

# Economies of Density in Multi-Stop Production: Evidence from Municipal Waste Collection\*

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## Abstract

How does population density reduce the operating requirements of services that combine work at dispersed locations with movement between them, and through which margins? I study municipal waste collection using one-second GPS data from trucks operating in a Japanese urban area. The records allow me to measure time spent servicing waste stations and moving between consecutive stations, together with the number and road distance of those movements. I develop and estimate a multi-stop production technology in which operating time depends on the service load handled at each stop, a time requirement associated with each inter-stop movement, and the distance connecting stops. The estimates show economies of scale in service at stops and a substantial time requirement for each movement beyond its distance-related component. A one-percent increase in population density is associated with a 0.547-percent reduction in measured service-and-movement time per resident. Expressing the three production margins in common time units, I find that lower station-service time per resident accounts for 41.7 percent of the calculated reduction, fewer station-to-station movements per resident for 32.3 percent, and lower connecting road distance per resident for 26.0 percent. The estimated model indicates that density reduces operating time mainly because denser areas serve more residents at each waste station, spreading station-service requirements over more residents and reducing the number of movements per resident. Finally, I use the estimates to simulate a five-percent population decline. With waste-station count adjusting, total operating time per resident rises by 2.79 percent when decline occurs in sparse areas and by 3.82 percent when it occurs in dense areas, because the former leaves the remaining population more spatially concentrated.

**Keywords:** Waste Collection; Spatial Public Services; Multi-Stop Production; Economies of Density

**JEL Codes:** R11, H72, R41, Q53

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# 1 Introduction

How does population density reduce the operating requirements of services that combine work at dispersed locations with movement between them? Parcel carriers, home-care workers, repair technicians, school buses, sales representatives, and waste-collection crews all visit multiple service points in sequence. In these activities, operating requirements depend not only on the amount of service delivered, but also on how demand is grouped across service points and how those points are connected.

Economies of density can arise through three margins. First, when a service point serves more users, its service requirement can rise less than proportionally, reducing service time per user. Second, when the number of service points rises less than proportionally with the number of users, fewer movements between consecutive points are required per user. Third, total connecting distance per user can fall both because fewer movements are required and because the distance between consecutive service points becomes shorter. The strength of economies of density therefore depends on how the number and spacing of service points change with the number of users. If service-point count grows one-for-one with users, service time per user and the number of movements per user remain unchanged, while connecting distance per user falls as service points become more closely spaced. If service-point count grows more slowly, more users are served at each point, further reducing service time per user, the number of movements per user, and connecting distance per user.

Understanding these margins matters because an aggregate density elasticity combines the underlying production technology with the way users are organized across service points. The same technology can therefore generate different density economies under different service-point networks. Separating the margins is necessary for predicting operating requirements when population changes or the network adjusts.

Municipal waste collection provides a useful setting for studying these mechanisms. Households pool their waste at shared neighborhood stations, while collection trucks visit those stations sequentially on recurring schedules. The service therefore combines work at shared stops with repeated movement between them. Moreover, the same provider serves both dense and sparse areas within a common operating system, allowing the three margins to be compared within a single service.

I use one-second GPS location data from trucks providing public waste collection in a Japanese urban area. The resulting records cover September through December 2025 and identify 45,107 service events at 1,393 waste stations over 553 truck-days. They allow me to separate service at waste stations from movement between consecutive serviced stations. Ordering the station visits within each truck-day reconstructs the collection sequence and identifies each leg from one serviced station to the next, together with its elapsed time and routed road distance.

I first estimate the multi-stop production technology underlying these three margins. At the waste-station level, the estimated elasticity of service time with respect to census-area population per station is 0.204, implying that service time rises much less than proportionally. Using within-truck-day variation in the number and road distance of station-to-station movements, I estimate a substantial time requirement for each movement in addition to the requirement that rises with road distance.

I then assess whether these estimates capture the intended production margins using two sources of

temporal variation. The recurring collection schedule creates three- and four-day intervals between visits to the same station. More waste should accumulate over four days than over three, so the longer interval should increase station-service time without changing the time required per leg or per road kilometer. Consistent with this prediction, station-service time is higher after a four-day interval, while the estimated movement requirements do not differ significantly between the two schedule positions. Winter snow provides a complementary comparison: standing snow substantially increases the time required per road kilometer, while its effect on the distance-independent time per leg is not statistically distinguishable from zero and the station-service elasticity remains broadly similar. These results support separating station service, the number of movements, and the road distance of those movements in the production technology.

I aggregate the service events and station-to-station legs to census-area weeks and estimate how measured service-and-movement time per resident varies with population density. A one-percent increase in population density is associated with 0.547 percent less station-service and station-to-station movement time per resident. I separately estimate how station-service time, the number of station-to-station movements, and their total road distance respond to density and express the resulting changes in common time units. Lower station-service time per resident accounts for 41.7 percent of this calculated time saving, fewer station-to-station movements per resident for 32.3 percent, and lower road distance traveled between stations per resident for 26.0 percent.

This component accounting shows where operating-time savings occur, but not why they arise. Holding land area fixed, a one-percent larger census-area population is associated with 0.504 percent more waste stations. Thus, denser areas have more residents per station. Using this relationship and the estimated production parameters, the model predicts that a one-percent increase in density reduces these three operating-time components per resident by 0.485 percent. To assess how much of this reduction comes from serving more residents at each station, I compare this prediction with a case in which each station continues to serve the same number of residents as density rises. This requires the number of stations to increase at the same rate as population. Station-service time per resident and the number of station-to-station movements per resident then remain unchanged. Because the same land area contains more stations, however, the distance between stations becomes shorter, so road distance per resident falls. The model predicts a reduction of only 0.082 percent in this case. Thus, in the model, serving more residents per station accounts for 83.1 percent of the predicted reduction in the sum of these three operating-time components per resident.

I use the estimated production technology and station-count relationship to quantify how the spatial distribution of population decline affects operating requirements. Holding the aggregate population loss at five percent, I compare uniform decline with decline concentrated in sparse or dense areas. When station count adjusts, total operating time per resident rises by 2.79 percent under sparse-area decline and by 3.82 percent under dense-area decline. The results show why density matters quantitatively: for the same aggregate population loss, a more spatially concentrated remaining population entails a smaller increase in operating requirements. Although station consolidation reduces the increase in operating time per resident, it can also increase the population-weighted average distance to a surviving waste station.

This paper is most closely related to research on the operating requirements of services produced along

routes. Postal-delivery research separates route, access, and load time (Cohen and Chu, 1997); home-care research estimates density economies using employees' service hours and exact travel miles (Bensaid et al., 2022); and last-mile delivery research studies how customer density affects route efficiency (Boyer et al., 2009). Using observed parcel and beverage deliveries, Dalla Chiara and Goodchild (2025) estimate how serving multiple customers from one vehicle stop affects stop time and show how it changes the number of stops and vehicle miles traveled. Related work estimates distribution-cost savings from dense retail networks (Holmes, 2011) and shipping-cost savings from dense fulfillment networks (Houde et al., 2023). This paper observes the sequence of operations within a recurring public service and separately estimates service at stops, the number of movements between stops, and the time and distance of those movements. It thereby connects the internal organization of a route-based service to its economies of density.

The paper also connects economic evidence on density in public-service provision with operational research on waste collection. The distinction between scale and density is central in spatial networks (Caves et al., 1984). Local-public-expenditure studies relate spending to population density and the spatial pattern of development (Ladd, 1992; Hortas-Rico and Solé-Ollé, 2010; Ihlanfeldt and Willardsen, 2018), while waste-collection cost functions estimate scale and density relationships from firm- or municipality-level totals (Hirsch, 1965; Antonioli and Filippini, 2002; Abrate et al., 2014). Engineering studies model how population density, waste-station count, and route design relate to transport distance and route time (Ishikawa, 1996; Apaydın and Gönüllü, 2011), and a broader operations literature studies waste-collection routing and related location problems (Hess et al., 2024). Other operational studies use GPS or field records to estimate service and travel time or to measure collection, movement, unloading, and total route time (Ghiani et al., 2015; Jaunich et al., 2016; Matsui and Kasai, 2018). Recent work in Japan uses collection-vehicle route logs to estimate waste quantities at individual stations and evaluate route changes (Maki et al., 2025). Aggregate cost studies quantify overall relationships but do not show which production margins account for them, while operational studies provide the measurements needed to separate those margins. This paper connects the two strands by linking component-specific density responses to the service and movement parameters of the production technology.

The quantitative application relates to research on compact cities, urban form, and public-service consolidation under population decline. Research on compact cities and density emphasizes that the consequences of concentration depend on how residents, service locations, and infrastructure are organized (OECD, 2012; Ahlfeldt and Pietrostefani, 2019; Akai et al., 2025). Japanese studies examine how within-municipality population distributions and low urban density relate to public-service expenditure (Nakamura and Tahira, 2008; Miyauchi and Setoguchi, 2023), while Harari (2020) shows more generally that average density does not exhaust the economically relevant geometry of urban development. Related work examines the fiscal and household consequences of school consolidation (Tanaka and Weese, 2023). Tachibana et al. (2021) develops a model for the layout of waste collection points in a Japanese municipality facing population decline, accounting for residents' distance to those points, while Fischer et al. (2024) jointly selects shared collection points and vehicle routes. Survey evidence also documents residents' willingness to carry waste to more distant disposal sites and their views on contactless collection in aging and shrinking communities (Pandyaswargo et al., 2024). The application here uses the estimated production

structure to quantify how the location of a common aggregate population loss changes operating time and physical access when waste-station count adjusts.

## 2 Institutional Setting

The study area consists of three municipalities located in Iwate Prefecture in northern Japan: the southern part of Morioka City, Shiwa Town, and Yahaba Town; Appendix Figure B.1 shows their location. Within Morioka, the contracted service territory is former Tonan Village, which was incorporated into Morioka City in 1992. In the 2020 Population Census, Morioka City had about 290,000 residents municipality-wide, while Shiwa and Yahaba had about 32,100 and 28,100, respectively; both towns are located close to Morioka City and belong to its commuting area.

In the 2020 Population Census, the study region is divided into small spatial units corresponding to *chō*, *chōme*, and *aza*. I refer to these units as census areas. Figure 1 shows the census-area boundaries, observed waste stations, and the incineration facility, which also serves as the truck depot.

Waste collection services in these municipalities operate through a station-based system.<sup>1</sup> Designated waste stations are distributed across neighborhoods. Household waste is separated into several categories—combustible waste, non-combustible waste, glass bottles, metal cans, and PET bottles—and each type is collected on a specific day of the week. Residents bring the corresponding type of waste, typically placed in plastic bags, to their assigned station on the morning of the designated collection day.

Waste-station installation, relocation, and closure are municipal decisions made in consultation with neighborhood representatives, landowners, users, and nearby residents. The municipalities outsource collection to the Morioka–Shiwa District Urban Environmental Services Cooperative, a consortium of private firms that organizes routes and allocates trucks and crews across collection areas. The cooperative therefore takes the number and location of waste stations as given when organizing daily collection.

This study focuses on combustible waste, which is collected twice per week. Stations are assigned to one of three collection schedules—Monday–Thursday, Tuesday–Friday, or Wednesday–Saturday. The cooperative operates six trucks dedicated to combustible waste collection; they operate simultaneously on each collection day and divide the scheduled stations among them.

Each truck is operated by a two-person crew consisting of one driver and one collection assistant. The cooperative rotates driver–assistant pairings and the areas served by each crew over time.<sup>2</sup> The workday begins at 8:00 a.m., and collection must be completed by 5:00 p.m.; in practice, crews typically finish collection by around 3:00 p.m. The crew travels sequentially between stations, loads waste bags at each stop, and then proceeds to the next station. The broad route through an assigned area is established in advance, but the route actually taken and the timing of station visits can vary with the volume of waste encountered that day.

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<sup>1</sup>Private collection is used occasionally by large apartment complexes. Morioka City officials estimate that it covers no more than 3 percent of the city’s population and likely less in the study footprint, which consists mainly of detached houses and small apartment buildings. I therefore treat the municipal station-based service as effectively universal in the analysis. The estimate is based on interviews with city officials responsible for waste collection.

<sup>2</sup>Interviews with cooperative staff indicate that these rotations are not assigned strategically in response to route conditions; their purpose is to distribute assignments fairly across workers.

The waste-incineration facility serves as both the disposal site and the truck depot. Trucks depart from the facility in the morning and collect waste in their assigned areas. To avoid overloading, a truck returns to unload once it has accumulated a substantial load and then resumes collection. The timing of these returns depends on the realized waste volume and can therefore change both the realized route and the timing of subsequent station visits. Crews also return to the facility for an approximately one-hour midday break, which includes lunch. A truck typically returns to the facility about three times during a collection day, with the final return marking the end of its operation.

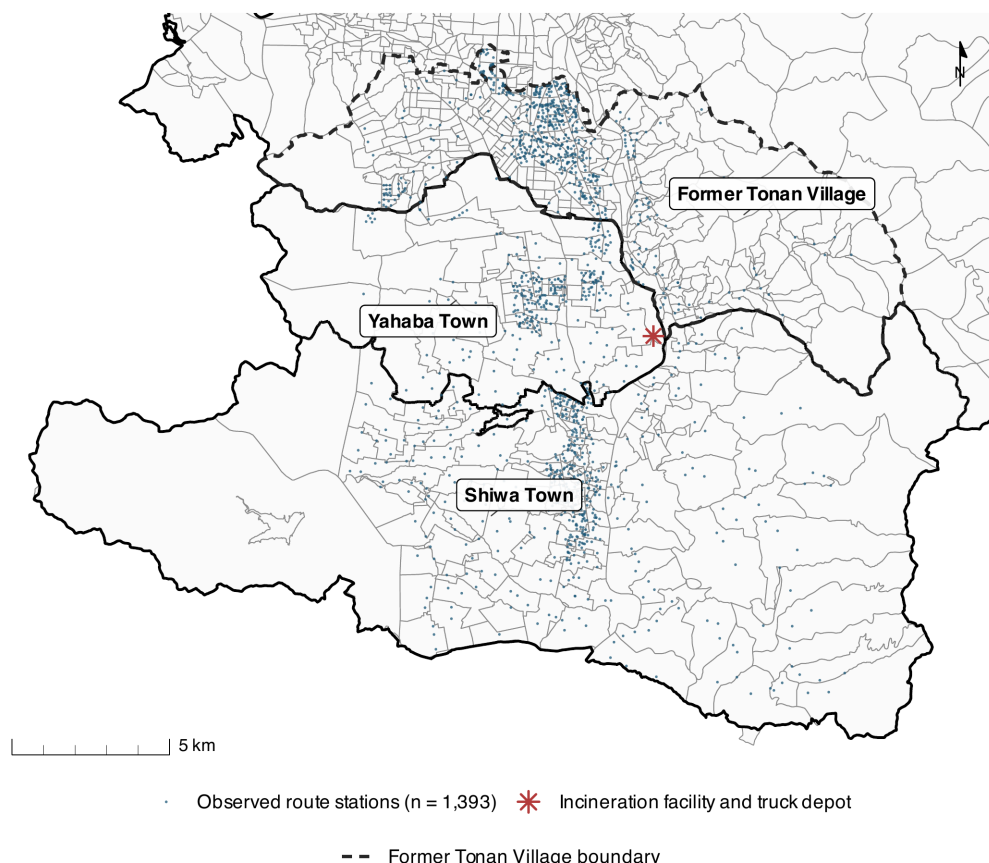


Figure 1: Census Areas, Waste Stations, and the Incineration Facility

Note: Gray lines are the boundaries of 2020 census areas, thick black lines are current municipal boundaries, and the dashed line is the 1985 boundary of former Tonan Village. Blue dots mark the 1,393 waste stations observed in the service events. The red star marks the Morioka–Shiwa District Environmental Facilities Association Clean Center, which serves as both the waste-incineration facility and the truck depot. Its plotted location is the facility coordinate associated with the weigh-in records. The map covers the complete study region: former Tonan Village, Yahaba Town, and Shiwa Town.

### 3 Data and Measurement

#### 3.1 Operational Records and Service Sequences

I use one-second GPS records from a waste collection management system developed by New Japan Knowledge Co., Ltd. The system tracks the position of each collection truck at one-second intervals through a GPS

device installed on the truck. During the observation period, it covered all trucks used for combustible-waste collection in the study area. The collection cooperative also provided waste-station coordinates and facility weigh-in records. From the GPS records, I construct 45,107 service events at 1,393 waste stations over 553 truck-days from September through December 2025, which form the main analysis sample. For the winter-snow validation in Subsection 5.4, I construct service events and legs from additional GPS records through June 2026 using the same definitions.

The basic observational unit is a service event. I construct these events by aggregating consecutive one-second GPS records in which a collection truck remains within 30 meters of a station and moves at a speed below 2 km/h continuously for at least 15 seconds. This rule limits positional noise. I measure the duration of each resulting stop as service time at that station. The event rule identifies service activity at 98.6% of the stations scheduled for collection on days for which schedules can be matched.

To construct station-to-station legs, I order the service events chronologically within each truck-day. Each adjacent pair defines an inter-service interval running from the end of service at the first station to the beginning of service at the next. Most of these intervals capture movement between serviced waste stations. Some instead include a return to the incineration facility or a long interruption such as the midday break. I therefore define an interval as a station-to-station leg only if its timing information is complete, it contains no facility weigh-in, and it lasts no more than 45 minutes. Intervals containing a facility weigh-in are classified as disposal trip and facility activity, while longer nonfacility intervals are classified as other intervals; both interrupt the station-to-station sequence. The movement time of each leg is its recorded inter-service interval, with negative intervals replaced by 15 seconds. I calculate directed road distance between its endpoint coordinates using the OSRM routing engine.<sup>3</sup> The resulting service-sequence data identify the ordered station visits, service duration at each station, and movement time and road distance for each leg.

### 3.2 Truck-Day Operating-Time Allocation

Using the service events and station-to-station legs, I calculate each truck-day’s total operating time as the sum of four activity-time components, net of the standard one-hour midday break when applicable.<sup>4</sup> Figure 2 summarizes this allocation for 482 truck-days covering all 104 collection dates and all six trucks.

*At-station service* is the sum of the recorded service-event durations, and *station-to-station movement* is the elapsed time associated with the legs constructed from the service sequence. Because each truck begins the workday at the facility, *disposal trip and facility activity* includes the interval from 8:00 a.m. to the first recorded service. It also includes inter-service intervals that contain a facility weigh-in, as well as the final trip from the last service to the final weigh-in; these intervals cover travel to the facility, unloading and other facility time, and, where applicable, travel back to collection. Remaining nonfacility intervals longer

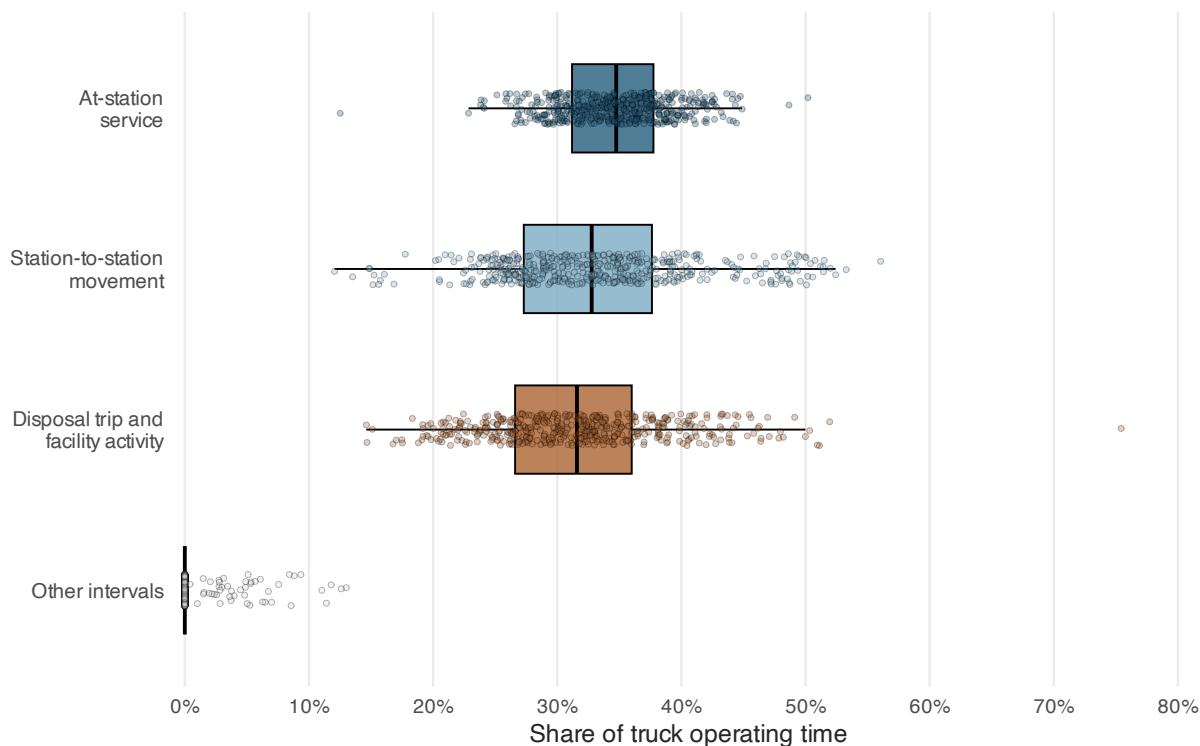
<sup>3</sup>Routing software: <https://project-osrm.org/>. Road-network data: <https://download.geofabrik.de/asia/japan/tohoku-260101.osm.pbf>. OpenStreetMap copyright and attribution: <https://www.openstreetmap.org/copyright>.

<sup>4</sup>The GPS records do not identify the exact start and end of the midday break. I therefore subtract 60 minutes from the inter-service interval that contains a facility weigh-in or lasts more than 45 minutes and overlaps at least one hour of the usual 11:30 a.m.–1:30 p.m. midday-break window. This adjustment applies to 446 of the 482 truck-days.

than 45 minutes are assigned to *other intervals*.

Across these truck-days, at-station service accounts on average for 34.7 percent of total operating time and station-to-station movement for 33.2 percent. Disposal trip and facility activity accounts for 31.7 percent, and other intervals for 0.5 percent. Thus, each of the first three activities absorbs about one-third of total operating time.

Figure 2: Allocation of Collection-Truck Operating Time



Note: Each point represents one of 482 truck-days with complete service durations and an observed final facility weigh-in. Total operating time is the sum of the four activity-time components, net of the standard one-hour midday break when applicable. Disposal trip and facility activity includes the interval from 8:00 a.m. to the first recorded service, inter-service intervals containing a facility weigh-in, and the final trip to the final weigh-in; other intervals are nonfacility inter-service intervals longer than 45 minutes. Boxes show the interquartile range, center lines show medians, and whiskers extend to 1.5 times the interquartile range.

The figure shows that collection trucks spend a substantial share of their operating time moving between waste stations. Movement is therefore a quantitatively important part of production, motivating the analysis below of how density changes both the number and distance of station-to-station movements.

Appendix C reports descriptive statistics for the station-service, movement, and census-area-week samples.

## 4 A Multi-Stop Production Framework

### 4.1 General Multi-Stop Production Technology

Many public and private services are produced through ordered multi-stop itineraries. Let  $\mathcal{I}$  denote an ordered itinerary with  $K$  service points, written as  $(s_1, \dots, s_K)$ . At stop  $s_k$ , let  $q_{s_k}$  denote the service load handled there—for example, the amount of waste collected at a waste station—and let  $S(q_{s_k})$  denote the associated service-time requirement. Write  $\mathbf{q} = (q_{s_1}, \dots, q_{s_K})$ . Let  $L(\mathcal{I})$  denote the number of inter-stop legs in the itinerary, each of which is a spatial connection between two consecutive service points, and let  $D(\mathcal{I})$  denote their total connecting distance. For an uninterrupted open itinerary,  $L(\mathcal{I}) = K - 1$ . Finally, let  $O(\mathcal{I}, \mathbf{q})$  collect other operating time that is not attributable to service at the listed points or movement between consecutive points. Total operating time is

$$\mathcal{T}(\mathcal{I}, \mathbf{q}) = \sum_{k=1}^K S(q_{s_k}) + \kappa L(\mathcal{I}) + \psi D(\mathcal{I}) + O(\mathcal{I}, \mathbf{q}). \quad (1)$$

The first term aggregates service time across stops. The next two terms decompose movement time into a distance-independent requirement per leg and a distance-related requirement.

The stop-level technology  $S(\cdot)$  is service-specific. Loading waste, delivering parcels, providing home care, and conducting repair or sales visits involve different tasks at a stop. The decomposition of movement requirements into a per-leg component and a distance-related component applies to a broader class of mobile services organized as multi-stop itineraries, although both the functional form and parameter values may be service-specific.

### 4.2 Waste-Collection Operating-Time Requirements

I now apply this framework to waste collection. Let  $A > 0$  denote the area of a fixed local service territory,  $N > 0$  its population, and  $M > 0$  the number of waste stations. In this application,  $q_s$  is the waste load handled at station  $s$ . Under the representative-station approximation, if each resident generates  $g > 0$  units of waste, this load is

$$q(N, M, g) = g \frac{N}{M}. \quad (2)$$

**Station service.** For waste collection, I specify station service time as a concave function of the amount of waste handled:

$$S(q) = \alpha q^\eta, \quad \alpha > 0, \quad 0 < \eta < 1. \quad (3)$$

Total station service time is

$$Y^S(N, M; g) = M \alpha \left( g \frac{N}{M} \right)^\eta = \alpha g^\eta N^\eta M^{1-\eta}. \quad (4)$$

Dividing by population gives per-capita station service time,

$$C_S(N, M; g) = \alpha g^\eta N^{\eta-1} M^{1-\eta}. \quad (5)$$

Because  $\eta < 1$ , more residents can share the work performed at a station.

**Number of legs.** At the area level, leg count rises approximately one-for-one with the number of waste stations, so I use  $L = M$  as the benchmark. This approximation abstracts from itinerary endpoints. The corresponding distance-independent time per resident is

$$C_L(N, M) = \kappa \frac{M}{N}. \quad (6)$$

This term captures maneuvering, acceleration, and other time associated with making another leg even when stations are geographically close.

**Connecting distance.** If  $M$  waste stations are spread approximately evenly over territory  $A$ , the typical separation between neighboring stations is proportional to  $\sqrt{A/M}$ . With approximately one leg per station, total connecting distance therefore scales with  $\sqrt{AM}$ . This square-root scaling is the classical Euclidean-routing benchmark and underlies continuous-approximation models of vehicle routing (Beardwood et al., 1959; Daganzo, 1984). Actual road layout changes the level of this relationship, so I write

$$D(A, M) = \chi \sqrt{AM}, \quad \chi > 0. \quad (7)$$

Here  $\chi$  is a fixed road-layout factor that converts the geometric spacing benchmark into road distance. Hence the connecting-distance component per resident is

$$C_D(N, M; A) = \psi \frac{D(A, M)}{N} = \psi \chi \frac{\sqrt{AM}}{N}. \quad (8)$$

Let the number of waste stations follow a differentiable adjustment schedule  $M(N; A, g)$ , and define its population elasticity, holding the service territory and waste generation per resident fixed, as

$$\varepsilon_M \equiv \left. \frac{\partial \log M(N; A, g)}{\partial \log N} \right|_{A, g}. \quad (9)$$

Consider a one-percent increase in population, holding the service territory and waste generation per resident fixed. Station count then rises by  $\varepsilon_M$  percent. Using equations (5), (6), and (8), the population

elasticities of the three modeled operating-time components per resident are

$$\frac{d \log C_S}{d \log N} = (\eta - 1)(1 - \varepsilon_M), \quad (10)$$

$$\frac{d \log C_L}{d \log N} = -1 + \varepsilon_M, \quad (11)$$

$$\frac{d \log C_D}{d \log N} = -1 + \frac{1}{2} \varepsilon_M. \quad (12)$$

A one-percent population increase therefore reduces service time per resident by  $(1 - \eta)(1 - \varepsilon_M)$  percent, leg-related time per resident by  $1 - \varepsilon_M$  percent, and distance-related movement time per resident by  $1 - \varepsilon_M/2$  percent. The service-time reduction reflects more users sharing work at each station; the leg-related reduction reflects fewer legs per resident; and the distance-related reduction combines fewer legs per resident with shorter distance per leg.

These channels can be combined to calculate how modeled operating time per resident changes with population density. Let  $C = C_S + C_L + C_D$  denote modeled operating time per resident. Because  $C$  is the sum of the three components, its population elasticity is their component-share-weighted average. Using the elasticities above,

$$-\frac{d \log C}{d \log N} = \frac{C_S}{C}(1 - \eta)(1 - \varepsilon_M) + \frac{C_L}{C}(1 - \varepsilon_M) + \frac{C_D}{C} \left(1 - \frac{\varepsilon_M}{2}\right).$$

Writing  $1 - \varepsilon_M/2 = 1/2 + (1 - \varepsilon_M)/2$  gives

$$-\frac{d \log C}{d \log N} = \frac{C_D}{2C} + (1 - \varepsilon_M) \frac{(1 - \eta)C_S + C_L + C_D/2}{C}. \quad (13)$$

The first term remains if waste-station count rises at the same rate as population: even with unchanged users per station and legs per resident, stations become closer together within a fixed territory. The second term arises when station count rises less than population. More users then share service at each station, fewer legs are required per resident, and connecting distance per resident falls further. Thus, economies of density in multi-stop production depend not only on spatial proximity but also on how the number of service points changes with the number of users.

**Proposition 1 (Three Components)** *Consider an increase in population within a fixed service territory. Suppose  $0 < \eta < 1$ , and station count follows a differentiable adjustment schedule satisfying  $0 < \varepsilon_M < 1$ . Then service time at waste stations, time associated with the number of legs, and time associated with connecting distance all decline per resident.*

### 4.3 Municipal Choice of Waste-Station Count

What determines how waste-station count responds to population density? To characterize this relationship, I model a municipality that balances operating-time requirements against residents' access to waste

stations. Under the uniform-spacing benchmark, let

$$r(M, A) = \zeta \sqrt{\frac{A}{M}}$$

denote representative resident-to-station distance, where  $\zeta > 0$  captures the geometry of station spacing. Write the household-access burden per resident as

$$C_H(M; A) = \omega_r r(M, A)^\theta = \omega \left( \frac{A}{M} \right)^{\theta/2}, \quad \omega_r > 0, \quad \theta \geq 1, \quad (14)$$

where  $\omega = \omega_r \zeta^\theta$ . Suppose the municipality chooses  $M > 0$  to minimize total cost per resident:

$$\min_{M>0} C_S(N, M; g) + C_L(N, M) + C_D(N, M; A) + C_H(M; A). \quad (15)$$

At an interior optimum, the first-order condition with respect to  $\log M$  is

$$(1 - \eta)C_S + C_L + \frac{1}{2}C_D - \frac{\theta}{2}C_H = 0. \quad (16)$$

The condition balances the increase in the three operating-time components from adding stations against the reduction in household access burden.

**Lemma 1 (Optimal Station-Count Adjustment)** *Suppose  $0 < \eta < 1$  and  $\theta \geq 1$ . Within a fixed service territory, the elasticity of the municipality's optimal number of waste stations with respect to population is*

$$\varepsilon_M = \frac{(1 - \eta)^2 C_S + C_L + \frac{1}{2}C_D}{(1 - \eta)^2 C_S + C_L + \frac{1}{4}C_D + \frac{\theta^2}{4}C_H}, \quad (17)$$

where the four components are evaluated at the optimal station count. This elasticity satisfies

$$0 < \varepsilon_M < 1.$$

Equation (17) follows by differentiating the station-count first-order condition with respect to population. Its numerator measures how population growth changes the marginal operating-time cost of another station when station count is held fixed, while its denominator measures how the entire first-order condition changes as station count adjusts. Appendix A.1 gives the derivation and shows that the denominator exceeds the numerator under the lemma's assumptions. Population growth spreads the operating-time requirements created by another station over more residents, so the optimal number of stations rises. It rises less than proportionally because the access gain from further station densification diminishes as stations become more closely spaced, while each additional station continues to create service and per-leg requirements.

## 5 Estimating the Multi-Stop Production Technology

This section estimates the service and movement parameters of the multi-stop production technology introduced in Section 4. The key parameters are the stop-service curvature  $\eta$ , the distance-independent time requirement per leg  $\kappa$ , and the time requirement per road kilometer  $\psi$ .

I first estimate  $\eta$  from waste-station service records and then estimate  $\kappa$  and  $\psi$  from station-to-station movement within truck-days. I then use two sources of temporal variation to assess the resulting decomposition. Recurring three-day and four-day collection intervals change waste accumulation, while winter snow changes travel conditions.

### 5.1 Stop-Service Technology

This subsection estimates the curvature  $\eta$  of the stop-service technology, which measures how service time scales with the quantity assigned to a waste station. I construct the station-service sample from the service events. The sample contains 44,760 observations for 1,388 waste stations over 104 collection dates.

I estimate the following equation:

$$\log S_{srt} = \eta \log P_s + \delta_t + \mu_r + \phi_{d(rt)} + \lambda_{c(rt)} + \nu_{j(s)} + u_{srt}. \quad (18)$$

Here  $S_{srt}$  is total service time for waste station  $s$ , truck  $r$ , and date  $t$ . I construct  $P_s$  by dividing the 2020 census population of a station's census area by the number of waste stations located in that area. Because station-level waste quantities are unavailable, I use this assigned population to measure station load. This requires waste generation per resident not to vary systematically across stations, so  $q_s$  is proportional to  $P_s$ . The coefficient on  $\log P_s$  therefore corresponds to the service-time elasticity  $\eta$ . The remaining terms are collection-date, truck, driver, collection-assistant, and municipality fixed effects.

Table 1 reports the results. Column 1 reports an elasticity of 0.261 with no fixed effects. Adding collection-date and municipality fixed effects in column 2 lowers it to 0.211. Column 3 adds truck, driver, and collection-assistant fixed effects and yields the baseline estimate of 0.204. Because this elasticity is well below one, service time rises much less than proportionally with  $P_s$ : doubling  $P_s$  is associated with only a 15.2-percent increase in service time. In columns 1–3, however, all stations within a census area receive the same value of  $P_s$ , even when residents are unevenly distributed within the area. Column 4 instead uses the 2020 population of the 250-meter census mesh containing each station, divided by the number of stations in that mesh. The estimated elasticity is 0.123 and remains well below one. Both constructions therefore indicate economies of scale in station service.

### 5.2 Movement Technology

This subsection estimates the distance-independent time requirement per leg,  $\kappa$ , and the time requirement per road kilometer,  $\psi$ . To do so, I construct a truck-day–census-area movement sample from the service-sequence data. Each observation corresponds to one census area to which at least one station-to-station leg is assigned during a truck-day. If both endpoint stations lie in the same census area, I assign the leg's

Table 1: Waste-Station Population and Service Time

| Dependent variable:              |           | Log waste-station service time     |                  |                                         |                  |
|----------------------------------|-----------|------------------------------------|------------------|-----------------------------------------|------------------|
| Population construction:         |           | Area population / stations in area |                  | 250m-mesh population / stations in mesh |                  |
| Model:                           |           | (1)                                | (2)              | (3)                                     | (4)              |
| <i>Variables</i>                 |           |                                    |                  |                                         |                  |
| Log population per waste station |           | 0.261<br>(0.028)                   | 0.211<br>(0.026) | 0.204<br>(0.025)                        | 0.123<br>(0.012) |
| <i>Fixed effects</i>             |           |                                    |                  |                                         |                  |
| Collection date                  | No        | Yes                                | Yes              | Yes                                     | Yes              |
| Truck                            | No        | No                                 | Yes              | Yes                                     | Yes              |
| Driver                           | No        | No                                 | Yes              | Yes                                     | Yes              |
| Collection assistant             | No        | No                                 | Yes              | Yes                                     | Yes              |
| Municipality                     | No        | Yes                                | Yes              | Yes                                     | Yes              |
| <i>Sample and fit</i>            |           |                                    |                  |                                         |                  |
| Sample period                    | Sep.–Dec. | Sep.–Dec.                          | Sep.–Dec.        | Sep.–Dec.                               | Sep.–Dec.        |
| Observations                     | 44,760    | 44,760                             | 44,760           | 43,990                                  | 43,990           |
| Waste stations                   | 1,388     | 1,388                              | 1,388            | 1,363                                   | 1,363            |
| $R^2$                            | 0.077     | 0.151                              | 0.169            | 0.165                                   | 0.165            |
| $p(\eta = 1)$                    | < 0.001   | < 0.001                            | < 0.001          | < 0.001                                 | < 0.001          |

Note: The unit is a waste-station-truck-day. Columns 1–3 divide each census area’s 2020 population by the number of waste stations in that area. Column 4 divides the 2020 population of the 250-meter census mesh containing a station by the number of waste stations in that mesh and retains stations in positive-population meshes. Column 1 includes no fixed effects; column 2 includes collection-date and municipality fixed effects; and columns 3 and 4 additionally include truck, driver, and collection-assistant fixed effects. Standard errors are two-way clustered by census area and collection date.

elapsed time, a leg count of one, and its road distance to that area. If a leg crosses a census-area boundary, I assign one-half of each quantity to its origin area and one-half to its destination area. I then sum the allocated elapsed time, leg count, and road distance within each truck-day and census area. I estimate

$$B_{rta} = \kappa L_{rta} + \psi D_{rta} + \alpha_{rt} + u_{rta}. \quad (19)$$

Here  $r$  indexes trucks,  $t$  collection dates, and  $a$  census areas.  $B_{rta}$  is total allocated station-to-station movement time,  $L_{rta}$  is allocated leg count, and  $D_{rta}$  is total allocated road distance in kilometers. Truck-day fixed effects  $\alpha_{rt}$  compare census areas served within the same truck-day and absorb the truck, collection date, and other conditions shared across those observations. The coefficient  $\kappa$  is the additional movement time associated with one more leg, conditional on road distance, and  $\psi$  is the additional movement time associated with one road kilometer, conditional on leg count.

Table 2 reports the estimates. Column 1 includes no fixed effects. Column 2 adds collection-date, truck, driver, and collection-assistant fixed effects. Column 3 replaces these controls with truck-day fixed effects and compares census-area observations within the same realized truck-day. The estimates are stable across specifications: the per-leg coefficient ranges from 63.7 to 65.6 seconds, while the distance coefficient ranges from 59.6 to 67.8 seconds per kilometer.

Column 3 is the preferred specification. The estimate of  $\hat{\kappa} = 63.7$  means that, holding total road distance fixed, one additional leg is associated with 63.7 seconds of additional movement time. The estimate is large relative to realized movement time: 63.7 seconds is about 64 percent of the average 99.9-second leg duration in the same sample. The estimate of  $\hat{\psi} = 67.8$  means that, holding leg count fixed, one additional

Table 2: Legs, Road Distance, and Station-to-Station Movement Time

| Dependent variable:<br>Model: | Station-to-station movement time (seconds) |               |               |
|-------------------------------|--------------------------------------------|---------------|---------------|
|                               | (1)                                        | (2)           | (3)           |
| <i>Variables</i>              |                                            |               |               |
| Leg count                     | 65.6<br>(2.3)                              | 64.6<br>(2.4) | 63.7<br>(2.6) |
| Allocated road distance (km)  | 59.6<br>(4.2)                              | 62.5<br>(4.2) | 67.8<br>(5.0) |
| <i>Fixed effects</i>          |                                            |               |               |
| Collection date               | No                                         | Yes           | No            |
| Truck                         | No                                         | Yes           | No            |
| Driver                        | No                                         | Yes           | No            |
| Collection assistant          | No                                         | Yes           | No            |
| Truck-day                     | No                                         | No            | Yes           |
| <i>Sample and fit</i>         |                                            |               |               |
| Observations                  | 14,274                                     | 14,274        | 14,273        |
| Truck-days                    | 553                                        | 553           | 552           |
| Station-to-station legs       | 43,126                                     | 43,126        | 43,125        |
| Recurring station sequences   | 60                                         | 60            | 59            |
| Collection dates              | 104                                        | 104           | 104           |
| $R^2$                         | 0.745                                      | 0.753         | 0.769         |

Note: The unit is a truck-day-census-area observation, and the dependent variable is total station-to-station movement time in seconds. Movement time excludes inter-service intervals that contain a facility weigh-in or last more than 45 minutes. A boundary-crossing leg is divided equally between its endpoint areas. Road distance is direction specific and measured in kilometers. Column 1 has no fixed effects; column 2 includes collection-date, truck, driver, and collection-assistant fixed effects; and column 3 includes truck-day fixed effects. Standard errors are two-way clustered by census area and truck-day.

road kilometer is associated with 67.8 seconds of additional movement time. The parameter  $\kappa$  captures the distance-independent time associated with making another movement between stations: dividing a given total distance into more legs raises movement time. By contrast, reducing a leg’s geographic distance lowers the distance-related component governed by  $\psi$ .

A concern is that  $\kappa$  captures unobserved road conditions that vary systematically with population density rather than a distance-independent per-leg requirement. To address this concern, Appendix Table F.1 divides the sample into census areas with population density above and below the median and estimates the movement equation separately for the two groups. The estimated per-leg requirement is 71.4 seconds in lower-density areas and 58.5 seconds in higher-density areas. The two estimates are statistically different ( $p = 0.015$ ) but quantitatively similar: both are approximately one minute per leg, are precisely estimated, and lie near the pooled estimate of 63.7 seconds. The positive estimate of  $\kappa$  therefore does not arise primarily from unobserved differences between higher- and lower-density areas, supporting a distance-independent time requirement associated with making a leg.

### 5.3 Schedule-Based Validation of the Service–Movement Decomposition

The estimates of  $\eta$ ,  $\kappa$ , and  $\psi$  above rely primarily on cross-sectional variation. I next exploit temporal variation to assess whether they capture the intended production margins. The idea is that the recurring collection schedule changes the quantity of waste handled at a station but should not change the per-leg or per-kilometer movement requirements. This contrast provides a complementary check of the production

margins.

Waste stations are normally served twice each week on one of three fixed weekday pairs. The early-week collection follows four days of waste accumulation, whereas the late-week collection follows three. More waste should therefore have accumulated at a given station before the four-day collection, increasing its service time.

Panel A of Table 3 compares log service time after exact four- and three-day intervals for the same waste station in the same collection week. Waste-station-week fixed effects hold constant the station and its weekly service cycle, while truck, driver, and collection-assistant fixed effects absorb persistent differences across vehicles and crews. Column 2 additionally controls for daily precipitation, mean temperature, new snowfall, snow depth, and holidays.

Panel B re-estimates equation (19) using the movement sample, adding interactions between the early-week (four-day) schedule position and leg count and road distance. The specification includes truck-day and census-area fixed effects.

Panel A shows that service time is 15.5 percent higher after a four-day interval than after a three-day interval. The estimate remains 14.1 percent after adding weather and holiday controls. In Panel B, the per-leg requirement is 67.1 seconds in the late-week (three-day) schedule position, and its interaction with the early-week (four-day) position is -0.5 seconds ( $p = 0.748$ ). The corresponding road-distance requirement is 53.5 seconds per kilometer, with an interaction of 1.4 seconds per kilometer ( $p = 0.774$ ). A joint test does not reject that both interactions are zero ( $p = 0.945$ ). Taken together, these patterns provide qualitative support for the distinction between service and movement requirements.

Table 3: Collection Intervals, Waste-Station Service, and Movement Requirements

| <i>Panel A. Waste-station service time</i> |                                |                         |
|--------------------------------------------|--------------------------------|-------------------------|
| Dependent variable:                        | Log waste-station service time |                         |
| Model:                                     | (1)                            | (2)                     |
| Four-day collection interval               | 0.144<br>(0.008)               | 0.132<br>(0.009)        |
| Waste station $\times$ week fixed effects  | Yes                            | Yes                     |
| Truck and crew fixed effects               | Yes                            | Yes                     |
| Weather and holiday controls               | No                             | Yes                     |
| Unit of observation                        | Waste-station-truck-day        | Waste-station-truck-day |
| Observations                               | 37,344                         | 36,776                  |
| Waste stations                             | 1,316                          | 1,316                   |
| Collection dates                           | 96                             | 94                      |
| $R^2$                                      | 0.858                          | 0.858                   |

| <i>Panel B. Station-to-station movement technology by schedule position</i> |                                            |
|-----------------------------------------------------------------------------|--------------------------------------------|
| Dependent variable:                                                         | Station-to-station movement time (seconds) |
| Model:                                                                      | (3)                                        |
| Leg count                                                                   | 67.1<br>(5.4)                              |
| Four-day schedule position $\times$ leg count                               | -0.5<br>(1.7)                              |
| Road distance (km)                                                          | 53.5<br>(7.1)                              |
| Four-day schedule position $\times$ road distance                           | 1.4<br>(5.0)                               |
| Truck-day fixed effects                                                     | Yes                                        |
| Census-area fixed effects                                                   | Yes                                        |
| Unit of observation                                                         | Truck-day $\times$ census area             |
| Joint test of interaction terms, $p$ -value                                 | 0.945                                      |
| Observations                                                                | 14,272                                     |
| Truck-days                                                                  | 552                                        |
| Census areas                                                                | 387                                        |
| Collection dates                                                            | 104                                        |

Note: Panel A compares exact four- and three-day collection intervals for the same waste station within the same week. All specifications include waste-station-week, truck, driver, and collection-assistant fixed effects; column 2 additionally controls for daily precipitation, mean temperature, new snowfall, snow depth, and holidays. Panel B uses the movement sample and interacts leg count and road distance with the early-week (four-day) schedule position. The uninteracted coefficients correspond to the late-week (three-day) schedule position. Panel B includes truck-day and census-area fixed effects. Movement time excludes inter-service intervals that contain a facility weigh-in or last more than 45 minutes. Standard errors are two-way clustered by waste station and collection date in Panel A and by census area and truck-day in Panel B.

## 5.4 Validation Using Winter Snow

The schedule-based exercise changes the quantity of waste accumulated at a station while leaving movement conditions largely unchanged. Winter snow provides a complementary source of temporal variation. If standing snow primarily slows travel over road distance, the coefficient on road distance should increase, while the distance-independent coefficient on leg count need not change. The elasticity of station-service time with respect to station load should also remain broadly stable if snow does not materially change how service time scales with the amount collected.

For this exercise, I extend the service events and station-to-station legs through June 2026, constructing them from the GPS records with the same definitions, and merge each collection date with standing snow depth recorded at the Japan Meteorological Agency station in Morioka. I use two measures: daily mean standing snow depth, calculated from the 24 hourly observations associated with each collection date, and an indicator for standing snow depth at 08:00 of at least 10 centimeters. The 08:00 observation is close to the beginning of collection.<sup>5</sup> The extended samples cover 250 collection dates, including 18 dates above the 10-centimeter morning threshold.

For station service, I add the interaction between each snow measure and  $\log P_s$  to equation (18). Collection-date fixed effects absorb the level of the snow measure, so the interaction coefficient shows how the station-service elasticity differs with standing snow. It does not identify the average change in station-service time on snowy dates.

Table 4 reports the results. The estimate without a snow interaction is 0.211, close to the main estimate of 0.204. An additional 10 centimeters of daily mean standing snow depth lowers the elasticity by 0.0075. When standing snow depth at 08:00 is at least 10 centimeters, the elasticity is lower by 0.0201, from 0.213 to 0.193. Thus, the station-service elasticity changes only modestly and remains well below one under substantial snow. The negative interactions do not imply that station-service time itself is lower on snowy dates, because collection-date fixed effects absorb the average daily effect of snow.

For movement, I add interactions of each snow measure with leg count and road distance to equation (19). The specification includes truck-day and census-area fixed effects and allows centered daily temperature and precipitation to affect both the leg-count and road-distance coefficients. Truck-day fixed effects absorb the level of the snow measure. Standard errors are two-way clustered by census area and collection date.

Table 5 reports the movement estimates. For an additional 10 centimeters of daily mean standing snow depth, the interaction with leg count is -1.84 seconds per leg, while the interaction with road distance is 29.83 seconds per kilometer. When standing snow depth at 08:00 is at least 10 centimeters, the corresponding estimates are -3.13 seconds per leg and 51.14 seconds per kilometer. The leg-count interactions are not statistically distinguishable from zero, whereas both road-distance interactions are positive and precisely estimated. At the sample average of 0.474 kilometers per leg, the estimates imply 12.3 and 21.1 additional seconds, respectively, for a leg of that distance.<sup>6</sup>

<sup>5</sup> Across 1,217 truck-days in the extended records, the median first service begins at 08:11, and 96.8 percent begin by 08:30.

<sup>6</sup> In a direct extension of equation (19) without census-area fixed effects or temperature and precipitation interactions, the leg-count interactions are -4.82 seconds and -8.16 seconds, while the corresponding road-distance interactions are 43.71 seconds per kilometer and 77.57 seconds per kilometer. Thus, the leg-count interaction is sensitive to the specification, whereas the

Table 4: Standing Snow Depth and the Station-Service Elasticity

| Dependent variable:<br>Model:                                    | Log waste-station service time |                     |                               |
|------------------------------------------------------------------|--------------------------------|---------------------|-------------------------------|
|                                                                  | (1)                            | (2)                 | (3)                           |
| Snow measure:                                                    | None                           | Daily mean          | 08:00 depth<br>at least 10 cm |
| <i>Variables</i>                                                 |                                |                     |                               |
| Log assigned population                                          | 0.211<br>(0.026)               | 0.213<br>(0.027)    | 0.213<br>(0.027)              |
| Daily mean snow depth $\times$ log assigned population           |                                | -0.0075<br>(0.0035) |                               |
| 08:00 snow depth at least 10 cm $\times$ log assigned population |                                |                     | -0.0201<br>(0.0055)           |
| <i>Fixed effects</i>                                             |                                |                     |                               |
| Collection date                                                  | Yes                            | Yes                 | Yes                           |
| Truck                                                            | Yes                            | Yes                 | Yes                           |
| Driver                                                           | Yes                            | Yes                 | Yes                           |
| Collection assistant                                             | Yes                            | Yes                 | Yes                           |
| Municipality                                                     | Yes                            | Yes                 | Yes                           |
| <i>Sample and fit</i>                                            |                                |                     |                               |
| Sample period                                                    | Sep.–Jun.                      | Sep.–Jun.           | Sep.–Jun.                     |
| Observations                                                     | 99,406                         | 99,406              | 99,406                        |
| Waste stations                                                   | 1,407                          | 1,407               | 1,407                         |
| Census areas                                                     | 389                            | 389                 | 389                           |
| Collection dates                                                 | 250                            | 250                 | 250                           |
| $R^2$                                                            | 0.152                          | 0.152               | 0.152                         |

Note: The unit is a waste-station-truck-day. Column 1 includes no snow interaction. Column 2 interacts log assigned population with daily mean standing snow depth; the reported coefficient is scaled to a 10-centimeter increase. Column 3 interacts log assigned population with an indicator for standing snow depth at 08:00 of at least 10 centimeters. The level of each snow measure is absorbed by collection-date fixed effects. Standard errors are two-way clustered by census area and collection date.

Table 5: Standing Snow Depth and Station-to-Station Movement Time

| Dependent variable:<br>Model:                          | Station-to-station movement time (seconds) |                 |                               |
|--------------------------------------------------------|--------------------------------------------|-----------------|-------------------------------|
|                                                        | (1)                                        | (2)             | (3)                           |
| Snow measure:                                          | None                                       | Daily mean      | 08:00 depth<br>at least 10 cm |
| <i>Variables</i>                                       |                                            |                 |                               |
| Leg count                                              | 67.54<br>(3.80)                            | 66.48<br>(3.85) | 66.86<br>(3.83)               |
| Road distance (km)                                     | 15.21<br>(6.17)                            | 15.58<br>(6.15) | 15.57<br>(6.12)               |
| Daily mean snow depth $\times$ leg count               |                                            | -1.84<br>(1.82) |                               |
| Daily mean snow depth $\times$ road distance           |                                            | 29.83<br>(5.64) |                               |
| 08:00 snow depth at least 10 cm $\times$ leg count     |                                            |                 | -3.13<br>(3.28)               |
| 08:00 snow depth at least 10 cm $\times$ road distance |                                            |                 | 51.14<br>(9.20)               |
| <i>Fixed effects and controls</i>                      |                                            |                 |                               |
| Truck-day fixed effects                                | Yes                                        | Yes             | Yes                           |
| Census-area fixed effects                              | Yes                                        | Yes             | Yes                           |
| Temperature and precipitation interactions             | Yes                                        | Yes             | Yes                           |
| <i>Sample and fit</i>                                  |                                            |                 |                               |
| Sample period                                          | Sep.–Jun.                                  | Sep.–Jun.       | Sep.–Jun.                     |
| Observations                                           | 32,290                                     | 32,290          | 32,290                        |
| Truck-days                                             | 1,216                                      | 1,216           | 1,216                         |
| Census areas                                           | 387                                        | 387             | 387                           |
| Collection dates                                       | 250                                        | 250             | 250                           |
| $R^2$                                                  | 0.848                                      | 0.851           | 0.850                         |

Note: The unit is a truck-day–census-area observation, and the dependent variable is total station-to-station movement time in seconds. A boundary-crossing leg is divided equally between its endpoint areas. Column 1 includes no snow interaction. Column 2 interacts leg count and road distance with daily mean standing snow depth; the reported interaction coefficients are scaled to a 10-centimeter increase. Column 3 uses an indicator for standing snow depth at 08:00 of at least 10 centimeters. Temperature and precipitation are centered; their interactions with leg count and road distance are included but not displayed. Standard errors are two-way clustered by census area and collection date. One singleton observation is removed by the census-area fixed effects.

These results are consistent with standing snow primarily increasing the time required to cover road distance, without materially changing the distance-independent time associated with making a leg. The station-service elasticity also remains broadly similar. Together with the schedule-based results, these findings support separating station service, leg count, and road distance in the multi-stop production technology. Appendix Tables D.1 and D.2 repeat both exercises using only collection dates from December through April and produce similar estimates. The snow measures come from one weather station, and the morning-threshold estimates rely on 18 collection dates, so I interpret the results as a validation of the production decomposition rather than as a separate causal study of snow.

## 6 Economies of Density and Their Sources

Having estimated the multi-stop production technology, I now examine the predictions of Proposition 1. I first ask whether weekly service-and-movement requirements and their components increase less than proportionally with population across census areas, conditional on land area. I then combine the area-week elasticities with the estimated movement parameters to quantify how service at waste stations, the number of legs, and connecting distance contribute to the overall economy of density. Finally, I estimate how the number of waste stations scales with population, a key determinant of the strength of these economies.

### 6.1 Area-Week Evidence

As in Subsection 5.2, I construct the census-area-week data from the service-sequence data by summing station-service time, station-to-station movement time, leg count, and road distance over all trucks and collection days for each census area and week.

I estimate each weekly operating measure as a function of population, conditional on land area:<sup>7</sup>

$$\log Y_{aw} = \beta_N^Y \log N_a + \beta_A^Y \log A_a + \gamma_w^Y + \mu_{j(a)}^Y + e_{aw}^Y, \quad Y \in \{T, S, B, L, D\}. \quad (20)$$

Here  $a$  indexes census areas and  $w$  indexes collection weeks. Measured service-and-movement time is  $T = S + B$ , where  $S$  is service time at waste stations and  $B$  is station-to-station movement time summed over the legs in an area-week;  $L$  is the number of those legs and  $D$  is their total directed road distance. The main specifications use the same 5,534 census-area weeks with positive, nonmissing values for all five outcomes. Because population and land area do not change during the observation period,  $\beta_N^Y$  is identified from variation across census areas. Repeated weekly observations measure recurring operating requirements and allow collection-week fixed effects to absorb common temporal conditions. Municipality fixed effects absorb differences in service organization across municipalities, and standard errors are clustered by census area. These estimates are conditional associations and need not represent causal effects of density.

Conditional on land area,  $\beta_N^Y$  is the population elasticity of the weekly total. Because  $\log(Y_{aw}/N_a) =$

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road-distance interaction remains large and positive.

<sup>7</sup>Regressing the measure per resident directly on population density would place  $\log N_a$  with opposite signs in  $\log(Y_{aw}/N_a)$  and  $\log(N_a/A_a)$ . Estimating the weekly total avoids this mechanical relationship; the per-resident elasticity is recovered after estimation.

$\log Y_{aw} - \log N_a$ , dividing a total by population subtracts one from this elasticity. Thus,  $\beta_N^Y - 1$  is the corresponding elasticity per resident. Proposition 1 and equations (10)–(12) imply negative per-resident elasticities and hence  $\beta_N^Y < 1$  for service time, leg count, and road distance.

Table 6 reports the regression results, with one outcome in each column. Column 1 uses measured service-and-movement time. Its log-population coefficient is 0.453, so holding land area constant, service-and-movement time rises by 0.453 percent when population rises by one percent. Service-and-movement time per resident therefore falls by 0.547 percent. Equivalently, a 10-percent larger population within a fixed land area is associated with about 5 percent less service-and-movement time per resident.

Columns 2 and 3 split this measure into station service and station-to-station movement time. Their population elasticities are 0.577 and 0.366, implying declines per resident of 0.423 percent for service time and 0.634 percent for movement time. Columns 4 and 5 display the corresponding physical movement quantities. Leg count has a population elasticity of 0.480, while road distance has an elasticity of 0.173. Per resident, leg count therefore falls by 0.520 percent and road distance by 0.827 percent. The null hypothesis that the population elasticity equals one is rejected in all five columns. The estimates therefore show substantial economies of density in both work at waste stations and movement between them.<sup>8</sup>

Table 6: Population Elasticities of Census-Area-Week Operating Requirements

| Dependent variable:            | Service-and-movement time | Service time at waste stations | Station-to-station movement time | Station-to-station legs | Station-to-station road distance |
|--------------------------------|---------------------------|--------------------------------|----------------------------------|-------------------------|----------------------------------|
| Model:                         | (1)                       | (2)                            | (3)                              | (4)                     | (5)                              |
| Estimator:                     | OLS                       | OLS                            | OLS                              | OLS                     | OLS                              |
| <i>Variables</i>               |                           |                                |                                  |                         |                                  |
| Log population                 | 0.453<br>(0.028)          | 0.577<br>(0.029)               | 0.366<br>(0.029)                 | 0.480<br>(0.032)        | 0.173<br>(0.027)                 |
| Log land area                  | 0.083<br>(0.024)          | -0.028<br>(0.028)              | 0.191<br>(0.024)                 | 0.066<br>(0.024)        | 0.377<br>(0.025)                 |
| <i>Fixed effects</i>           |                           |                                |                                  |                         |                                  |
| Collection week                | Yes                       | Yes                            | Yes                              | Yes                     | Yes                              |
| Municipality                   | Yes                       | Yes                            | Yes                              | Yes                     | Yes                              |
| <i>Sample and fit</i>          |                           |                                |                                  |                         |                                  |
| Observations                   | 5,534                     | 5,534                          | 5,534                            | 5,534                   | 5,534                            |
| Census areas                   | 385                       | 385                            | 385                              | 385                     | 385                              |
| Collection weeks               | 17                        | 17                             | 17                               | 17                      | 17                               |
| Adjusted $R^2$                 | 0.567                     | 0.651                          | 0.434                            | 0.543                   | 0.472                            |
| <i>Per-resident elasticity</i> |                           |                                |                                  |                         |                                  |
| $\hat{\beta}_N - 1$            | -0.547                    | -0.423                         | -0.634                           | -0.520                  | -0.827                           |
| $p$ -value: $\beta_N = 1$      | < 0.001                   | < 0.001                        | < 0.001                          | < 0.001                 | < 0.001                          |

Note: Each column estimates equation (20) on the same 5,534 census-area weeks with positive, nonmissing values for all five outcomes. The movement outcomes exclude inter-service intervals that contain a facility weigh-in or last more than 45 minutes. Road distance is direction specific. Standard errors, clustered by census area, are reported in parentheses. All specifications include collection-week and municipality fixed effects. The bottom panel reports the post-estimation elasticity of the operating requirement per resident,  $\hat{\beta}_N^Y - 1$ , holding land area constant.

One concern is that demographic and housing composition may vary systematically with density and

<sup>8</sup>I assess robustness to the treatment of boundary-crossing legs by re-estimating the movement specifications after assigning each such leg entirely to its origin area, destination area, or midpoint area. Appendix Tables E.3–E.5 report similar results under all three alternatives.

may also affect waste generation and collection conditions. Appendix Table E.2 controls for the share of residents age 65 or older and the share of households living in apartments. It also reports estimates using inhabited land area instead of the total area of each census area. The estimated population elasticities remain below one for all outcomes.

Appendix E.1 reconstructs the outcomes at the truck-day–census-area level and includes truck-day fixed effects. The estimates therefore compare census areas served within the same truck-day, absorbing differences across truck-days in vehicles, crews, collection dates, and other conditions common to the truck-day. The resulting population elasticities are somewhat smaller than the area-week estimates and remain below one. Population still varies across census areas, so fixed differences across areas are not absorbed.

## 6.2 Component Accounting for Economies of Density

Table 6 establishes economies of density: holding land area fixed, station-service time, leg count, and road distance per resident all decrease as population rises. These elasticities alone do not reveal how much each margin contributes to the resulting decline in service-and-movement time per resident: the margins differ in their baseline magnitudes, and leg count and road distance are not measured in units of time.

To express all three margins in minutes, I use the movement-time estimates in Table 2. I multiply the estimated seconds per leg and seconds per road kilometer by baseline leg count and road distance, respectively, and use their relative magnitudes to allocate observed movement time between time associated with leg count and time associated with road distance. This allocation preserves total observed movement time. I then combine the baseline minutes for station service, time associated with leg count, and time associated with road distance with each component’s estimated reduction per resident following a one-percent increase in density. Table 7 reports each component’s share of the resulting time saving.<sup>9</sup>

Table 7: Component Accounting for Economies of Density

| Component               | Share of time saving (%) |
|-------------------------|--------------------------|
| Station service         | 41.7                     |
| Station-to-station legs | 32.3                     |
| Road distance           | 26.0                     |
| Total                   | 100.0                    |

Note: The table reports each component’s share of the time saving associated with a one-percent increase in population density, holding land area fixed. The calculation combines baseline time with the per-resident elasticities in Table 6; movement time is divided between leg count and road distance using the coefficients in Table 2. Shares sum to 100 percent.

The decomposition shows that the time saving associated with higher density arises primarily through lower station-service time per resident (41.7 percent), followed by fewer station-to-station legs per resident (32.3 percent). In the model, equation (13) shows that both effects arise when waste-station count grows less than population, so that more residents share each station. Together, these two margins account for

<sup>9</sup>Appendix G explains the decomposition in detail, including the construction of baseline component minutes, the elasticities used, and the calculation underlying Table 7.

74.0 percent of the time saving, highlighting the importance of shared waste stations for economies of density.

### 6.3 Population and the Number of Waste Stations

The model implies that the reduction in the sum of these three time components per resident associated with higher density depends on how the number of waste stations changes with population. I estimate  $\varepsilon_M$  by comparing waste-station count with population across 2020 census areas. I count waste stations in each census area and merge the counts with census population and land area. The estimation sample contains 390 positive-population areas with at least one station and covers 1,416 stations. I estimate

$$\log M_a = \alpha_M + \varepsilon_M \log N_a + \beta_M \log A_a + \mu_{j(a)}^M + \xi_a. \quad (21)$$

Conditional on land area,  $\varepsilon_M$  measures how waste-station count scales with population across census areas. Municipality fixed effects absorb differences in service organization across the three municipalities.

Table 8: Population and the Number of Waste Stations

|                       |                              |                         |
|-----------------------|------------------------------|-------------------------|
| Dependent variable:   | Log number of waste stations |                         |
| Model:                | (1)                          | (2)                     |
| Estimator:            | OLS                          | OLS                     |
| <i>Variables</i>      |                              |                         |
| Log population        | 0.508<br>(0.029)             | 0.504<br>(0.030)        |
| Log land area         | 0.043<br>(0.019)             | 0.042<br>(0.021)        |
| <i>Fixed effects</i>  |                              |                         |
| Municipality          | No                           | Yes                     |
| <i>Sample and fit</i> |                              |                         |
| Geography             | 2020 census subdistrict      | 2020 census subdistrict |
| Land-area control     | Yes                          | Yes                     |
| Observations          | 390                          | 390                     |
| Stations              | 1,416                        | 1,416                   |
| Adjusted $R^2$        | 0.630                        | 0.629                   |

Note: The unit is a 2020 census area with positive population and at least one waste station listed in the cooperative's register of waste stations. Both columns regress log station count on log population and log land area. Column 2 includes municipality fixed effects. Heteroskedasticity-robust standard errors are in parentheses.

Table 8 reports the results. The preferred specification in column 2 yields  $\hat{\varepsilon}_M = 0.504$ : across the included areas and conditional on land area, a one-percent larger population is associated with 0.504 percent more waste stations. Waste-station count thus rises only about half as much as population, so residents per station increase with population.

Equation (13) directly gives the percentage reduction in  $C = C_S + C_L + C_D$  per resident associated with a one-percent increase in population density, holding land area fixed. Substituting the underlying estimates, reported here after rounding as  $\hat{\eta} = 0.204$ ,  $\hat{\varepsilon}_M = 0.504$ ,  $C_S = 42.12$ ,  $C_L = 26.64$ ,  $C_D = 13.45$ ,

and  $C = 82.22$  weekly minutes per 1,000 residents, gives

$$\begin{aligned} -\frac{d \log C}{d \log N} &= \frac{13.45}{2(82.22)} + (1 - 0.504) \frac{(1 - 0.204)42.12 + 26.64 + 13.45/2}{82.22} \\ &= 0.082 + 0.403 = 0.485. \end{aligned}$$

The first term, 0.082, is the contribution of distance-related time to the reduction in  $C$  that would remain if waste-station count increased at the same rate as population. The second term, 0.403, is the additional reduction because station count increases by only 0.504 percent when population increases by one percent: more residents share each station, fewer legs are required per resident, and road distance per resident falls further. Together, the two terms imply that a one-percent increase in population density reduces the sum of the three time components per resident by 0.485 percent.

If waste-station count increased by one percent when population increased by one percent, setting  $\varepsilon_M = 1$  in equation (13) would eliminate the second term, leaving a 0.082-percent reduction. The second term therefore accounts for 83.1 percent of the 0.485-percent reduction.

## 7 Quantitative Application: Population Decline and Station Adjustment

I use the estimated production technology and station-count relationship to examine how changes in the spatial distribution of population affect total operating time per resident. I consider three scenarios that hold the aggregate population loss fixed but vary where it occurs: uniform decline, decline concentrated in low-density areas, and decline concentrated in high-density areas. The latter two make the remaining population more spatially concentrated and more dispersed, respectively. For each scenario, I calculate this outcome first with all waste stations retained and then allowing their number to adjust. I subsequently report the associated changes in physical access.

### 7.1 Counterfactual Design

All three scenarios reduce aggregate population by five percent. Under uniform decline, every census area's population falls by five percent. For the sparse-area scenario, I rank census areas by baseline population density and reduce population by 20 percent, starting with the least dense areas, until the aggregate loss reaches five percent. If reducing the last affected area by the full 20 percent would exceed this target, I apply only the smaller reduction needed in that area. The dense-area scenario applies the same procedure starting with the densest areas. The two scenarios therefore differ only in whether population loss makes the remaining population more concentrated or more dispersed.

Total operating time has already been separated into service at waste stations, time associated with the number of station-to-station legs, time associated with their road distance, disposal trip and facility activity, and other intervals. The counterfactual holds the last two components fixed and changes the first three as follows.

**Waste stations fixed.** Every observed station remains in service. The assigned population of each station in area  $a$  becomes  $P_s^1 = N_a^1/M_a^0$ . I calculate counterfactual service time as  $S_{srt}^1 = S_{srt}^0(P_s^1/P_s^0)^{\hat{\eta}}$ . Because the stations and their observed collection sequence do not change, leg count and road distance remain at their baseline values. Thus, only station service time changes in this case.

**Waste-station count adjusts.** Let  $N_a^0$  and  $M_a^0$  denote observed population and station count in area  $a$ , and let  $N_a^1$  denote population under the counterfactual scenario. The number of stations adjusts according to

$$M_a^1 = M_a^0 \left( \frac{N_a^1}{N_a^0} \right)^{\hat{\varepsilon}_M}. \quad (22)$$

Because  $\hat{\varepsilon}_M < 1$ , station count falls less than population. Users per station therefore decline, weakening the service- and leg-sharing economies described by the model.

Equation (22) determines the target number of stations in each census area. I round  $M_a^1$  to an integer, set the assigned population of every surviving station in area  $a$  to  $N_a^1/M_a^1$ , and recalculate service time. This is the same equal-allocation approximation used to construct  $P_s$  in the service estimation.

Because realized routes vary across days, I apply each set of station closures to every observed truck-day sequence. For each of the 553 truck-days spanning 104 collection dates, I remove closed stations from the observed station sequence, preserve the order of the surviving stations, and recompute the number and directed road distance of the resulting legs. Surviving stations are connected only within a run of consecutive station-to-station legs, so no new leg spans a disposal trip or an other interval. I calculate counterfactual movement time as  $B^1 = B^0 + \hat{\kappa}(L^1 - L^0) + \hat{\psi}(D^1 - D^0)$ , where  $B^0$  is observed baseline movement time. The operating-time results use the 447 truck-days for which service, movement, and facility time can all be measured. The area-specific station counts determine how many stations close but not which stations close. I therefore draw 100 sets of closed stations and report the median result. Holding the parameters at their estimates, I also report the 5th and 95th percentiles across these sets to show how the result varies with which stations close. The key parameters in the simulation— $\eta$ ,  $\varepsilon_M$ ,  $\kappa$ , and  $\psi$ —are themselves estimated. I therefore construct confidence intervals that account for uncertainty in these parameter estimates. Appendix H.1 describes the simulation algorithm, and Appendix H.2 explains how the confidence intervals are constructed.

## 7.2 Operating-Time Effects

Table 9 reports this decomposition. Panel A holds the number of waste stations fixed, while Panel B allows it to adjust according to  $\hat{\varepsilon}_M$ . In Panel A, aggregate time associated with leg count and road distance does not change, nor does time in disposal trip and facility activity and other intervals. Their per-resident values nevertheless rise because the same aggregate time is divided by a population that is five percent smaller. This denominator effect explains the positive entries for these components even though their aggregate quantities are fixed. Service time also rises per resident because it falls less than proportionally with population. Total operating time per resident consequently rises by 4.88 percent under uniform decline, 4.78 percent under sparse-area decline, and 4.94 percent under dense-area decline.

Allowing station count to adjust lowers these increases to 3.50, 2.79, and 3.82 percent, respectively. The reduction relative to the fixed-station case is largest under sparse-area decline: 1.99 percentage points, compared with 1.38 points under uniform decline and 1.12 points under dense-area decline. In each targeted scenario, the affected areas have a combined baseline population of about 26,100, which then falls by 20 percent. That population is served by roughly 463 stations in the sparse-area group but only 268 stations in the dense-area group—about one station per 56 versus 97 residents. With  $\hat{\varepsilon}_M = 0.504$ , a 20-percent population loss reduces station count by about 10.6 percent, so the simulation closes 49 stations under sparse-area decline but only 29 under dense-area decline. Closing more stations saves time through two direct channels. First, the post-decline population is served at fewer stops. Because service time rises much less than proportionally with station load, the additional service time at the surviving stations is smaller than the time eliminated at the closed stations. Second, removing a closed station from a route replaces the legs into and out of it with a direct leg between the neighboring surviving stations, reducing both leg count and road distance. Disposal trip and facility activity and other intervals are held fixed and make the same 1.71-percentage-point contribution in every scenario.

Table 9: Effects on Total Operating Time of a Five-Percent Population Decline, by Component

|                                                                      | Uniform decline | Sparse-area decline | Dense-area decline |
|----------------------------------------------------------------------|-----------------|---------------------|--------------------|
| <i>Panel A. Number of waste stations fixed</i>                       |                 |                     |                    |
| Service at waste stations                                            | 1.45            | 1.35                | 1.51               |
| Time associated with leg count                                       | 1.15            | 1.15                | 1.15               |
| Time associated with road distance                                   | 0.57            | 0.57                | 0.57               |
| Disposal trip and facility activity and other intervals (held fixed) | 1.71            | 1.71                | 1.71               |
| <b>Total operating time</b>                                          | <b>4.88</b>     | <b>4.78</b>         | <b>4.94</b>        |
| Uncertainty in parameter estimates (95% confidence interval)         | [4.79, 4.98]    | [4.67, 4.89]        | [4.86, 5.03]       |
| <i>Panel B. Number of waste stations adjusts</i>                     |                 |                     |                    |
| Service at waste stations                                            | 0.72            | 0.39                | 0.91               |
| Time associated with leg count                                       | 0.58            | 0.35                | 0.70               |
| Time associated with road distance                                   | 0.49            | 0.33                | 0.50               |
| Disposal trip and facility activity and other intervals (held fixed) | 1.71            | 1.71                | 1.71               |
| <b>Total operating time</b>                                          | <b>3.50</b>     | <b>2.79</b>         | <b>3.82</b>        |
| Uncertainty in parameter estimates (95% confidence interval)         | [3.32, 3.69]    | [2.55, 3.05]        | [3.70, 3.97]       |
| Variation in which stations close (5th–95th percentiles)             | [3.45, 3.57]    | [2.69, 2.86]        | [3.77, 3.88]       |

Note: Component entries are percentage-point contributions to the percentage change in total operating time per resident relative to the observed baseline. For component  $j$ , the entry is  $100(C_j^1 - C_j^0)/T^0$ , where  $C_j^0$  and  $C_j^1$  are baseline and counterfactual minutes per 1,000 residents per six-day operating week and  $T^0$  is baseline total operating time in the same unit. The rows add to the reported total before rounding. Time associated with leg count, time associated with road distance, disposal trip and facility activity, and other intervals are fixed in aggregate levels in Panel A; their per-resident values rise because population falls by five percent. The two reported ranges are calculated separately. Rows labeled “Uncertainty in parameter estimates” are 95% confidence intervals for parameter estimation error. Panel A has this interval because its service-time calculation depends on  $\eta$  even though no stations close. In Panel B, each parameter draw is summarized by the median across 100 sets of closed stations. The row labeled “Variation in which stations close” instead holds all parameters at their estimates and reports the 5th and 95th percentiles across the 100 sets. It appears only in Panel B because Panel A has no station closures. The observed baseline quantities are held fixed across parameter draws.

### 7.3 Physical Access Effects

Station consolidation lowers total operating time but can lengthen the distance to a surviving waste station, thereby increasing the household cost of bringing waste to a station. Household coordinates and actual station assignments are unavailable, so I approximate residents as uniformly distributed within each 2020 census area. I cover each census area with points spaced 100 meters apart and distribute the area's population equally across these points.<sup>10</sup>

For each point on the 100-meter lattice, I identify the nearest observed waste station in the same municipality. If that station closes, I assign the residents represented by the point to the surviving station closest to the closed station within the same municipality and collection-schedule group. For each population scenario  $s$ , I calculate the population-weighted average distance from the lattice points to their assigned stations,  $r_s = \sum_i w_{is} d_{is} / \sum_i w_{is}$ , where  $d_{is}$  is the straight-line distance from lattice point  $i$  to its assigned station and  $w_{is} = N_{a(i)}^s / n_{a(i)}$  is the population represented by that point. Here,  $a(i)$  denotes the census area containing point  $i$ ,  $N_{a(i)}^s$  is that area's population under scenario  $s$ , and  $n_{a(i)}$  is the number of lattice points in the area.

Table 10 separates two sources of change in representative distance. With station count fixed, the change reflects only the geographic composition of population decline. Comparing the station-adjustment outcome with that fixed-station benchmark adds the physical effect of closure and reassignment. The baseline mean is 162.2 meters. With station count fixed, the means are 162.2, 152.1, and 167.6 meters under uniform, sparse-area, and dense-area decline; with station count adjusting, they are 163.7, 157.6, and 168.9 meters. The closure-induced increases are therefore 0.92, 3.65, and 0.74 percent. The baseline stations that close account for 2.53, 2.41, and 2.29 percent of the scenario population weight, respectively. Operating-time savings from station adjustment are largest in sparse areas, but closure also causes the largest proportional increase in physical station access distance there. Even after this increase, however, representative distance under sparse-area decline remains 2.8 percent below the baseline. The population loss in this scenario is concentrated in locations whose baseline station distance averages 354.7 meters, more than twice the overall mean. Reducing the population weight placed on these initially distant locations lowers the fixed-station mean to 152.1 meters. Station closures partly offset this composition effect by raising the mean to 157.6 meters, but do not eliminate it. Sparse-area decline can therefore improve average household access distance even though closure itself worsens access for the affected locations. These distances describe geographic coverage rather than household welfare.

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<sup>10</sup> Appendix H.3 repeats the complete access-distance calculation for the same 300 station-closure configurations using finer 50- and 25-meter lattices and shows that the results are nearly unchanged. Appendix H.4 instead uses the positive-population cells of the 2015 500-meter population mesh to allow population density to vary within census areas.

Table 10: Physical Access Effects of Population Decline and Station Adjustment

|                                                          | Baseline | Uniform decline | Sparse-area decline | Dense-area decline |
|----------------------------------------------------------|----------|-----------------|---------------------|--------------------|
| Population-weighted access distance, stations fixed (m)  | 162.2    | 162.2           | 152.1               | 167.6              |
| Population-weighted access distance, stations adjust (m) | 162.2    | 163.7           | 157.6               | 168.9              |
| Closure-induced change in access distance (%)            | –        | 0.92            | 3.65                | 0.74               |
| Population weight attached to closed stations (%)        | –        | 2.53            | 2.41                | 2.29               |

Note: Access distance is the population-weighted mean straight-line distance from 100-meter lattice points to their assigned waste stations. Each census area’s population is distributed equally across all lattice points in its polygon. The fixed-station calculation changes only these population weights. The station-adjustment calculation also closes stations using  $\hat{\varepsilon}_M$  and updates the assignment of points attached to closed stations. Closure-induced changes compare the station-adjustment outcome with the fixed-station outcome for the same population scenario. Station-adjustment entries are medians over 100 closure configurations. Appendix Table H.2 reports results using 2015 population-mesh weights. The measures describe physical geographic coverage, not observed household trips or welfare.

## 8 Conclusion

This paper uses municipal waste collection to study how density shapes operating requirements in multi-stop production. By separating service at waste stations from movement between them, the analysis identifies two important features of the production technology. Station-service time rises much less than proportionally with assigned population, with an estimated elasticity of 0.204, and each station-to-station leg entails a large, statistically significant time requirement even conditional on road distance. These features create economies of density through service sharing and fewer movements per resident, in addition to shorter connecting distance.

The component accounting describes where these savings occur, while equation (13) describes their source. The model gives a 0.485-percent reduction in the three operating-time components per resident for a one-percent increase in density, compared with 0.082 percent if a one-percent increase in population came with a one-percent increase in waste stations. The difference accounts for 83.1 percent of the 0.485-percent reduction. Holding land area fixed, a one-percent larger census-area population is associated with 0.547 percent less measured service-and-movement time per resident. Under a five-percent population loss, with station count adjusting, the increase in total operating time per resident is 1.03 percentage points smaller when decline is concentrated in sparse rather than dense areas. Under sparse-area decline, representative access distance remains 2.8 percent below its observed baseline because population loss is concentrated in initially distant locations, although station closures themselves increase access distance by 3.65 percent relative to the fixed-station benchmark. These results show that the spatial distribution of population loss affects how much of the reduction associated with density is preserved.

In this setting, aggregating users at shared service points is central to economies of density in multi-stop production. A user absorbed into an existing stop raises its service requirement less than proportionally and need not add a leg, whereas serving the same user at a separate stop fragments demand and adds a fixed movement requirement. More generally, the effect of density depends on both the production technology and how the number of service points changes with the number of users. The same stop-level technology can produce different reductions in operating time depending on whether additional users require additional stops. The operating value of density therefore depends not only on geographic proximity but also on how demand is organized across service points.

## A Derivations for the Multi-Stop Production Framework

### A.1 Proof of Lemma 1: Optimal Station-Count Adjustment

Let

$$\begin{aligned} C_S &= \alpha g^\eta N^{\eta-1} M^{1-\eta}, & C_L &= \kappa \frac{M}{N}, \\ C_D &= \psi \chi \frac{\sqrt{AM}}{N}, & C_H &= \omega \left( \frac{A}{M} \right)^{\theta/2}. \end{aligned}$$

The first-order condition with respect to  $\log M$  is

$$(1 - \eta)C_S + C_L + \frac{1}{2}C_D - \frac{\theta}{2}C_H = 0. \quad (\text{A.1})$$

The objective diverges as  $M$  approaches either zero or infinity. Moreover, the derivative of the left-hand side of equation (A.1) with respect to  $\log M$  is

$$(1 - \eta)^2 C_S + C_L + \frac{1}{4}C_D + \frac{\theta^2}{4}C_H > 0.$$

The first-order condition therefore defines a unique interior optimum.

Define

$$\varepsilon_M = \left. \frac{\partial \log M^*(N, A, g)}{\partial \log N} \right|_{A, g}.$$

Differentiating equation (A.1) with respect to  $\log N$ , holding  $A$  and  $g$  fixed and evaluating all components along  $M^*(N, A, g)$ , gives

$$\begin{aligned} 0 &= (1 - \eta)C_S [(\eta - 1) + (1 - \eta)\varepsilon_M] + C_L(-1 + \varepsilon_M) \\ &\quad + \frac{1}{2}C_D \left( -1 + \frac{1}{2}\varepsilon_M \right) + \frac{\theta^2}{4}C_H \varepsilon_M. \end{aligned}$$

Solving gives equation (17).

Let  $s_j = C_j/pc$ , where  $pc = C_S + C_L + C_D + C_H$ . Using equation (A.1) to eliminate  $C_H$ , equation (17) can equivalently be written as

$$\varepsilon_M = \frac{(1 - \eta)^2 s_S + s_L + \frac{1}{2}s_D}{(1 - \eta)^2 s_S + s_L + \frac{1}{4}s_D + \frac{\theta}{2} \left[ (1 - \eta)s_S + s_L + \frac{1}{2}s_D \right]}, \quad (\text{A.2})$$

The numerator and denominator are positive. The denominator exceeds the numerator by

$$\frac{\theta}{2} [(1 - \eta)s_S + s_L] + \frac{\theta - 1}{4}s_D > 0 \quad (\text{A.3})$$

when  $0 < \eta < 1$  and  $\theta \geq 1$ . Hence

$$0 < \varepsilon_M < 1. \quad (\text{A.4})$$

This proves Lemma 1. Equations (10)–(12) then make all three operating-time elasticities negative along the optimal station-count schedule.

## B Study Area

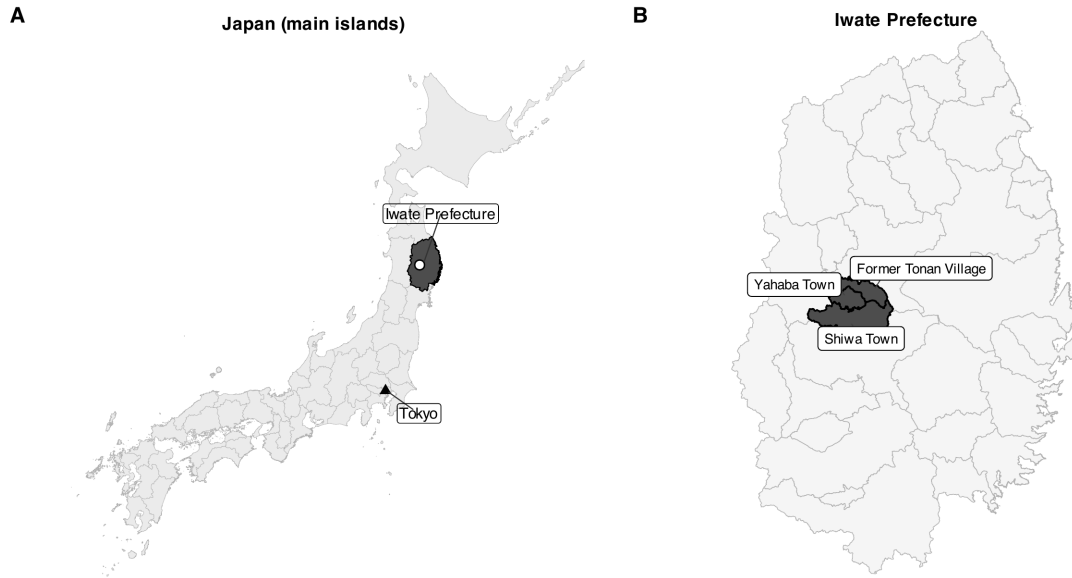


Figure B.1: Location of the Study Area

Note: Panel A shows prefectural boundaries on Japan's main islands. Iwate Prefecture is shaded, the white circle marks the location of the study region, and the black triangle marks Tokyo. Panel B shows municipal boundaries in Iwate Prefecture. The shaded area is the study region: former Tonan Village (now part of Morioka City), Yahaba Town, and Shiwa Town. Boundary data are from the National Land Numerical Information of the Ministry of Land, Infrastructure, Transport and Tourism.

## C Descriptive Statistics

Table C.1 reports descriptive statistics for the station-service, movement, and census-area-week samples.

Table C.1: Descriptive Statistics for the Main Analysis Samples

| Variable                                                               | Mean   | Std. dev. | p25   | Median | p75    | N      |
|------------------------------------------------------------------------|--------|-----------|-------|--------|--------|--------|
| <i>Panel A: Station-service estimation sample</i>                      |        |           |       |        |        |        |
| Service time (seconds)                                                 | 101.80 | 66.53     | 62.00 | 85.00  | 121.00 | 44,760 |
| Assigned population (residents)                                        | 74.4   | 37.8      | 49.9  | 69.2   | 90.9   | 44,760 |
| <i>Panel B: Station-to-station legs underlying the movement sample</i> |        |           |       |        |        |        |
| Movement time (seconds)                                                | 99.89  | 113.89    | 36.00 | 72.00  | 126.00 | 43,125 |
| Road distance (km)                                                     | 0.47   | 0.64      | 0.14  | 0.28   | 0.58   | 43,125 |
| <i>Panel C: Census-area-week sample</i>                                |        |           |       |        |        |        |
| Population (residents)                                                 | 249.9  | 270.1     | 68.0  | 145.0  | 328.0  | 5,534  |
| Land area (km <sup>2</sup> )                                           | 0.70   | 1.38      | 0.10  | 0.19   | 0.74   | 5,534  |
| Service-and-movement time (minutes)                                    | 21.21  | 18.55     | 9.07  | 15.08  | 26.48  | 5,534  |
| Station-service time (minutes)                                         | 10.72  | 10.76     | 3.65  | 6.83   | 13.38  | 5,534  |
| Station-to-station movement time (minutes)                             | 10.50  | 8.65      | 4.56  | 7.97   | 13.38  | 5,534  |
| Station-to-station legs                                                | 6.17   | 5.83      | 2.00  | 4.00   | 8.00   | 5,534  |
| Station-to-station road distance (km)                                  | 3.10   | 2.38      | 1.31  | 2.48   | 4.33   | 5,534  |

Note: Panel A uses the station-service sample. Panel B uses the station-to-station legs in the movement sample. Panel C uses the 5,534 census-area weeks common to the five outcomes in Table 6.

## D Validation Using Winter Snow: December through April

The estimates in Subsection 5.4 use the full extended sample from September 2025 through June 2026. To examine whether comparisons with snow-free dates farther from winter affect the results, I repeat the station-service and movement specifications using only collection dates from December 1, 2025, through April 30, 2026. All 44 collection dates with positive daily mean standing snow depth, including all 18 dates above the 10-centimeter morning threshold, remain in the restricted sample.

The estimates are similar to those from the full period. The station-service interactions are -0.0095 for daily mean snow depth and -0.0233 for the morning indicator. In the movement specification, the leg-count interactions remain statistically indistinguishable from zero, while the road-distance interactions are 28.56 and 46.01 seconds per kilometer, respectively.

Table D.1: Standing Snow Depth and the Station-Service Elasticity: December–April

| Dependent variable:<br>Model:                                    | Log waste-station service time |                     |                               |
|------------------------------------------------------------------|--------------------------------|---------------------|-------------------------------|
|                                                                  | (1)                            | (2)                 | (3)                           |
| Snow measure:                                                    | None                           | Daily mean          | 08:00 depth<br>at least 10 cm |
| <i>Variables</i>                                                 |                                |                     |                               |
| Log assigned population                                          | 0.211<br>(0.025)               | 0.215<br>(0.026)    | 0.214<br>(0.025)              |
| Daily mean snow depth $\times$ log assigned population           |                                | -0.0095<br>(0.0023) |                               |
| 08:00 snow depth at least 10 cm $\times$ log assigned population |                                |                     | -0.0233<br>(0.0035)           |
| <i>Fixed effects</i>                                             |                                |                     |                               |
| Collection date                                                  | Yes                            | Yes                 | Yes                           |
| Truck                                                            | Yes                            | Yes                 | Yes                           |
| Driver                                                           | Yes                            | Yes                 | Yes                           |
| Collection assistant                                             | Yes                            | Yes                 | Yes                           |
| Municipality                                                     | Yes                            | Yes                 | Yes                           |
| <i>Sample and fit</i>                                            |                                |                     |                               |
| Sample period                                                    | Dec.–Apr.                      | Dec.–Apr.           | Dec.–Apr.                     |
| Observations                                                     | 49,668                         | 49,668              | 49,668                        |
| Waste stations                                                   | 1,406                          | 1,406               | 1,406                         |
| Census areas                                                     | 389                            | 389                 | 389                           |
| Collection dates                                                 | 123                            | 123                 | 123                           |
| $R^2$                                                            | 0.158                          | 0.158               | 0.158                         |

Note: The sample is limited to collection dates from December 1, 2025, through April 30, 2026. The specification, variable definitions, and inference otherwise follow Table 4.

Table D.2: Standing Snow Depth and Station-to-Station Movement Time: December–April

| Dependent variable:<br>Model:                          | Station-to-station movement time (seconds) |                 |                               |
|--------------------------------------------------------|--------------------------------------------|-----------------|-------------------------------|
|                                                        | (1)                                        | (2)             | (3)                           |
| Snow measure:                                          | None                                       | Daily mean      | 08:00 depth<br>at least 10 cm |
| <i>Variables</i>                                       |                                            |                 |                               |
| Leg count                                              | 68.31<br>(3.69)                            | 66.88<br>(3.82) | 67.47<br>(3.75)               |
| Road distance (km)                                     | 11.09<br>(5.08)                            | 9.11<br>(4.30)  | 10.13<br>(4.57)               |
| Daily mean snow depth $\times$ leg count               |                                            | -1.80<br>(1.98) |                               |
| Daily mean snow depth $\times$ road distance           |                                            | 28.56<br>(5.85) |                               |
| 08:00 snow depth at least 10 cm $\times$ leg count     |                                            |                 | -3.14<br>(3.36)               |
| 08:00 snow depth at least 10 cm $\times$ road distance |                                            |                 | 46.01<br>(9.16)               |
| <i>Fixed effects and controls</i>                      |                                            |                 |                               |
| Truck-day fixed effects                                | Yes                                        | Yes             | Yes                           |
| Census-area fixed effects                              | Yes                                        | Yes             | Yes                           |
| Temperature and precipitation interactions             | Yes                                        | Yes             | Yes                           |
| <i>Sample and fit</i>                                  |                                            |                 |                               |
| Sample period                                          | Dec.–Apr.                                  | Dec.–Apr.       | Dec.–Apr.                     |
| Observations                                           | 16,172                                     | 16,172          | 16,172                        |
| Truck-days                                             | 598                                        | 598             | 598                           |
| Census areas                                           | 387                                        | 387             | 387                           |
| Collection dates                                       | 123                                        | 123             | 123                           |
| $R^2$                                                  | 0.846                                      | 0.851           | 0.850                         |

Note: The sample is limited to collection dates from December 1, 2025, through April 30, 2026. The specification, variable definitions, and inference otherwise follow Table 5. Temperature and precipitation are centered within the restricted sample.

## E Robustness of the Density-Economy Estimates

### E.1 Within-Truck-Day Estimates

As a robustness check, I aggregate the same five outcomes by census area within each truck-day. This comparison asks whether operating requirements continue to rise less than proportionally with population when areas are compared within the same realized truck-day. I also examine the distance and movement time required per leg.

For truck  $r$  on collection date  $t$ , let  $T_{rta}$ ,  $S_{rta}$ ,  $B_{rta}$ ,  $L_{rta}$ , and  $D_{rta}$  denote measured service-and-movement time, service time, station-to-station movement time, leg count, and road distance attributed to census area  $a$ . I estimate

$$\log Y_{rta} = \theta_N^Y \log N_a + \theta_A^Y \log A_a + \alpha_{rt}^Y + u_{rta}^Y, \quad Y \in \{T, S, B, L, D\}, \quad (\text{E.1})$$

where  $\alpha_{rt}^Y$  is a truck-day fixed effect and therefore absorbs the truck, crew, date, and other conditions common to the truck-day.

An area may account for many legs even if each one is short. To separate leg count from what each leg requires, I estimate

$$\log \left( \frac{D_{rta}}{L_{rta}} \right) = \rho_N^D \log N_a + \rho_A^D \log A_a + \alpha_{rt}^D + \epsilon_{rta}^D, \quad (\text{E.2})$$

$$\log \left( \frac{B_{rta}}{L_{rta}} \right) = \rho_N^B \log N_a + \rho_A^B \log A_a + \alpha_{rt}^B + \epsilon_{rta}^B. \quad (\text{E.3})$$

Here  $D_{rta}/L_{rta}$  is road distance per leg and  $B_{rta}/L_{rta}$  is station-to-station movement time per leg.<sup>11</sup>

Table E.1 reports the within-truck-day estimates on a common sample with positive, complete values for all five operating requirements. Columns 1–5 use the same area totals as the area-week analysis. Columns 6 and 7 divide road distance and movement time by leg count.

Columns 1–5 show that all five outcomes also rise less than proportionally with population within truck-days, as they do at the area-week level. Conditional on land area, a one-percent increase in area population is associated with 0.345 percent more measured service-and-movement time, 0.452 percent more service time, 0.268 percent more movement time, 0.371 percent more legs, and 0.118 percent more road distance. All five estimates are well below one. Thus, areas with larger populations use more of each operating input within a truck-day, but substantially less of each input per resident.

Columns 6 and 7 ask why a shorter road distance per leg need not translate proportionally into less movement time per leg. Under the movement technology estimated in Subsection 5.2, movement time per leg is  $\kappa + \psi(D/L)$ . If the distance-independent term  $\kappa$  were negligible, density would reduce distance per leg and movement time per leg by similar percentages. Instead, a one-percent increase in area population is associated with 0.253 percent shorter road distance per leg but only 0.103 percent less movement time

<sup>11</sup>Each ratio is estimated for truck-day-area observations in which the numerator and leg count are positive and observed. Under the uniform-spacing benchmark, distance per leg is proportional to  $\sqrt{A/M}$ , so holding land area fixed, its predicted population elasticity is  $-\varepsilon_M/2$ .

Table E.1: Population and Operating Requirements within Truck-Days

| Dependent variable (in logs):<br>Model: | Area totals                          |                        |                         |                                   |                         | Per-leg outcomes                |                                 |
|-----------------------------------------|--------------------------------------|------------------------|-------------------------|-----------------------------------|-------------------------|---------------------------------|---------------------------------|
|                                         | Service-and-<br>movement time<br>(1) | Service<br>time<br>(2) | Movement<br>time<br>(3) | Station-to-station<br>legs<br>(4) | Road<br>distance<br>(5) | Road distance<br>per leg<br>(6) | Movement time<br>per leg<br>(7) |
| Log population                          | 0.345<br>(0.031)                     | 0.452<br>(0.031)       | 0.268<br>(0.035)        | 0.371<br>(0.036)                  | 0.118<br>(0.031)        | -0.253<br>(0.025)               | -0.103<br>(0.014)               |
| Log land area                           | 0.094<br>(0.030)                     | -0.005<br>(0.030)      | 0.197<br>(0.036)        | 0.064<br>(0.031)                  | 0.324<br>(0.041)        | 0.260<br>(0.024)                | 0.134<br>(0.014)                |
| Truck-day fixed effects                 | Yes                                  | Yes                    | Yes                     | Yes                               | Yes                     | Yes                             | Yes                             |
| Observations                            | 12,895                               | 12,895                 | 12,895                  | 12,895                            | 12,895                  | 12,895                          | 12,895                          |
| Census areas                            | 385                                  | 385                    | 385                     | 385                               | 385                     | 385                             | 385                             |
| Truck-days                              | 487                                  | 487                    | 487                     | 487                               | 487                     | 487                             | 487                             |
| Within $R^2$                            | 0.318                                | 0.383                  | 0.213                   | 0.322                             | 0.233                   | 0.294                           | 0.095                           |

Note: The unit is a truck-day–census-area observation. The common sample has positive, complete values for service time, station-to-station movement time, leg count, and directed road distance. Service-and-movement time is service plus movement time. Each column regresses the indicated log outcome on log population and log land area with truck-day fixed effects. Standard errors are two-way clustered by census area and truck-day.

per leg. This smaller response of movement time is consistent with the positive estimate of  $\kappa$ : reducing a leg’s geographic distance lowers only its distance-related time and does not remove the time associated with making the leg itself.

## E.2 Additional Controls and Inhabited Land Area

The baseline specifications do not directly control for differences across census areas in the amount or composition of waste generated per resident. If demographic or housing composition varies with population density and also affects waste generation or collection conditions, part of the estimated density relationship could reflect these differences. A separate concern is that census-polygon area may not accurately represent the land area over which residents are distributed.

Table E.2 compares the Table 6 estimates with these two changes. Panel A reproduces the Table 6 specification. Panel B adds the share of residents age 65 or older and the share of households living in apartments. Panel C separately replaces census-polygon area with inhabited land area. The population elasticities remain below one for all five outcomes under both changes.

Table E.2: Population Elasticities with Additional Controls and Inhabited Land Area

| Dependent variable:<br>Model:                    | Service-and-<br>movement time<br>(1) | Service time at<br>waste stations<br>(2) | Station-to-station<br>movement time<br>(3) | Station-to-station<br>legs<br>(4) | Station-to-station<br>road distance<br>(5) |
|--------------------------------------------------|--------------------------------------|------------------------------------------|--------------------------------------------|-----------------------------------|--------------------------------------------|
| <i>Panel A. Controls for census-polygon area</i> |                                      |                                          |                                            |                                   |                                            |
| Log population                                   | 0.453<br>(0.028)                     | 0.577<br>(0.029)                         | 0.366<br>(0.029)                           | 0.480<br>(0.032)                  | 0.173<br>(0.027)                           |
| Log census-polygon area                          | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Log inhabited land area                          | No                                   | No                                       | No                                         | No                                | No                                         |
| Share age 65 or older                            | No                                   | No                                       | No                                         | No                                | No                                         |
| Share of households in apartments                | No                                   | No                                       | No                                         | No                                | No                                         |
| Collection-week fixed effects                    | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Municipality fixed effects                       | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Observations                                     | 5,534                                | 5,534                                    | 5,534                                      | 5,534                             | 5,534                                      |
| Census areas                                     | 385                                  | 385                                      | 385                                        | 385                               | 385                                        |
| <i>Panel B. Adds age and apartment shares</i>    |                                      |                                          |                                            |                                   |                                            |
| Log population                                   | 0.400<br>(0.030)                     | 0.539<br>(0.032)                         | 0.302<br>(0.031)                           | 0.397<br>(0.033)                  | 0.133<br>(0.031)                           |
| Log census-polygon area                          | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Log inhabited land area                          | No                                   | No                                       | No                                         | No                                | No                                         |
| Share age 65 or older                            | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Share of households in apartments                | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Collection-week fixed effects                    | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Municipality fixed effects                       | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Observations                                     | 5,534                                | 5,534                                    | 5,534                                      | 5,534                             | 5,534                                      |
| Census areas                                     | 385                                  | 385                                      | 385                                        | 385                               | 385                                        |
| <i>Panel C. Uses inhabited land area</i>         |                                      |                                          |                                            |                                   |                                            |
| Log population                                   | 0.443<br>(0.028)                     | 0.581<br>(0.027)                         | 0.342<br>(0.030)                           | 0.474<br>(0.032)                  | 0.123<br>(0.027)                           |
| Log census-polygon area                          | No                                   | No                                       | No                                         | No                                | No                                         |
| Log inhabited land area                          | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Share age 65 or older                            | No                                   | No                                       | No                                         | No                                | No                                         |
| Share of households in apartments                | No                                   | No                                       | No                                         | No                                | No                                         |
| Collection-week fixed effects                    | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Municipality fixed effects                       | Yes                                  | Yes                                      | Yes                                        | Yes                               | Yes                                        |
| Observations                                     | 5,534                                | 5,534                                    | 5,534                                      | 5,534                             | 5,534                                      |
| Census areas                                     | 385                                  | 385                                      | 385                                        | 385                               | 385                                        |

Note: Each column within each panel reports a separate OLS regression for the dependent variable shown at the top of the column. Panel A reproduces the Table 6 specification. Panel B adds the share of residents age 65 or older and the share of households living in apartments. Panel C separately replaces log census-polygon area with log inhabited land area. When the census reports the demographic and housing variables only for a combined disclosure group, I assign the group's share to each member area. Standard errors clustered by census area are in parentheses.

### E.3 Allocation of Boundary-Crossing Legs

Boundary-crossing legs are divided equally between their origin and destination census areas in the main specification. Tables E.3–E.5 compare this rule with three alternatives that assign the entire leg to the census area containing the origin station, the destination station, or the midpoint of the straight line connecting the two stations. Each table re-estimates equation (20) for movement time, leg count, or road distance under all four allocation rules. The population coefficients are similar across the rules, so the subproportional scaling estimates are not driven by dividing boundary-crossing legs equally between their endpoint areas.

Table E.3: Boundary Allocation: Station-to-Station Movement Time

| <i>Station-to-station movement time</i> |                                  |                  |                  |                  |
|-----------------------------------------|----------------------------------|------------------|------------------|------------------|
| Dependent variable:                     | Station-to-station movement time |                  |                  |                  |
| Model:                                  | (1)                              | (2)              | (3)              | (4)              |
| Boundary allocation:                    | Half to endpoints                | Origin           | Destination      | Midpoint         |
| <i>Variables</i>                        |                                  |                  |                  |                  |
| Log population                          | 0.367<br>(0.029)                 | 0.366<br>(0.033) | 0.404<br>(0.028) | 0.417<br>(0.036) |
| Log land area                           | 0.191<br>(0.024)                 | 0.184<br>(0.026) | 0.195<br>(0.025) | 0.248<br>(0.024) |
| <i>Fixed effects</i>                    |                                  |                  |                  |                  |
| Collection week                         | Yes                              | Yes              | Yes              | Yes              |
| Municipality                            | Yes                              | Yes              | Yes              | Yes              |
| <i>Sample and inference</i>             |                                  |                  |                  |                  |
| Census-area clustering                  | Yes                              | Yes              | Yes              | Yes              |
| Observations                            | 5,540                            | 5,508            | 5,462            | 5,588            |
| Census areas                            | 386                              | 385              | 385              | 456              |

Note: The unit is a census-area week. “Half to endpoints” is the main specification and assigns one-half of a boundary-crossing leg to each endpoint area. Origin, destination, and midpoint assign the entire leg to the indicated census area. All specifications include collection-week and municipality fixed effects. Standard errors are clustered by census area.

Table E.4: Boundary Allocation: Number of Legs

| <i>Station-to-station legs</i> |                         |                  |                  |                  |
|--------------------------------|-------------------------|------------------|------------------|------------------|
| Dependent variable:            | Station-to-station legs |                  |                  |                  |
| Model:                         | (1)                     | (2)              | (3)              | (4)              |
| Boundary allocation:           | Half to endpoints       | Origin           | Destination      | Midpoint         |
| <i>Variables</i>               |                         |                  |                  |                  |
| Log population                 | 0.498<br>(0.032)        | 0.494<br>(0.031) | 0.497<br>(0.032) | 0.548<br>(0.030) |
| Log land area                  | 0.065<br>(0.024)        | 0.063<br>(0.023) | 0.052<br>(0.023) | 0.086<br>(0.019) |
| <i>Fixed effects</i>           |                         |                  |                  |                  |
| Collection week                | Yes                     | Yes              | Yes              | Yes              |
| Municipality                   | Yes                     | Yes              | Yes              | Yes              |
| <i>Sample and inference</i>    |                         |                  |                  |                  |
| Census-area clustering         | Yes                     | Yes              | Yes              | Yes              |
| Observations                   | 6,498                   | 6,461            | 6,410            | 6,566            |
| Census areas                   | 386                     | 385              | 385              | 457              |

Note: The unit, allocation rules, fixed effects, and inference are identical to Table E.3.

Table E.5: Boundary Allocation: Road Distance

| <i>Station-to-station road distance</i> |                                  |                  |                  |                  |
|-----------------------------------------|----------------------------------|------------------|------------------|------------------|
| Dependent variable:                     | Station-to-station road distance |                  |                  |                  |
| Model:                                  | (1)                              | (2)              | (3)              | (4)              |
| Boundary allocation:                    | Half to endpoints                | Origin           | Destination      | Midpoint         |
| <i>Variables</i>                        |                                  |                  |                  |                  |
| Log population                          | 0.186<br>(0.027)                 | 0.181<br>(0.031) | 0.214<br>(0.026) | 0.237<br>(0.030) |
| Log land area                           | 0.381<br>(0.025)                 | 0.373<br>(0.026) | 0.379<br>(0.028) | 0.445<br>(0.030) |
| <i>Fixed effects</i>                    |                                  |                  |                  |                  |
| Collection week                         | Yes                              | Yes              | Yes              | Yes              |
| Municipality                            | Yes                              | Yes              | Yes              | Yes              |
| <i>Sample and inference</i>             |                                  |                  |                  |                  |
| Census-area clustering                  | Yes                              | Yes              | Yes              | Yes              |
| Observations                            | 6,498                            | 6,461            | 6,410            | 6,566            |
| Census areas                            | 386                              | 385              | 385              | 457              |

Note: Distance is directed road distance. The unit, allocation rules, fixed effects, and inference are identical to Table E.3.

## F Movement Coefficients by Census-Area Population Density

The main movement equation assumes common per-leg and per-kilometer requirements across census areas. A concern is that the positive per-leg coefficient instead reflects unobserved local conditions that differ systematically with population density. I examine this possibility using the same truck-day–census-area observations, outcome, and endpoint allocation as in equation (19). I divide the 388 census areas represented in the estimation sample at the median of their 2020 population density, calculated across areas rather than across repeated observations, and re-estimate the movement equation separately for the two groups. I also estimate a pooled specification that allows both coefficients and the average level of movement time to differ between the groups; this specification provides the equality tests reported in the table.

Table F.1: Movement Coefficients by Census-Area Population Density

| Dependent variable:               | Station-to-station movement time (seconds) |               |                |
|-----------------------------------|--------------------------------------------|---------------|----------------|
| Model:                            | (1)                                        | (2)           | (3)            |
| Census areas:                     | All                                        | Lower density | Higher density |
| <i>Variables</i>                  |                                            |               |                |
| Allocated leg count               | 63.7<br>(2.6)                              | 71.4<br>(4.8) | 58.5<br>(3.9)  |
| Allocated road distance (km)      | 67.8<br>(5.0)                              | 52.2<br>(5.2) | 91.3<br>(11.8) |
| <i>Fixed effects</i>              |                                            |               |                |
| Truck-day                         | Yes                                        | Yes           | Yes            |
| <i>Inference and fit</i>          |                                            |               |                |
| $p$ : equal per-leg coefficients  |                                            | 0.015         |                |
| $p$ : equal distance coefficients |                                            | 0.005         |                |
| Observations                      | 14,273                                     | 6,683         | 7,548          |
| Truck-days                        | 552                                        | 460           | 508            |
| Census areas                      | 388                                        | 194           | 194            |
| Within $R^2$                      | 0.736                                      | 0.642         | 0.748          |

Note: The unit is a truck-day–census-area observation, and the dependent variable is total station-to-station movement time in seconds. Lower-density census areas have 2020 population density at or below the median across the 388 census areas in the estimation sample; higher-density areas are above the median. Columns 2 and 3 re-estimate equation (19) separately for the two groups. All columns include truck-day fixed effects. Standard errors are two-way clustered by census area and truck-day. The equality-test  $p$ -values come from a pooled specification that allows the per-leg coefficient, the distance coefficient, and the average level of movement time to differ between the two groups.

Table F.1 reports the results. Column 1 reproduces the pooled specification. Columns 2 and 3 estimate a per-leg requirement of 71.4 seconds in lower-density census areas and 58.5 seconds in higher-density census areas. Both estimates are positive and statistically significant. Their difference is statistically significant ( $p = 0.015$ ), but the magnitudes are similar: both are approximately one minute per leg and bracket the pooled estimate of 63.7 seconds. The corresponding per-kilometer estimates are 52.2 and 91.3 seconds and also differ statistically ( $p = 0.005$ ). Thus, the mapping from legs and distance into movement time is not identical across the density distribution, but a substantial distance-independent per-leg requirement is present in both groups. The positive pooled estimate of  $\kappa$  therefore does not appear to be driven primarily by unobserved local conditions correlated with density. This comparison is a specification check rather than evidence that all local road conditions are irrelevant.

## G Density-Accounting Details

Table 7 reports how the calculated time saving is distributed across service at waste stations, the number of station-to-station legs, and the road distance of those legs. The calculation has three steps: construct the baseline amount of time used by each component, apply that component's estimated per-resident elasticity, and express its implied time saving as a share of the sum across the three components. This section records each step.

The baseline uses the same 5,534 census-area-week observations as Table 6. For each census area, I first average total time, service time, movement time, leg count, and road distance across its included weeks. I then sum these area-specific weekly averages across the 385 represented census areas. Thus, for any component  $X$ , its study-area weekly level is

$$X_0 = \sum_a \left( \frac{1}{W_a} \sum_{w \in \mathcal{W}_a} X_{aw} \right), \quad (\text{G.1})$$

where  $\mathcal{W}_a$  is the set of included weeks for area  $a$  and  $W_a$  is its number of included weeks. Dividing the resulting time totals by the population represented by these areas, converting seconds to minutes, and multiplying by 1,000 gives weekly minutes per 1,000 residents. This produces 42.12 minutes of service time and 40.09 minutes of observed station-to-station movement time, for 82.22 minutes in total. Write these two baseline levels as  $C_S$  and  $C_B$ , respectively.

Service time is observed directly, but observed movement time must be divided between time associated with leg count and time associated with road distance. Let  $B_0$ ,  $L_0$ , and  $D_0$  denote the aggregate weekly movement time, number of legs, and road distance from equation (G.1). The movement estimates imply  $\hat{\kappa}L_0$  seconds associated with leg count and  $\hat{\psi}D_0$  seconds associated with distance. I use their relative magnitudes to allocate the observed movement-time total:

$$C_L = C_B \frac{\hat{\kappa}L_0}{\hat{\kappa}L_0 + \hat{\psi}D_0}, \quad (\text{G.2})$$

$$C_D = C_B \frac{\hat{\psi}D_0}{\hat{\kappa}L_0 + \hat{\psi}D_0}, \quad (\text{G.3})$$

where  $C_B$  is observed movement time in weekly minutes per 1,000 residents. This allocation uses  $\hat{\kappa}$  and  $\hat{\psi}$  only to determine the two shares of observed movement time; it therefore preserves  $C_L + C_D = C_B$  and does not create an additional residual category. The resulting baseline levels are 26.64 minutes associated with leg count and 13.45 minutes associated with road distance.

Table 6 reports the population elasticity of the weekly total for each measure. Subtracting one from each coefficient gives the corresponding elasticity per resident: -0.423 for station-service time, -0.520 for leg count, and -0.827 for road distance. Because land area is held fixed, these are also the elasticities with respect to population density.

To express these changes in time units, I combine each elasticity with the baseline minutes assigned to the corresponding component. For the two movement components, I use the minutes allocated above

to leg count and road distance together with the elasticities estimated for those respective outcomes. For example, the calculation for station service is

$$42.12 \times \frac{0.423}{100} \simeq 0.178.$$

Thus, the first-order reduction associated with a one-percent increase in density is approximately 0.178 weekly minutes per 1,000 residents for station-service time. Repeating this calculation for leg count and road distance and dividing each reduction by their sum gives the shares reported in Table 7: 41.7 percent, 32.3 percent, and 26.0 percent, respectively. All calculations use unrounded values.

## H Counterfactual Calculations

### H.1 Simulation Algorithm

For each population-loss scenario, the simulation proceeds as follows.

1. Construct the counterfactual population vector  $N_a^1$  such that  $\sum_a N_a^1 = 0.95 \sum_a N_a^0$  and  $0 \leq N_a^1 \leq N_a^0$ .
2. Compute each area's station target from equation (22); its implied fractional number of closures is  $M_a^0 - M_a^1$ .
3. Convert these fractional closure targets to integers. Starting from  $\lfloor M_a^0 - M_a^1 \rfloor$ , allocate the remaining closures to the eligible areas with the largest fractional remainders, breaking ties by census-area identifier and requiring at least one surviving station in every area. This fixes the aggregate number of closures at  $\text{round}[\sum_a (M_a^0 - M_a^1)]$ . I use the resulting integer number of survivors as  $M_a^1$ .
4. Draw the required number of closed stations without replacement within each area, while leaving at least one surviving station in every municipality-schedule group.
5. Set the assigned population of every surviving station in area  $a$  to  $N_a^1/M_a^1$ .
6. Delete closed stations from every observed truck-day sequence without changing the order of surviving stations.
7. Recompute  $L_{rt}^1$  and directed road distance  $D_{rt}^1$ , connecting surviving stations only within a run of consecutive station-to-station legs so that no new leg spans a disposal trip or an other interval. Relative to baseline, movement time changes by  $\hat{\kappa}(L_{rt}^1 - L_{rt}^0) + \hat{\psi}(D_{rt}^1 - D_{rt}^0)$ . Recompute service time using the resulting station loads and  $\hat{\eta}$ , and add the unchanged baseline time in disposal trip and facility activity and other intervals.

### H.2 Construction of Confidence Intervals

Table 9 reports the uncertainty from parameter estimation separately from the variation in which stations close. The confidence intervals reflect estimation error in  $\eta$ ,  $\varepsilon_M$ ,  $\kappa$ , and  $\psi$ , holding fixed the observed

baseline station-service time, leg count, road distance, and time in disposal trip and facility activity and other intervals. I draw 1,999 parameter vectors. Within each vector, the four parameters are drawn independently on their original scales from normal distributions centered at their estimates, with standard deviations equal to their reported standard errors. For each draw of  $\eta$ , I adjust  $\alpha$  in the station-service equation so that it continues to reproduce observed aggregate baseline station-service time. The parameter draws therefore change the counterfactual response without changing the observed starting point.

For each population-loss scenario with station-count adjustment, the draw of  $\varepsilon_M$  determines the area-level closure counts using the rounding procedure above. I use the same 100 random seeds as in the point calculation, compute the outcome for each seed, and record the median within each parameter draw. The 95% confidence interval is the 2.5th and 97.5th percentiles of the resulting 1,999 medians. When the number of stations is fixed, there is no closure-location randomization, and I take the same percentiles across the 1,999 parameter-specific outcomes. In this case only  $\eta$  affects the counterfactual outcome, because station count and routes remain fixed. The 5th and 95th percentiles reported separately in Panel B instead hold all parameters at their estimates and vary only which stations close.

### H.3 Access-Distance Construction and Grid Resolution

The main access calculation places a common 100-meter lattice over the full polygons of the 386 modeled census areas. If an area is too small to contain a lattice point, I add one point on its surface. Within each area, every point receives equal weight and the weights sum to the area's 2020 population. Counterfactual population change replaces that sum with the area's scenario population while preserving equal weights within the area. The resulting 26,338 points therefore approximate an integral under a uniform-within-area population assumption; they are not imputed household coordinates.

I repeat the complete access-distance calculation using 50- and 25-meter lattices. Table H.1 shows that both the baseline distance and the closure-induced changes are nearly unchanged.

Table H.1: Access Distance by Lattice Spacing

| Lattice spacing | Baseline distance<br>(meters) | Closure-induced increase (%) |                     |                    |
|-----------------|-------------------------------|------------------------------|---------------------|--------------------|
|                 |                               | Uniform decline              | Sparse-area decline | Dense-area decline |
| 100 meters      | 162.207                       | 0.92                         | 3.65                | 0.74               |
| 50 meters       | 161.735                       | 0.94                         | 3.63                | 0.74               |
| 25 meters       | 161.857                       | 0.93                         | 3.65                | 0.76               |

Note: Baseline distance is the population-weighted mean straight-line distance to the assigned waste station. The other columns report the percentage increase caused by station closures relative to the same population scenario with the number of stations fixed. Each lattice spacing uses the same 100 station-closure configurations for each population scenario.

## H.4 Access Distance Using the 2015 Population Mesh

As an alternative to distributing population evenly within each census area, I use the 2015 500-meter population mesh to describe how population is distributed within the area.<sup>12</sup> Because the mesh cells and census-area boundaries do not coincide, I calculate the part of each mesh cell lying within each census area. I assign to each part the share of the cell's population equal to its share of the cell's area and divide that population evenly among the 100-meter grid points it contains.<sup>13</sup> For each population-loss scenario, the population assigned to every point in a census area changes in the same proportion as the area's population.

I repeat the access-distance calculation using the same station closures and reassignment rule as in the main analysis. Thus, only the distribution of population within census areas differs from the main calculation. Table H.2 compares the results. Using the population mesh produces shorter average distances because it places more residents in the populated parts of each census area. Station closures nevertheless produce the largest percentage increase in access distance under sparse-area decline, as in the main calculation.

Table H.2: Access-Distance Results Using the 2015 Population Mesh

|                                                  | Baseline | Uniform decline | Sparse-area decline | Dense-area decline |
|--------------------------------------------------|----------|-----------------|---------------------|--------------------|
| <i>Panel A. Number of waste stations fixed</i>   |          |                 |                     |                    |
| Population distributed evenly within census area | 162.2    | 162.2           | 152.1               | 167.6              |
| Population distributed using 2015 500-meter mesh | 121.5    | 121.5           | 114.9               | 124.8              |
| <i>Panel B. Number of waste stations adjusts</i> |          |                 |                     |                    |
| Population distributed evenly within census area | 162.2    | 163.7           | 157.6               | 168.9              |
| Population distributed using 2015 500-meter mesh | 121.5    | 122.9           | 119.5               | 126.1              |
| Closure-induced change, evenly distributed (%)   | –        | 0.92            | 3.65                | 0.74               |
| Closure-induced change, 2015 population mesh (%) | –        | 1.16            | 3.99                | 1.02               |

Note: Distance entries are population-weighted mean straight-line meters. The first calculation distributes each census area's population evenly over the 100-meter grid covering the full area. The second distributes population using the 2015 500-meter population mesh as described in the text. Both calculations use the same station closures and reassignment rule. Closure-induced changes compare station-adjustment with fixed-station outcomes within each scenario.

<sup>12</sup>The mesh reports population in 2015. I use it only to determine the relative distribution of population within each census area. I multiply the population assigned to all points in an area by the same factor so that their sum equals the area's 2020 census population.

<sup>13</sup>If a part is too small or narrow to contain a point from the fixed 100-meter grid, I evaluate the distance for the population assigned to that part at one representative point inside it.

## References

- Abrate, Graziano, Fabrizio Erbetta, Giovanni Fraquelli, and Davide Vannoni**, “Size and Density Economies in Refuse Collection,” in Thomas C. Kinnaman and Kenji Takeuchi, eds., *Handbook on Waste Management*, Edward Elgar Publishing, 2014, pp. 416–441.
- Ahlfeldt, Gabriel M. and Elisabetta Pietrostefani**, “The Economic Effects of Density: A Synthesis,” *Journal of Urban Economics*, 2019, 111, 93–107.
- Akai, Nobuo, Ryuji Kutsuzawa, and Toru Takemoto**, *Public Finance of Urban Spatial Management*, Yuhikaku, February 2025. In Japanese.
- Antonioli, Barbara and Massimo Filippini**, “Optimal Size in the Waste Collection Sector,” *Review of Industrial Organization*, 2002, 20 (3), 239–252.
- Apaydın, Ömer and Mustafa Talha Gönüllü**, “Route Time Estimation of Solid Waste Collection Vehicles Based on Population Density,” *Global NEST Journal*, 2011, 13 (2), 162–169.
- Beardwood, Jillian, J. H. Halton, and J. M. Hammersley**, “The Shortest Path through Many Points,” *Mathematical Proceedings of the Cambridge Philosophical Society*, October 1959, 55 (4), 299–327.
- Bensaid, Bernard, Solen Croiset, and Robert J. Gary-Bobo**, “Economies of Density, Team Synergies and Unobserved Heterogeneity: A Study of Home Care Services,” CESifo Working Paper 9864, CESifo July 2022.
- Boyer, Kenneth K., Andrea M. Prud’homme, and Wenming Chung**, “The Last Mile Challenge: Evaluating the Effects of Customer Density and Delivery Window Patterns,” *Journal of Business Logistics*, 2009, 30 (1), 185–201.
- Caves, Douglas W., Laurits R. Christensen, and Michael W. Tretheway**, “Economies of Density versus Economies of Scale: Why Trunk and Local Service Airline Costs Differ,” *The RAND Journal of Economics*, 1984, 15 (4), 471–489.
- Cohen, Robert H. and Edward H. Chu**, “A Measure of Scale Economies for Postal Systems,” in Michael A. Crew and Paul R. Kleindorfer, eds., *Managing Change in the Postal and Delivery Industries*, Boston, MA: Kluwer Academic Publishers, 1997, pp. 115–132.
- Daganzo, Carlos F.**, “The Distance Traveled to Visit  $N$  Points with a Maximum of  $C$  Stops per Vehicle: An Analytic Model and an Application,” *Transportation Science*, November 1984, 18 (4), 331–350.
- Dalla Chiara, Giacomo and Anne Goodchild**, “The Role of Walking in Last-Mile Urban Deliveries,” *Transportation*, 2025.
- Fischer, Vera, Meritxell Pacheco Paneque, Antoine Legrain, and Reinhard Bürgy**, “A Capacitated Multi-Vehicle Covering Tour Problem on a Road Network and Its Application to Waste Collection,” *European Journal of Operational Research*, 2024, 315 (1), 338–353.

- Ghiani, Gianpaolo, Antonio Guerrieri, Andrea Manni, and Emanuele Manni**, “Estimating Travel and Service Times for Automated Route Planning and Service Certification in Municipal Waste Management,” *Waste Management*, 2015, 46, 40–46.
- Harari, Mariaflavia**, “Cities in Bad Shape: Urban Geometry in India,” *American Economic Review*, 2020, 110 (8), 2377–2421.
- Hess, Christina, Alina-Gabriela Müller, Karl Franz Dörner, and Daniele Vigo**, “Waste Collection Routing: A Survey on Problems and Methods,” *Central European Journal of Operations Research*, 2024, 32 (2), 399–434.
- Hirsch, Werner Z.**, “Cost Functions of an Urban Government Service: Refuse Collection,” *Review of Economics and Statistics*, 1965, 47 (1), 87–92.
- Holmes, Thomas J.**, “The Diffusion of Wal-Mart and Economies of Density,” *Econometrica*, January 2011, 79 (1), 253–302.
- Hortas-Rico, Miriam and Albert Solé-Ollé**, “Does Urban Sprawl Increase the Costs of Providing Local Public Services? Evidence from Spanish Municipalities,” *Urban Studies*, 2010, 47 (7), 1513–1540.
- Houde, Jean-François, Peter Newberry, and Katja Seim**, “Nexus Tax Laws and Economies of Density in E-Commerce: A Study of Amazon’s Fulfillment Center Network,” *Econometrica*, January 2023, 91 (1), 147–190.
- Ihlanfeldt, Keith and Kevin Willardsen**, “Local Public Services Costs and the Geography of Development: Evidence from Florida Counties,” *Journal of Regional Science*, January 2018, 58 (1), 5–37.
- Ishikawa, Masanobu**, “A Logistics Model for Post-Consumer Waste Recycling,” *Journal of Packaging Science & Technology, Japan*, 1996, 5 (2), 119–130.
- Jaunich, Megan K., James W. Levis, Joseph F. DeCarolus, Eliana V. Gaston, Morton A. Barlaz, Shannon L. Bartelt-Hunt, Elizabeth G. Jones, Lauren Hauser, and Rohit Jaikumar**, “Characterization of Municipal Solid Waste Collection Operations,” *Resources, Conservation and Recycling*, November 2016, 114, 92–102.
- Ladd, Helen F.**, “Population Growth, Density and the Costs of Providing Public Services,” *Urban Studies*, 1992, 29 (2), 273–295.
- Maki, Seiya, Minoru Fujii, Mitsuhiro Murasaki, Takahiro Ohtagaki, and Kazutoshi Manabe**, “Verification Experiments on CO2 Reduction Planning from the Estimated Waste Collection Amount at Waste Stations Using Waste Collection Vehicle Route Log Data,” *Waste Management*, June 2025, 200, 114756.
- Matsui, Yasuhiro and Shogo Kasai**, “A Study on Operational Efficiency of Collection and Transport of Waste and Recyclables,” in “Proceedings of the Annual Conference of Japan Society of Material Cycles and Waste Management,” Vol. 29 2018, pp. 73–74. In Japanese.

**Miyauchi, Takashi and Tsuyoshi Setoguchi**, “Does Low Urban Density Increase Municipal Expenditure? Population Density as a Performance Target for Compact City Planning in Japan,” *Journal of Urban Management*, 2023, 12 (4), 375–384.

**Nakamura, Kazuyuki and Masanori Tahira**, “Distribution of Population Density and the Cost of Local Public Services: The Case of Japanese Municipalities,” Working Paper 231, Faculty of Economics, University of Toyama April 2008.

**OECD**, *Compact City Policies: A Comparative Assessment* OECD Green Growth Studies, Paris: OECD Publishing, 2012.

**Pandyaswargo, Andante Hadi, Chaoxia Shan, Akihisa Ogawa, Ryota Tsubouchi, and Hiroshi Onoda**, “Redesigning Municipal Waste Collection for Aging and Shrinking Communities,” *Smart Cities*, May 2024, 7 (3), 1149–1168.

**Tachibana, Junzo, Takuya Mori, Kouki Miyakubo, Jin Matsuzaki, and Kazutoshi Sakakibara**, “Development of Model for Planning the Layout of Waste Collection Points Taking into Account the Residents’ Consiousness,” *Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research)*, 2021, 77 (5), I\_317–I\_323. In Japanese.

**Tanaka, Ryuichi and Eric Weese**, “Inefficiency in School Consolidation Decisions,” RIETI Discussion Paper Series 23-E-002, Research Institute of Economy, Trade and Industry (RIETI) January 2023.