure, consolidation hubs, common carrier lockers, and data-sharing platforms.

This package follows the logic of self-supported freight demand management [20]. Revenue from charges can be returned to the freight system through targeted investments

that help supply chain actors reduce external costs. For example, a small peak-period surcharge could finance off-hour delivery incentives, loading-zone technology, or microhub infrastructure. Revenue recycling is important for acceptability because stakeholders are more likely to support charges when they see direct improvements in freight productivity and urban livability.

Off-hour delivery programs illustrate the complementarity between pricing and incentives. Evidence from New York City shows that receiver incentives can change delivery-hour behavior and produce operational benefits [21]. Environmental assessment also suggests that large-scale off-hour delivery programs can reduce emissions under certain traffic and operational conditions, although outcomes depend on vehicle technology, routing, noise constraints, and the spatial distribution of demand [22]. The policy lesson is not that all deliveries should move to nighttime periods; rather, cities should identify the subset of deliveries for which time shifting reduces total social cost after considering congestion, emissions, labor, safety, and noise. Table 7 presents the design principles derived from the proposed framework.

Table 7. Design principles for Pigouvian urban logistics policy.

Principle	Rationale	Operational Implication
Cost specificity	External costs vary by time, zone, vehicle, and stopping behavior.	Avoid uniform fees; differentiate charges by external-cost driver.
Decision-maker alignment	The payer must be able to change the behavior that causes the externality.	Design instruments for receivers, shippers, platforms, and building managers, not only carriers.
Charge-incentive balance	Charges discourage high-cost behavior; incentives enable feasible alternatives.	Pair peak charges with off-hour, consolidation, and clean-vehicle support.
Revenue recycling	Policy legitimacy improves when revenue is reinvested in logistics and public-space improvements.	Ring-fence revenue for loading zones, microhubs, EV charging, data systems, and safety upgrades.
Adaptive governance	Urban freight markets and technologies change quickly.	Use pilots, monitoring, stakeholder feedback, and periodic recalibration.

Table 7 translates the conceptual synthesis into design rules for policy pilots and provides a checklist for avoiding blunt, carrier-only, or administratively opaque pricing schemes.

4.4. Implementation Pathway

The fourth component outlines a staged implementation pathway. Cities rarely have complete data on freight movements, delivery contracts, receiver preferences, loading-space use, or platform algorithms. An immediate attempt to implement a fully optimized Pigouvian tax may therefore fail. A practical pathway should begin with data collection and pilot programs, then move toward differentiated pricing and incentive allocation as institutional capacity improves.

In the first stage, the city should map freight activity and externalities. This includes vehicle counts by class, delivery time profiles, loading-zone occupancy, violations, curbside dwell time, emission factors, and hotspot analysis. In the second stage, the city should identify decision-makers and market segments. Parcel delivery, food service, construction logistics, retail replenishment, healthcare logistics, and platform-based quick commerce have different delivery constraints and externality profiles. In the third stage, the city should implement pilot pricing and incentive programs in selected districts. In the fourth stage, the city should scale the program and integrate digital enforcement, permit systems,

and revenue recycling. In the fifth stage, the city should regularly recalibrate charges and incentives based on measured outcomes.

Technology can support this pathway. GPS, automatic number plate recognition, electronic permits, loading-zone sensors, digital curb reservations, and logistics data platforms can help identify where and when externalities occur. These tools can also record truck distance, delivery location, and loading-space dwell time, enabling more realistic allocation of externalities [2,25]. However, technology is not a substitute for governance. Data rules, privacy safeguards, enforcement legitimacy, and stakeholder cooperation remain essential.

Table 8 emphasizes that Pigouvian urban logistics policy should be implemented as a learning system. The first objective is not to maximize charge complexity, but to build credible data, trust, and institutional capacity.

Table 8. Staged implementation pathway for cities.

Stage	Main Task	Key Outputs	Risks to Manage
1. Diagnosis	Map freight flows, loading-space demand, emissions, congestion, and safety hotspots.	Externality baseline; freight typology; priority corridors and districts.	Insufficient data; informal deliveries; lack of carrier participation.
2. Actor mapping	Identify who controls delivery timing, frequency, fleet choice, and receiving conditions.	Decision-maker matrix by sector and delivery type.	Misidentifying carriers as sole responsible actors.
3. Pilot design	Test limited pricing and incentives in a high-impact district or corridor.	Pilot charge schedule; incentive eligibility; monitoring plan.	Political resistance; burden on small businesses; noise or labor concerns.
4. Revenue recycling	Allocate revenue to freight and public-space improvements.	Dedicated fund for loading zones, microhubs, EV charging, and safety.	Stakeholder distrust if revenue is absorbed into general budget.
5. Scaling and recalibration	Expand geographically and adjust charges based on measured outcomes.	Dynamic pricing rules; annual evaluation; adaptive governance.	Technology lock-in; inequitable impacts; enforcement disputes.

4.5. Korean Scenario Simulation and Cost–Benefit Comparison

The illustrative Korean scenario compares four policy alternatives. S0 is the baseline with no additional freight-specific pricing or incentive package. S1 is a carrier-only peak-period charge, such as a simple cordon or area toll imposed on vehicles entering the district during peak hours. S2 combines dynamic road pricing with curbside pricing and basic loading-zone management. S3 represents the integrated Pigouvian package proposed in this study: dynamic road-user charging, curbside pricing, receiver-oriented off-hour delivery incentives, clean-vehicle support, consolidation incentives, and revenue recycling.

The simulation results support the conceptual argument. The carrier-only charge produces only a modest reduction because it affects vehicle operators without sufficiently influencing the receivers, platforms, or shippers that determine delivery timing and frequency. It therefore shifts only a limited share of peak deliveries and does not directly reduce dwell time, shipment fragmentation, or fleet-technology externalities. The combined pricing and curbside scenario produces larger benefits because it reduces both movement-related and stopping-related costs. The integrated package performs best because it reaches multiple decision-makers: carriers respond to road and curb prices, receivers respond to off-hour and secure receiving incentives, fleet owners respond to clean-vehicle support, and platforms or shippers respond to consolidation and delivery-window signals.

Under the baseline assumptions, total monetized external costs are approximately KRW 101.84 million per weekday. The carrier-only peak charge reduces the estimate to KRW 100.50 million before implementation costs, which is a reduction of 1.3%. By contrast, the pricing-and-curb package reduces the estimate to KRW 89.15 million, or 12.5%, and the integrated package reduces it to KRW 77.80 million, or 23.6%. In the integrated package, the congestion component falls from KRW 58.88 million to KRW 46.94 million, the emission component falls from KRW 16.96 million to KRW 13.21 million, and the curbside component falls from KRW 18.00 million to KRW 11.34 million under the stated assumptions. After subtracting illustrative administrative, enforcement, and incentive costs, the net social benefit remains negative or marginal for the carrier-only scenario but positive for the integrated package. These values should not be interpreted as empirical estimates; they show how a city can use the framework to compare policy packages before designing a full pilot evaluation.

Figure 2 visualizes the resulting differences in monetized daily external costs across the four policy scenarios.

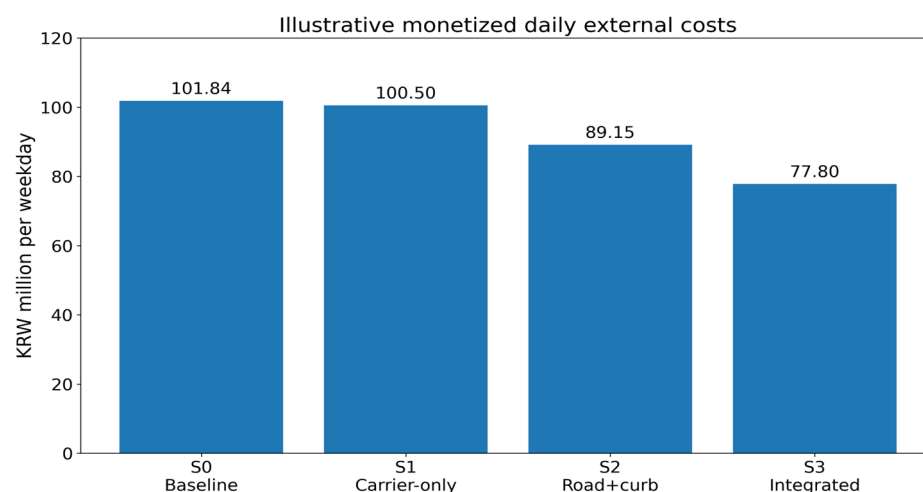


Figure 2. Illustrative change in monetized daily external costs under Korean urban logistics policy scenarios.

Table 3 provides the policy scenario comparison. It shows that the highest-performing package is not simply the one with the highest charge, but the one that changes delivery timing, curbside dwell time, vehicle choice, and shipment fragmentation together.

The implementation-cost term in the net social benefit calculation includes real resource costs rather than pricing revenue transfers. For S1, the illustrative cost represents basic charging administration and enforcement. For S2, it additionally includes curbside technology, loading-zone monitoring, permit administration, and compliance support. For S3, it further includes receiver incentives, secure receiving or locker support, clean-vehicle transition support, consolidation incentives, stakeholder engagement, data governance, and program evaluation. Gross charge revenue is treated as a transfer when it is recycled into the freight system and is therefore not counted as a social cost. This clarification prevents implementation costs from being confused with revenue transfers or with the private incidence of the charge.

4.6. Robustness of Policy Rankings Under Sensitivity Assumptions

The sensitivity analysis directly addresses the uncertainty in the illustrative Korean scenario. A low-cost bound is calculated by reducing the peak congestion-cost coefficient by 20% and the peak-period delivery share by 15%. A high-cost bound is calculated by increasing the peak congestion-cost coefficient by 20% and the peak-period delivery share

by 15%. For S1–S3, the net social benefit range is calculated relative to the baseline under the same sensitivity condition, after subtracting the same implementation and incentive costs used in Table 3.

Table 9 shows that the integrated package remains the highest-performing option under both lower and higher congestion assumptions. The absolute value of the benefit changes with the congestion-cost coefficient and peak-period share, but the policy ranking does not change: carrier-only charging remains weak, dynamic road and curbside pricing performs better, and the integrated Pigouvian package produces the largest net social benefit. This strengthens the claim that decision-maker alignment and charge-incentive integration matter more than the choice of a single charge base.

Table 9. Sensitivity analysis of key external-cost assumptions.

Scenario	Base External Cost	Low-Cost Bound	High-Cost Bound	Net Social Benefit Range
S0 Baseline	KRW 101.84 million/day	KRW 90.95 million/day	KRW 115.15 million/day	Reference case
S1 Carrier-only peak charge	KRW 100.50 million/day	KRW 90.15 million/day	KRW 113.14 million/day	KRW −1.20 to 0.01 million/day
S2 Dynamic road + curbside pricing	KRW 89.15 million/day	KRW 80.36 million/day	KRW 99.90 million/day	KRW 3.59 to 8.25 million/day
S3 Integrated Pigouvian package	KRW 77.80 million/day	KRW 70.45 million/day	KRW 86.78 million/day	KRW 8.51 to 16.37 million/day

Because behavioral uncertainty may be more important than a single congestion-cost coefficient, the sensitivity interpretation also covers compliance rate, receiver participation, curbside dwell-time response, clean-vehicle uptake, implementation cost, and contract pass-through. Figure 3 summarizes this expanded robustness logic. The integrated package remains preferable because it can still generate benefits through several channels even when one behavioral response is weaker than expected.

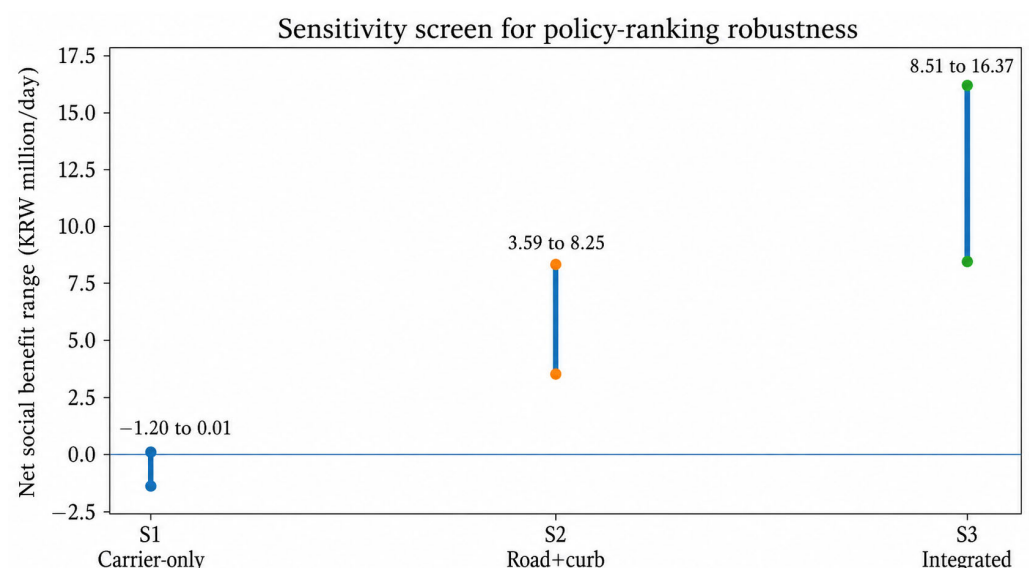


Figure 3. Expanded sensitivity screen for net social benefit and policy-ranking robustness.

4.7. Stakeholder Acceptability and Distributional Effects

The scenario results also show why policy acceptability must be treated as part of policy design. A carrier-only charge is administratively simple, but it can be perceived as unfair if carriers cannot change delivery times because receivers, platforms, or shippers

impose service requirements. In Korea, this concern is especially relevant for small carriers, subcontracted delivery drivers, and low-margin small retailers. If policy costs are imposed only on carriers, the result may be cost shifting, resistance, or deterioration in service conditions rather than external-cost reduction.

A differentiated package can improve acceptability if it clearly connects costs to alternatives. Carriers may accept pricing if revenue is recycled into more loading zones, predictable access, EV charging, and reduced illegal parking risk. Receivers may accept off-hour delivery if secure parcel rooms, unattended receiving systems, or noise-mitigation equipment are subsidized. Residents may accept night or shoulder-hour delivery only when quiet-delivery standards are enforced. Small retailers may require transitional grants because they cannot easily absorb labor, security, or facility costs. Platforms can be required to display flexible delivery options or internalize the social cost of ultra-fast delivery promises.

The key design implication is that equity should not be addressed through broad exemptions that undermine effectiveness. Instead, exemptions and support should be targeted, temporary, and conditional. Essential medical logistics, disability-support deliveries, and small firms adopting low-externality practices may receive transitional support. Large platforms and high-volume shippers should not be exempted simply because they are operationally complex; they are often the actors best able to change delivery windows, consolidate orders, and transmit price signals to consumers. Table 10 summarizes the expected stakeholder positions and mitigation measures. Table 10 adds a policy acceptability layer to the cost model. It shows that Pigouvian pricing becomes more credible when stakeholders can see both the reason for the charge and the operational pathway for avoiding it.

Table 10. Stakeholder acceptability matrix for Pigouvian urban logistics policy.

Stakeholder	Likely Concern	Policy Response	Governance Requirement
Small carriers and subcontracted drivers	Higher charges may reduce margins while delivery schedules remain controlled by receivers or platforms.	Transitional credits, clean-vehicle grants, loading-zone priority, and contractual pass-through rules.	Freight advisory committee; monitoring of cost pass-through and labor impacts.
Large carriers and logistics platforms	Complex pricing may increase compliance costs but can also improve operating reliability.	API-based permitting, predictable price schedules, consolidation incentives, and performance-based access privileges.	Data-sharing agreements with privacy and commercial-confidentiality safeguards.
Receivers, retailers, and building managers	Off-hour receiving can create security, staffing, and noise concerns.	Subsidies for secure unattended receiving, parcel lockers, quiet equipment, and shoulder-hour pilots.	Building-level participation agreements and noise compliance rules.
Residents and pedestrians	Night delivery may create noise; daytime freight creates safety and public-space conflicts.	Quiet-delivery standards, local consultation, curbside redesign, and transparent air-quality/safety indicators.	Public reporting of benefits and complaint-response mechanisms.
Local government	Limited data, enforcement burden, and political resistance.	Start with pilots, simple differentiated fees, and visible revenue recycling before full-scale dynamic pricing.	Dedicated freight governance unit and annual recalibration.
Consumers	Fast delivery benefits are visible; social costs are hidden.	Default flexible delivery windows, green delivery options, and transparent fee signals for ultra-fast delivery.	Consumer-facing communication and platform cooperation.

For future Korean implementation, the stakeholder analysis should be converted into a survey and accounting module. Key variables include average charge incidence per delivery tour, contract pass-through from carrier to shipper or receiver, owner–operator net margin after tolls and curb charges, night-receiving labor or security premiums, parcel-room or locker installation costs, quiet-delivery equipment costs, platform compliance costs, and complaint-response costs. Because reliable city-level values are not publicly available for all variables, this paper treats them as empirical calibration requirements rather than inserting unsupported point estimates. This distinction prevents the scenario from being misread as a city-specific estimate.

4.8. Comparative Interpretation Against Existing Policy Approaches

The scenario results should be interpreted comparatively rather than as city-specific forecasts. A carrier-only peak charge resembles a narrow congestion-pricing approach and performs weakly because it reaches the vehicle operator but not the receiver or platform that controls timing and service promises. A road-and-curb side package improves on single-instrument pricing by adding a stopping-space cost signal. The integrated package outperforms both because it combines negative price signals for high-externality behavior with positive incentives for feasible alternatives such as off-hour receiving, cleaner fleets, consolidation, and improved loading management. This comparison clarifies the progressiveness of the proposed framework relative to separate pricing, low-emission, curbside, and consolidation policies.

5. Discussion

5.1. From Vehicle-Based Charging to Supply Chain Governance

The proposed framework shifts Pigouvian policy from vehicle-based taxation to supply chain governance. This shift is necessary because externalities are physically produced by vehicles but often organizationally produced by ordering, inventory, platform, or receiving decisions. A city may observe a truck in a congested corridor, but the reason for that trip may be a receiver requirement, platform promise, small-batch replenishment policy, or inadequate loading facility. A narrowly vehicle-based fee can identify the immediate source of emissions or road use, yet still fail to reach the actor able to change the system.

This distinction has direct implications for policy design. Reducing peak-hour deliveries requires not only carrier charges but also receiver incentives, secure receiving systems, and flexible delivery-window pricing. Reducing curbside conflict requires not only fines for illegal parking but also priced loading spaces, adequate legal loading zones, building-code integration, and digital reservation systems. Reducing emissions requires clean-vehicle mandates, charging infrastructure, procurement coordination, and charge designs that do not penalize zero-emission adoption.

The framework also explains why some urban freight initiatives perform poorly. Urban consolidation centers can reduce vehicle kilometers and emissions, but they often struggle financially when shippers, carriers, retailers, and local authorities do not share costs and benefits [29]. Pigouvian revenue recycling can support such facilities, but only if governance prevents subsidy dependence and preserves incentives for lower-externality logistics behavior.

5.2. Policy Acceptability and Equity

Policy acceptability is not a secondary issue; it is part of policy effectiveness. Stakeholder studies show that freight policies can face resistance when public authorities do not understand the operational constraints of carriers and receivers [27]. Evidence from congestion-pricing implementation also indicates that acceptability improves when users

observe benefits and revenue use is transparent [28]. Carriers may fear reduced competitiveness, small retailers may fear higher labor or security costs, residents may oppose nighttime noise, and consumers may demand fast delivery without seeing its social cost. Pigouvian pricing must therefore be accompanied by transparent communication, gradual implementation, and visible reinvestment.

Equity should be embedded in the charge design. A uniform fee can burden small carriers and low-margin retailers more heavily than large platforms or national logistics companies. Differentiated instruments can mitigate this problem. For instance, cities can offer transitional credits for small carriers adopting cleaner vehicles, exemptions for essential medical logistics, or grants for small retailers that install secure off-hour receiving systems. At the same time, equity should not become a blanket justification for exempting all freight from pricing. Exemptions should be targeted, temporary, and linked to measurable public interest criteria.

Revenue recycling is a key equity and acceptability mechanism. Freight users should see corresponding improvements in loading zones, curb information, EV charging, and predictable access rules, while residents should see improvements in air quality, safety, noise management, and public-space quality. The legitimacy of Pigouvian urban logistics policy depends on whether it visibly converts external costs into system improvements.

5.3. Digitalization and Dynamic Pricing

Digital technology makes differentiated freight pricing more feasible. Modern systems can combine time, location, vehicle class, emission category, distance, and loading-space occupancy. They can also support permits for specific delivery windows, loading-zone reservations, and automatic enforcement, thereby moving policy from approximate taxes toward more precise external-cost allocation.

Dynamic pricing should nevertheless be introduced cautiously. Complex price schedules may reduce transparency and increase compliance costs; small firms may lack digital capacity; data sharing may raise privacy and commercial confidentiality concerns; and frequently changing fees may create operational uncertainty. Cities should therefore start with simple differentiated categories and refine them as data quality and stakeholder trust improve.

A feasible digital roadmap has four phases. The first uses existing data such as vehicle registration, tolling records, complaints, traffic speeds, delivery permits, and loading-space inventories. The second adds pilot technologies such as automatic number plate recognition, GPS-based fleet reporting, loading-zone sensors, and electronic curb permits. The third integrates dynamic pricing with logistics dashboards, platform APIs, and revenue-recycling accounts. The fourth scales and recalibrates the system through annual evaluation, platform integration, and dedicated freight-infrastructure investment. The transition should remain modular and should follow, rather than precede, legal authority, privacy rules, appeal procedures, and stakeholder trust.

Table 11 converts this roadmap into implementation attributes. The time horizons are indicative and should be adjusted to local procurement rules, legal authority, data infrastructure, and stakeholder readiness.

This staged approach clarifies why a city should not begin with a complex dynamic toll. The first phase establishes a defensible externality baseline; the second tests monitoring and permit compliance; the third links pricing to visible revenue recycling; and only then should the city consider wider dynamic pricing or platform-level data integration.

Table 11. Indicative digital implementation roadmap for Pigouvian urban logistics pricing.

Phase	Indicative Period	Investment and Staffing Focus	Legal and Governance Requirements
1. Data integration and baseline diagnosis	0–12 months	Low to moderate investment; interdepartmental freight task force; use existing traffic speeds, vehicle registration, complaints, logistics facility, and loading-zone inventory data.	Legal review of data sharing, privacy, public complaints, and freight permit authority.
2. Pilot enforcement and electronic permits	12–24 months	Moderate investment; ANPR at selected gateways, GPS reporting for participating fleets, electronic curb permits, and selected loading-zone sensors; dedicated analysts and enforcement staff.	Ordinance or administrative rule for permits, exemptions, appeals, small-firm transition support, and data-retention limits.
3. Dynamic pricing and revenue recycling	24–36 months	Moderate to high investment; pricing engine, payment and rebate system, logistics dashboard, and dedicated revenue-recycling account.	Fee base, rate-adjustment procedure, earmarked revenue use, audit mechanism, and stakeholder advisory committee.
4. Scaling and adaptive recalibration	After 36 months	Staged expansion; platform APIs, citywide curb reservation, EV charging, microhubs, and annual evaluation capacity.	External evaluation, transparency reporting, periodic recalibration, and formal procedure for revising charges and incentives.

The transition to electric and autonomous vehicles will also change the external-cost profile of urban logistics. Electric vehicles reduce tailpipe emissions and can reduce noise, but they do not eliminate congestion, curbside occupation, road safety risk, or public-space conflict. Connected and autonomous vehicle technologies may improve routing and compliance, but they may also increase vehicle kilometers if delivery becomes cheaper. A future-oriented Pigouvian framework should therefore avoid equating decarbonization with full externality internalization. Emissions are only one component of the urban logistics external-cost bundle.

5.4. Implications for Korean Cities and Hinterland Regions

Although the framework is general, it is particularly relevant to dense, platform-intensive urban logistics markets, including Korean cities, where last-mile deliveries interact with constrained street space, apartment-based receiving systems, and regional freight corridors. Many urban logistics externalities emerge not only in metropolitan cores but also in secondary cities linked to ports, airports, industrial estates, and regional distribution centers. In port–airport hinterland regions, urban deliveries may overlap with drayage, industrial logistics, e-commerce distribution, and neighborhood-level parcel flows.

For Korean cities, the first policy implication is that apartment logistics should be treated as a receiving-system problem, not only as a vehicle problem. Apartment complexes can reduce external costs by improving parcel rooms, delivery bays, secure unattended receiving, elevator access rules, and platform coordination. A receiver-side incentive can be justified when the receiving system reduces peak-hour vehicle circulation, repeat delivery attempts, and curbside dwell time. This is especially relevant where parcel volumes are high and one-person households make daytime receiving difficult.

The second implication is that low-emission policy should be connected to freight-space management. Seoul and other Korean metropolitan areas already use vehicle emis-

sions regulation and clean-vehicle support [6,7]. However, a zero-emission parcel vehicle can still occupy a bus stop, double park in a commercial alley, or generate nighttime noise. A Korean Pigouvian package should therefore combine emission-based access rules with loading-zone pricing, curb reservation, microhub development, and quiet-delivery standards. The policy target should be total external cost, not only tailpipe emissions.

The third implication concerns port and airport hinterlands. In areas such as Busan, Incheon, and Gimhae, urban freight policy cannot be separated from regional freight corridors, logistics parks, ports, airports, and industrial estates. Port-hinterland corridors may require time-distance charging, truck route management, staging areas, and digital gate appointment systems. Airport-hinterland logistics may require cold-chain vehicle management, off-peak access, and consolidation rules for high-frequency express shipments. Secondary cities may need to begin with priority corridors rather than citywide pricing because freight data and enforcement capacity are more limited.

For a Busan- or Incheon-type calibration, the unit of analysis should be a corridor-district pair rather than an isolated neighborhood. A port corridor application would require hourly truck shares, corridor speed loss, gate appointment distribution, truck staging demand, road geometry, and loading-space conflicts near logistics facilities. An airport or cold-chain corridor application would require time-sensitive cargo flows, refrigerated-vehicle dwell time, delivery-window rigidity, and energy-use implications of delayed or consolidated shipments. A Gimhae-type hinterland application would require attention to logistics park access roads, industrial estate freight demand, apartment delivery hotspots, and the interface between regional truck corridors and local streets.

A Korean Pigouvian policy should therefore begin with priority corridors and districts rather than a single citywide freight tax. Port-hinterland corridors may require time-distance charging and truck-route management; commercial cores may require curbside pricing and delivery-window coordination; and residential districts may require parcel lockers, microhubs, quiet-delivery standards, and platform cooperation.

Korean cities can also link urban logistics pricing with smart city infrastructure. Traffic data, vehicle registration data, loading-zone sensors, logistics facility data, and public complaints can be integrated into an urban logistics dashboard. However, the framework should remain policy-driven rather than technology-driven: the key question is how data can be translated into fair price signals, feasible incentives, and measurable reductions in external costs. Future research should apply this framework to port-hinterland contexts using empirical freight corridor data, including GPS truck trajectories, port gate appointment records, corridor-level speed loss, loading-zone occupancy, refrigerated-vehicle dwell time, and local delivery records.

5.5. Limitations and Future Research

This study has several limitations. First, the empirical component is illustrative rather than city-specific. The Korean scenario uses stated assumptions, official contextual statistics, and sensitivity tests, but it does not estimate actual external costs for Seoul, Busan, Gimhae, or any other city. Future research should apply the framework to empirical data, including vehicle trajectories, delivery records, traffic speeds, emission factors, curbside occupancy, noise exposure, accident risk, and stakeholder cost data.

Second, the study applies a structured narrative synthesis and does not conduct a full systematic review. This choice is consistent with the policy design objective, but it means that the literature base is selective. The synthesis prioritizes theoretical and policy evidence relevant to pricing, incentives, off-hour delivery, curbside management, and acceptability. It does not fully cover all grey literature, all municipal pilot reports, or all platform logistics

business practices. Future research could extend the evidence base through a systematic review and meta-analysis of urban freight pricing and curbside policies.

Third, the framework identifies decision-makers but does not estimate contract pass-through rates between carriers, shippers, platforms, receivers, and consumers. Future research should analyze how logistics contracts transmit or block price signals. This is essential because a Pigouvian charge is effective only if the relevant decision-maker experiences the marginal cost signal.

Fourth, the scenario model does not include a formal welfare optimization model for charge levels. A future model could evaluate the optimal balance between charges, incentives, administrative costs, behavioral elasticities, and equity adjustments. Such a model should also compare different revenue-recycling rules and exemption designs.

Fifth, the sensitivity analysis varies only two influential parameters: the peak congestion-cost coefficient and the peak-period delivery share. This improves robustness relative to a single-point scenario, but it does not test the full uncertainty space. Future models should also vary behavioral elasticities, contract pass-through rates, off-hour delivery acceptance, EV adoption rates, curbside dwell-time response, administrative costs, and revenue-recycling efficiency.

Sixth, future research should examine policy acceptability through surveys, stated-preference experiments, Delphi surveys, or stakeholder workshops. Carriers, receivers, platform operators, local retailers, residents, and public officials may evaluate the same policy package differently. The external costs of urban logistics are shaped not only at the curb but also by logistics facility location, platform governance, building design, and metropolitan freight network planning.

5.6. Constraint Relationships Within the Pigouvian Policy Framework

The framework also reveals several constraint relationships. Stronger pricing can improve allocative efficiency but may reduce acceptability unless revenue recycling and transition support are visible. Emission-based instruments reduce tailpipe impacts but do not remove congestion, curbside dwell time, or public-space conflict. Curbside pricing improves loading turnover only when legal loading alternatives exist. Receiver-oriented incentives can shift deliveries away from peaks, but they require building access, quiet-delivery standards, and security arrangements. More precise digital pricing can improve cost allocation, yet it raises privacy, administrative burden, and small-firm capacity concerns. The practical policy task is therefore to balance efficiency, behavioral reach, equity, enforceability, and adaptability rather than to maximize any single instrument.

6. Conclusions

This article developed a Pigouvian policy framework for internalizing external costs in urban logistics. The central argument is that urban logistics externalities cannot be effectively managed by carrier-only charges or uniform vehicle taxes. Urban freight is a supply chain activity in which vehicles physically generate externalities but multiple actors determine the behaviors that create those externalities. Therefore, the design of road pricing and incentives must identify and reach the appropriate decision-maker. The framework further clarifies that these factors are constrained by trade-offs among pricing strength, actor reach, equity, data precision, and implementation capacity.

The proposed framework decomposes external costs into congestion, emissions, noise, safety risk, curbside occupancy, and public-space conflict. It then links these costs to a differentiated policy package combining dynamic road-user charges, freight parking and loading-zone pricing, emission-based fees, receiver-oriented off-hour delivery incentives, clean-vehicle support, consolidation incentives, and revenue recycling. The framework

also emphasizes five design principles: cost specificity, decision-maker alignment, charge-incentive balance, revenue recycling, and adaptive governance.

The Korean application strengthens the practical contribution of the paper. Official data show that Korea combines rapid parcel growth, high mobile commerce dependence, and apartment-dominant receiving environments [3–5]. These conditions make it important to target receivers, platforms, building managers, and fleet owners, not only vehicle operators. The illustrative scenario shows that a carrier-only peak charge produces limited external cost reduction, whereas an integrated package can reduce congestion, emissions, and curbside costs more substantially under stated assumptions. The sensitivity test further shows that the ranking of policy alternatives remains stable when the peak congestion-cost coefficient and peak-period delivery share are varied. The scenario should therefore be interpreted as a policy design demonstration and robustness exercise, not as a city-specific empirical estimate.

For cities, a key practical implication is that urban logistics should be managed as a public–private system in which freight efficiency and urban sustainability are jointly optimized. A city that charges freight activity without improving logistics infrastructure may face resistance and limited behavioral change. A city that subsidizes cleaner logistics without pricing external costs may lack funding and long-term incentives. A feasible pathway is a self-reinforcing policy package in which external-cost charges finance the transition toward lower-impact delivery systems.

If implemented with reliable data and stakeholder safeguards, an integrated Pigouvian package can be expected to reduce peak-period freight concentration, shorten curbside dwell time, accelerate cleaner fleet adoption, improve delivery-space turnover, and increase the visibility of logistics externalities to platforms and consumers. Future empirical work should calibrate this framework in specific urban contexts and evaluate its effects on congestion, emissions, noise, curbside performance, logistics costs, and policy acceptability.

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Abbreviations

The following abbreviations are used in this manuscript:

ANPR	Automatic number plate recognition
API	Application programming interface
EV	Electric vehicle
GHG	Greenhouse gas
ICE	Internal combustion engine
MEC	Marginal external cost
MPC	Marginal private cost
MSC	Marginal social cost
NSB	Net social benefit
OHD	Off-hour delivery
TEC	Total external cost
UCC	Urban consolidation center
ZEV	Zero-emission vehicle

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