Online Supplement

Appendix A. Notation Summary

Parameter	Definition
A, ρ, N	area of the market, household density in the market, number of grocery stores
n	store index $n \in \{0, 1, 2, \ldots, N\}$, subscript refers to quantities relevant to store n
D_n,$h_n(z)$, p_n, ζ	demand of store n, number of customer household at distance z, per-unit retail price, grocery sourcing cost
S_n, β_n,$\bar{\beta}_n$, τ	quantity procured every period, fill rate, $\bar{\beta}_n \equiv 1 - \beta_n$, inter-replenishment time/sell-by duration
μ	expected rate of household's grocery consumption (Poisson-process generated)
d_n^θ, c, Γ	distance to store n of customer at location θ, cost per unit of distance traveled, fixed cost of store visit
q, p_o	quantity purchased to tide over the stockout, per-unit price of outside option
$E[T(Q)]$	expected length of the consumption cycle when basket size is Q
$\mathbb{C}_n$, Q_n,R_n	long-run cost, at cost-minimizing basket size Q_n of househ. shopping from store n, opt. grocery acquisit. rate
d_n^{-n},d_n^o,	distance "threshold" when customers switch to other stores, use outside option
$\bar{d}_n$, $\bar{d}$	highest distance at which customers still shop at store n: $\bar{d}_n \equiv \min\{d_n^{-n}, d_n^o\}$, $\bar{d} \equiv \sqrt{A/(4N)}$
m_n, σ_n^2, c_{vn}	mean store demand, variance of store demand, coefficient of variation $c_{vn} \equiv \sigma_n m_n^{-1}$
ψ_k, $P(Q, \mu T)$, $\bar{P}$,ϕ, Φ, $\bar{\Phi}$	$\psi_k \equiv \frac{(\mu T)^k}{k!} e^{-\mu T}$, $P(Q, \mu T) \equiv \sum_{j=0}^{Q} \psi_j(\mu T)$, $\bar{P} = 1 - P(Q, \mu T)$, pdf, cdf of standard normal, $\bar{\Phi} \equiv 1 - \Phi$
$\mathbb{I}\{x \in X\}$	indicator function, $\mathbb{I}\{x \in X\} = 1$ if $x \in X$, otherwise $\mathbb{I}\{x \in X\} = 0$
$\boldsymbol{z} = \{x\}$	in such expressions, $\{x\}$ signifies vector of length $\lvert\boldsymbol{z}\rvert$, all elements of which are x

Appendix B. Alternate Model Formulations

B.1. **Joint Price and Service Competition.** Our key findings arise from the dominance of the direct effects (access and scale) which are unaffected by the strategic variable. Thus, our main findings are unlikely to change even if stores competed by simultaneously setting price and service-levels. That said, it is worth noting that in our analysis increased competition has a much larger effect on prices than on service-levels (which is minimal). As a result, in so far as the strategic effects influence the analysis on the margin, they are likely to operate like they do in the price setting, and the joint analysis is likely identical to price setting.

B.2. **Lifetime of Household and Store Inventory.** *Store Shelf-Life:* For analytical tractability, we assumed the fresh items at the store are offered for sale only till the next replenishment cycle and are removed from the shelves afterward. If the leftover fresh inventory were carried to the next replenishment cycle, some of it would be used rather than discarded, thus reducing food waste at the store. Recall that store waste in our analysis was already relatively low as compared to household waste, and as such, its further reduction would only make it even less significant and strengthen our conclusions. Regarding households, the store will now provide a higher equilibrium service level (as the cost of leftover inventory at the end of the replenishment cycle would go down); however, a higher service level does not affect our key comparisons of household waste, the access effects drive the result and the higher store service will only further diminish the dominated strategic effects.

Household Shelf-Life: We assumed that the at-home-shelf-life does not depend on the time spend at stores by the product. Incorporating this dependency fully is hard. However, given that households do not know the exact amount of time the product spent in store, the remaining life could be viewed as random from household perspective. As we noted earlier, random shelf life does not change the outcome of our study. Typically, time spend in store is significantly lower than time spent at home and as such this assumption is only concerned with minor fluctuations to the at home life time.

B.3. **Fresh Goods and Dry (Non-perishable) Goods.** Our model considers a fresh-grocery retailer and focuses only on the fresh purchases of the households, yet households typically purchase fresh and dry (non-perishable) goods. An extension reveals that the relevant household replenishment behavior is driven by the consumption dynamics of perishable products; dry products are simply batched with the time-dependent perishable orders. Dry products can thus be included in the analysis with minor modifications. Unsurprisingly, incorporating dry products does not change any food-waste outcomes, and all comparisons at the heart of this study remain unaffected (for more details, see the consumer analysis in Belavina et al. (2017), which explicitly incorporates the role of dry goods and can be directly applied to the household analysis in this study).

B.4. **Cost of Sourcing.** Bigger stores might enjoy higher market power and could buy groceries at a lower price. If a bigger store can indeed source more cheaply, it may transfer some part of these gains to households and, thus, higher density might be associated with higher price, further reinforcing our findings that higher density lowers waste.

B.5. **Uniform Store and Household Density.** Our analysis assumed a uniform distribution of stores and households in the market area. A non-uniform household density has practically no impact on our analysis. The calculations for the number of household-customers (Lemma 6, Figure 4.1, Panel (c)), are more involved, and the driving effects are confounded with the household distribution, but non-uniformity has no significant impact on our analytical techniques.

The impacts of a non-uniform store distribution are also predictable, and our analysis guides us to the outcomes. Stores located closer to other stores (in high-density regions) face higher spatial competition and behave similarly to stores in markets with higher N or density, in the original analysis. On the other hand, stores in lower-density regions behave similarly to stores in markets with lower N. Interestingly, none of our key results (in section 6 or 8) depend on the density of the market (as long as it is high enough to represent a meaningful interaction between stores). As such, all our analysis equally applies to stores in dense regions and to stores in less dense regions. Overall, none of our key results are altered due to a non-uniform household/store distribution.

B.6. **Endogenous Market Entry.** We study the impact of density, without specifying any one particular action that results in the change, allowing our analysis to apply to any action that changes density. An alternate presentation of the results could explicitly consider the cost of establishing a store, endogenize market entry decisions and study the impact of reducing this costs. The above analysis and implications would remain equally valid in this presentation.

B.7. **Store Substitution on Stockout.** If households were to visit their second most preferred store on a stockout (as opposed to using an outside option), this decision would create another (second-order) linkage between different store demands, over and above the primary market competition. Given the relatively high service levels in our models, these effects are much smaller than the primary effects. Nevertheless, allowing for store demand substitution increases store service level (as shown in Netessine and Rudi 2003), reducing consumer waste and potentially increasing retail waste, though the effects are vanishingly small. Further recall the main effect arises out of the household's ease of access to groceries, and thus remain unchanged.

B.8. **Travel Emissions.** Although travel emissions are much smaller than food-waste emissions (Belavina et al. 2017), thinking of the impact density on these emissions is interesting. An increase in density will also reduce travel emissions (Cachon 2014), enhancing our main result on the environmental benefits of higher density.

Appendix C. Additional Lemmas

The following technical assumptions are used for proofs of Lemmas and Theorems: $P(Q,\mu T) - \frac{\psi_Q}{\bar{P}} - Q\partial_Q \frac{\psi_Q}{\bar{P}} < 0$; $E[T(Q_n)] > \mu^{-1}q$; $2\delta(\beta_\delta \bar{d}) > \delta(\bar{d})$, here $8\rho[\int_0^{\bar{d}} 2z\delta(z)dz] \equiv 8\rho\frac{1}{2}\bar{d}^2 2\delta(\beta_\delta\bar{d})$; $-\partial_N \frac{\delta(\bar{d})}{2\sigma_n} > 0$; $\partial_{v_n}\delta \leq 0$, $\partial_Q\delta_n(z) > 0$; $\Delta(\bar{d}) < 2\Delta(z)$; $\partial_Q A_\xi(z) > 0$ for all z. These hold for reasonable parameter values.

Lemma 5. ***Expected Mean and Variance of Cycle Time***

For basket-size Q purchased from store n, expected mean and variance of cycle time are, respectively, given by $E[T(Q)] = \beta_n E[CT(Q)] + \bar{\beta}_n\mu^{-1}q$ *and* $var[T(Q)] = \beta_n E[(CT(Q))^2] + \bar{\beta}_n(\frac{q}{\mu^2} + \frac{q^2}{\mu^2}) - E[T(Q)]^2$. *Here,* $E[CT(Q)] = \mu^{-1}(Q - \omega(Q))$ *and* $E[(CT(Q))^2] = \mu^{-2}\{Q(Q+1) - \sum_{k=0}^{Q}[Q(Q+1) - k(k-1)]\psi_k\}$. *Further,* $\partial_Q \frac{var[CT(Q)]}{E[CT(Q)]} < 0$.

Proof. Cycle time as a function of order quantity Q is a random variable, upon stockout $T(Q) = t_q$ and in no stock-out situation $T(Q) = CT(Q) \equiv \min\{t_Q, T\}$; random variable t_x has Erlang-x distribution and captures time of x consumption instances (arrivals of the Poisson Process). Now $E[t_q] = \int_0^\infty t\mu\frac{(\mu t)^{q-1}}{(q-1)!}e^{-\mu t}dt = \mu^{-1}q$ and $E[CT(Q)] = \int_0^\infty \min\{T,t\}\mu\frac{(\mu t)^{Q-1}}{(Q-1)!}e^{-\mu t}dt = \mu^{-1}(Q - \omega(Q))$. As stockout happens with probability β_n, $E[T(Q)] = \beta_n E[CT(Q)] + (1-\beta_n)\mu^{-1}q$. *One* of the customers might experience partial stockout; that is, stock available at the store is less than Q. Given that the overall number of customers is substantially higher than one, we ignore this.

Variance of cycle time by definition is $var[T(Q)] = E[T^2(Q)] - (E[T(Q)])^2$. Now $E[T^2(Q)] = \beta_n E[(CT(Q))^2] + (1-\beta_n)E[t_q^2]$, with $E[(CT(Q))^2] = \int_0^\infty (\min\{T,t\})^2\mu\frac{(\mu t)^{Q-1}}{(Q-1)!}e^{-\mu t}dt$, which, after a series of manipulations, transforms into $E[(CT(Q))^2] = \mu^{-2}\{Q(Q+1) - \sum_{k=0}^{Q}[Q(Q+1) - k(k-1)]\psi_k\}$ and $E[t_q^2] = \int_0^\infty t^2\mu\frac{(\mu t)^{q-1}}{(q-1)!}e^{-\mu t}dt = (\frac{q}{\mu^2} + \frac{q^2}{\mu^2})$.

Finally, to show $\partial_Q \frac{var[CT(Q)]}{E[CT(Q)]} < 0$, we need to obtain $\partial_Q \frac{var[CT(Q)]}{E[CT(Q)]} = \mu^{-3}\bar{P}\perp(Q)E[CT(Q)]^{-2} < 0$, here $\perp(Q) = (2Q + 1 - 2Q\frac{\psi_Q}{\bar{P}})(Q\bar{P} + \sum_{k=0}^{Q} k\cdot\psi_k) - Q(Q+1)\bar{P} - \sum_{k=0}^{Q} k(k-1)\psi_k - (Q\bar{P} + \sum_{k=0}^{Q} k\cdot\psi_k)^2$, $\bar{P} = (1 - P(Q,\mu T))$. Note $\perp(0) = 0$, that is, if $\perp(Q)$ is a decreasing function of Q ($\partial_Q\perp(Q) < 0$), it would imply $\perp(Q) \leq 0$ and $\partial_Q \frac{var[CT(Q)]}{E[CT(Q)]} < 0$. Now $\partial_Q\perp(Q) = 2\mu E[CT(Q)](P(Q,\mu T) - \frac{\psi_Q}{\bar{P}} - Q\partial_Q\frac{\psi_Q}{\bar{P}})$, because $P(Q,\mu T) - \frac{\psi_Q}{\bar{P}} - Q\partial_Q\frac{\psi_Q}{\bar{P}} < 0$ and $E[CT(Q)] > 0$ for $Q > 0$ we obtain the desired result.

□

Lemma 6. ***The number of customer-households of store** n **located at a dist.*** *z is* $\mathbb{I}\{z < \bar{d}_n\}h_n(z; p_n, \beta_n, \boldsymbol{p}_{-n}, \boldsymbol{\beta}_{-n})$, *$h_n = 4\rho\cdot 2z$ for $0 < z \leq \underline{d}_n$ and $h_n = 4\rho\cdot 2(z + 2\chi_n - 2\bar{d})$, for $\underline{d}_n < z \leq d_n^{-n}(p_n, \beta_n, \boldsymbol{p}_{-n}, \boldsymbol{\beta}_{-n})$. Here, $\underline{d}_n$ is a solution to $\mathbb{C}(\underline{d}_n, p_n, \beta_n) = \mathbb{C}(\bar{d}, p_{-n}, \beta_{-n})$ if $v_n < v_{-n}$ and $\underline{d}_n = d_n^{-n}$ if $v_n \geq v_{-n}$, d_n^{-n} is implicitly defined as $\mathbb{C}(d_n^{-n}, p_n, \beta_n) = \mathbb{C}(2\bar{d} - d_n^{-n}, p_{-n}, \beta_{-n})$, $v \in \{p, -\beta\}$. Function $\chi_n(z)$ is implicitly given by $\mathbb{C}(z, p_n, \beta_n) = \mathbb{C}(\chi_n, p_{-n}, \beta_{-n})$.*

Proof. A household located at distance z from store n will consider shopping from store n only if her cost is lower than the outside option, $\mathbb{C}(z, p_n, \beta_n) \leq p_o\mu$. In the proof of Lemma 1 we establish $\mathbb{C}_n = \mu p_n\bar{P}^{-1}$, and it is increasing in

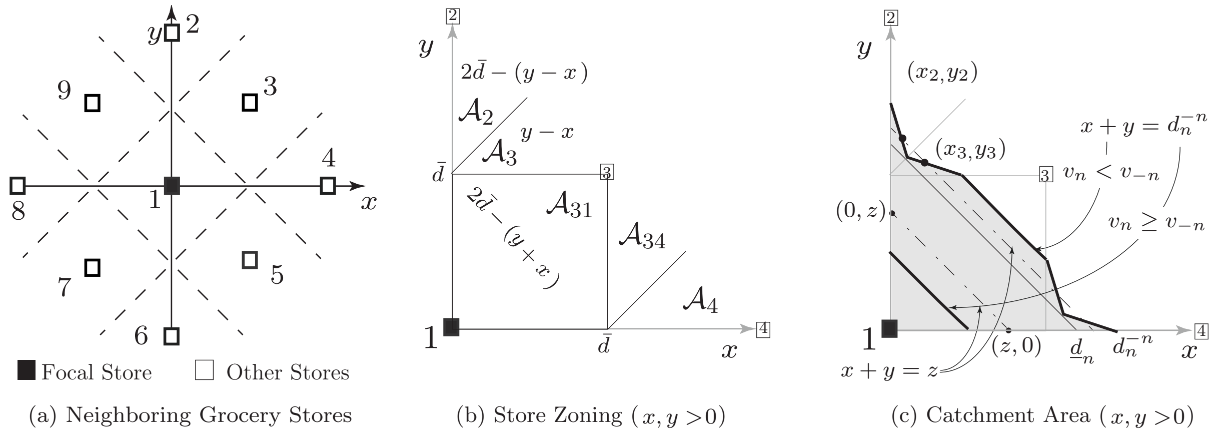


FIGURE C.1. Focal Store 1: Neighborhood and Catchment Area

distance. That is, a distance from the store n, d_n^o, exists beyond which the households would rather shop from an outside option, and d_n^o is a unique solution to $P\left(Q^*(d_n^o, p_n, \beta_n), \mu T\right) = 1 - p_n p_o^{-1}$. We next explore when a household would shop from store n rather than another store. Here and in derivation of number of customer-household at distance z, we consider the range of p_n/β_n such that the service area of store n does not spread beyond the neighboring stores, and all other stores set the same price/service level $\boldsymbol{p}_{-n} = \{p_{-n}\}$ and $\boldsymbol{\beta}_{-n} = \{\beta_{-n}\}$, and the non-decision variable of store n is set at the market level. Consider a focal store $n = 1$ surrounded by the neighboring stores, as depicted on Figure C.1 (a). Due to symmetry, we can focus only on one fourth of the picture as depicted on Figures C.1 (b) and simply multiply the resulting number by 4ρ, hence 4ρ in the expression for h_n. On Figure C.1 (b) in the area labeled 2 , store 1 competes with store 2; in the area labeled 4, it competes with store 4, and in 3, with store 3 (as in these areas the respective stores offer the lowest cost as compared to all other stores but store 1). Figure C.1 (b) also provides distances to the competing store: for example in area 2, distance to store 2 for a point within this area that has coordinates (x_2, y_2) is $2\bar{d} - (y_2 - x_2)$.

The border of the catchment area–the solid line surrounding the grey area on Figures 4.1(b) and C.1(c), is given by $\mathbb{C}(z, p_n, \beta_n) = \mathbb{C}(\chi_n, p_{-n}, \beta_{-n})$. Here, $z = x + y$ denotes the distance to store 1, χ_n denotes the distance to the nearest competing store. It depends on which area point (x, y) falls in: $\chi_n = 2\bar{d} - (y - x)$ for $(x, y) \in \mathcal{A}_2$, $\chi_n = y - x$ for $(x, y) \in \mathcal{A}_3$ and $\chi_n = 2\bar{d} - (x + y)$ for $(x, y) \in \mathcal{A}_{31}$.

If $v_n \geq v_{-n}$, the border of the catchment area lies only within 3_1 and is simply a side of a rhombus. When prices/service levels are equal, stores share the market equally. If $v_n < v_{-n}$, the border of the catchment area lies within areas 2, 3, and 4 (Figure C.1 c). In this case the shape of the catchment area is no longer a rhombus, it is a super-ellipse-like area. The super-ellipse-like shape is due to the non-linearity of the household cost function. Distance $x_2 + y_2 = \underline{d}_n$ is the distance from origin to a coordinate (x_2, y_2) with $y_2 = \bar{d} + x_2$ (in area 2), that is, it is defined from $\mathbb{C}(\underline{d}_n, p_n, \beta_n) = \mathbb{C}(\bar{d}, p_{-n}, \beta_{-n})$, $v_n < v_{-n}$. When $v_n \geq v_{-n}$, however, $\underline{d}_n = d_n^{-n}$. Further, d_n^{-n} is the distance to store 1 of farthest point (x, y) within the catchment area, this point lies within area 3_1, and the expression for d_n^{-n} now also follows.

The number of customer-households at distance z is obtained by considering the "l_1-norm-length" of the iso-(l_1)-distance lines that lie within the catchment area (the part of the dash-dot lines, $x + y = z$, in Figure C.1(c) that lies in the shaded area). For $x + y = z \leq \underline{d}_n$, the distance is simply part of the segment of line $x + y = z$ between two points $(0, z)$ and

$(z,0)$. This length is $2z$ in l_1-norm. For greater distances from the store $x+y=z>\underline{d}_n$, it is the full length $2z$ minus the part outside the shaded area–between points (x_2,y_2) and (x_3,y_3) and their counterparts in area 3_4 and 4. This distance in l_1-norm is $2z-2[x_3-x_2+y_2-y_3]$, using $2\bar{d}-(y_2-x_2)=\chi_n$ and $y_3-x_3=\chi_n$ we can transform this into $2(z+2\chi_n-2\bar{d})$. This concludes the derivation of h_n. The indicator function $\mathbb{I}\{z<\bar{d}_n\}$ captures the loss of customers to both the outside option and the other stores.

□

Lemma 7. *Mean and variance of store demand are (respectively) given by m_n and σ_n^2.*

Proof. A contiguous "catchment area" for each store n: $\Theta_n \equiv \{\theta \,|n=\arg\min\{\mathbb{C}_n\}_{n\in\{0,1,\dots,N\}}\}$: households within the catchment area choose store n. Denote by $N_n^\theta(t)$ a counting process for number of visits to store n by time t for customer at location θ who buys optimal quantity Q_n. Thus, $E[D_n]=\rho\int_{\Theta_n} Q_n(E[N_n^\theta(t+\tau)]-E[N_n^\theta(t)])d\theta$. The times of grocery purchases constitute stopping times (given our assumption that the households' ex-ante odds of finding groceries at the store are the same at any point in time, see the manuscript), from the elementary renewal theorem, $E[N_n^\theta(t)]\approx\frac{1}{E[T(Q_n)]}t$, and thus $E[D_n]\approx\rho\int_{\Theta_n} Q_n\frac{\tau}{E[T(Q_n)]}d\theta$. Now $var[D_n]=\rho\int_{\Theta_n}(Q_n)^2(var[N_n^\theta(\tau)])d\theta$. This expression also obtained using the independence of individual demands of the households (and thus their store visits) and the elementary renewal theorem. The only source that introduces potential correlation in demands (store visits) of different customers is the stockout at the store. Given large number of the customers that shop at each store, and low enough probability of stockout, we can ignore/neglect these correlations. Mikosch (2009) proposition 2.2.10 shows $var[N_n^\theta(t)]\approx\frac{var[T(Q_n)]}{(E[T(Q_n)])^3}t$. Expression for σ_n^2 now follows.

□

Appendix D. Proofs

Section A provides a summary of the notation used.

D.1. **Proof of Lemma 1.** Optimal order quantity Q_n is a solution $\partial_Q\mathbb{C}(d_n^\theta,p_n,\beta_n,Q)=0$ with $\mathbb{C}_n=\mu p_n\bar{P}^{-1}$. Next, we establish the sign of $\partial_v\mathbb{C}_n$: $\partial_{d_n^\theta}\mathbb{C}_n=2cE[T(Q_n)]^{-1}>0$, $\partial_{p_n}\mathbb{C}_n=\beta_nR_n>0$ and $\partial_{\beta_n}\mathbb{C}_n=(\beta_nE[T(Q_n)])^{-1}\{(\mathbb{C}_n\mu^{-1}-\beta_np_o)q+E[T(Q_n)](\beta_np_nR_n-\mathbb{C}_n)\}<0$. The last inequality due to the fact that a household will shop from store n only if $\mathbb{C}_n\le\mu p_o$, using $\mathbb{C}_n=\beta_np_nR_n+E[T(Q_n)]^{-1}(\Gamma+2cd_n^\theta+(1-\beta_n)p_oq)$ we obtain $\partial_{\beta_n}\mathbb{C}_n\le-(\beta_nE[T(Q_n)])^{-1}(\Gamma+2cd_n^\theta)<0$. Next, because Q_n is defined from $\mathbb{C}_n=\mu p_n\bar{P}^{-1}$, using the implicit function theorem, $\partial_v\mathbb{C}_n+\partial_{Q_n}\mathbb{C}_nQ_n=\frac{1}{p_n}\mathbb{C}_n\partial_vp_n+\mu p_n\bar{P}^{-2}\psi_{Q_n}\partial_vQ_n$. Due to the optimality of Q_n, $\partial_{Q_n}\mathbb{C}_n=0$; $\mu p_n\bar{P}^{-2}\psi_{Q_n}>0$, and because $\partial_vp_n=0$, for $v\in\{\beta_n,d_n^\theta\}$, the sign of ∂_vQ_n coincides with that of $\partial_v\mathbb{C}_n$ for $v\in\{\beta_n,d_n^\theta\}$. Now $\frac{1}{p_n}(\beta_np_nR_n-\mathbb{C}_n)=\frac{\mu p_n}{(1-P(Q_n,\mu T)^2}\psi_{Q_n}\partial_{p_n}Q_n$, and because $\beta_np_nR_n-\mathbb{C}_n<0$, we obtain $\partial_{p_n}Q_n<0$. Further, $\partial_v\omega_n=P\partial_vQ_n$ and its sign coincides with that of ∂_vQ_n.

It only remains to establish the sign of ∂_vR_n= $E[T(Q_n)]^{-1}\{\partial_vQ_n(1-R_n\partial_{Q_n}E[T(Q_n)])-R_n\partial_vE[T(Q_n)]\}$. Here, $1-R_n\partial_{Q_n}E[T(Q_n)]=1-\frac{\beta_np_nR_n}{\mathbb{C}_n}>0$, $\partial_{p_n}E[T(Q_n)]=\partial_{d_n^\theta}E[T(Q_n)]=0$ and $\partial_{\beta_n}E[T(Q_n)]>0$ (if $E[T(Q_n)]>\mu^{-1}q$). With this, we obtain $\partial_vR_n<0$, $v\in\{\beta_n,p_n,-d_n^\theta\}$.

D.2. **Proof of Lemma 2.** Derivative $d_{v_n}m_n=\tau[\int_0^{\bar{d}_n}(\partial_{v_n}R_n)h_ndz+\int_0^{\bar{d}_n}R_n(\partial_{v_n}h_n)dz+R(\bar{d}_n)h_n(\bar{d}_n)\partial_{v_n}\bar{d}_n]$, with $\partial_{p_n}R_n<0$ and $\partial_{-\beta_n}R_n>0$ (Lemma 1). For $z<\underline{d}_n$ and $z>d_n^{-n}$, $\partial_{v_n}h_n=0$; for $\underline{d}_n<z\le d_n^{-n}$, $\partial_{v_n}h_n(z)=16\rho\partial_{v_n}\chi_n(z)<0$, as $(\partial_{v_n}\chi_n)\partial_y\mathbb{C}(y,p_{-n},\beta_{-n})|_{y=\chi_n}=-\partial_{v_n}\mathbb{C}(z,p_n,\beta_n)$. From the proof of Lemma 1, $\partial_y\mathbb{C}>0$ and

$\partial_{v_n}\mathbb{C} > 0$, and thus $\partial_{v_n}\chi_n(z) < 0$, $v \in \{p, -\beta\}$. This establishes $\partial_{v_n}h_n \le 0$, $v \in \{p, -\beta\}$. Using the implicit function theorem, $\partial_{d_n^o}Q_n\partial_{v_n}d_n^o = -\psi_{Q_n}\partial_{v_n}Q_n - p_o^{-1}\partial_{v_n}p_n$. From the proof of Lemma 1, $\partial_{d_n^o}Q_n > 0$, $\partial_{p_n}Q_n < 0$, $\partial_{-\beta_n}Q_n > 0$, and $\psi_{Q_n}\partial_{p_n}Q_n = \frac{\mu}{\mathbb{C}_n^2}(\beta_n p_n R_n - \mathbb{C}_n)$. Thus, $-\psi_{Q_n}\partial_{p_n}Q_n - p_o^{-1} = p_o^{-1}(\frac{\mu p_o}{\mathbb{C}_n^2}(\mathbb{C}_n - \beta_n p_n R_n) - 1)$ =(at d_n^o $\mathbb{C}_n = \mu p_o$)$= -\frac{\beta_n p_n R_n}{p_o \mathbb{C}_n} < 0$. This establishes $\partial_{v_n}d_n^o < 0$, $v \in \{p, -\beta\}$. Using the implicit function theorem, $(\partial_z\mathbb{C}(z, p_n, \beta_n)|_{z=d_n^{-n}} + \partial_z\mathbb{C}(z, p_{-n}, \beta_{-n})|_{z=2\bar{d}-d_n^{-n}})\partial_{v_n}d_n^{-n} = -\partial_{v_n}\mathbb{C}(d_n^{-n}, p_n, \beta_n)$. From the proof of Lemma 1, $\partial_z\mathbb{C} > 0$ and $\partial_{v_n}\mathbb{C} > 0$, and thus $\partial_{v_n}d_n^{-n} < 0$, $v \in \{p, -\beta\}$. The threshold $\bar{d}_n = \min\{d_n^{-n}, d_n^o\}$, jointly $\partial_{v_n}d_n^{-n} < 0$ and $\partial_{v_n}d_n^o < 0$ imply $\partial_{v_n}\bar{d}_n < 0$, $v \in \{p, -\beta\}$. Together, $\partial_{p_n}R_n, \partial_{p_n}h_n, \partial_{p_n}\bar{d}_n \le 0$ imply $d_{p_n}m_n < 0$, whereas $\partial_{\beta_n}R_n < 0$ and $\partial_{\beta_n}h_n, \partial_{\beta_n}\bar{d}_n \ge 0$ leave the sign of $d_{\beta_n}m_n$ ambiguous.

D.3. **Proof of Lemma 3.** We next explore demand variance σ_n^2. Using $\delta \equiv R_n^2\frac{var[T(Q_n)]}{E[T(Q_n)]}$, we can express $\partial_{v_n}\sigma_n^2 \equiv \tau[\int_0^{\bar{d}_n}\partial_{v_n}\delta h_n dz + \int_0^{\bar{d}_n}\delta(\partial_{v_n}h_n)dz + \delta(\bar{d}_n)h_n(\bar{d}_n)\partial_{v_n}\bar{d}_n]$, because $\partial_{p_n}\delta, \partial_{p_n}h_n, \partial_{p_n}\bar{d}_n \le 0$ (as shown in the proof of Lemmas 2, 1 and 5) we obtain $\partial_{p_n}\sigma_n^2 < 0$, whereas $\partial_{\beta_n}\delta < 0$ and $\partial_{\beta_n}h_n, \partial_{\beta_n}\bar{d}_n \ge 0$ leave the sign of $\partial_{\beta_n}\sigma_n^2$ ambiguous.

We next explore demand variability as captured by the coefficient of variation $c_{vn} = m_n^{-1}\sigma_n$, with $\partial_{v_n}c_{vn} = (2\sigma_n m_n^2)^{-1}\xi$, where $\xi \equiv m_n\partial_{v_n}\sigma_n^2 - 2\sigma_n^2\partial_{v_n}m_n$. Using $\Delta = R_n\frac{var[T(Q_n)]}{E[T(Q_n)]}$, $A = (\partial_{v_n}R_n)h_n + R_n(\partial_{v_n}h_n)$, $B = R(\bar{d}_n)h_n(\bar{d}_n)\partial_{v_n}\bar{d}_n$, and $D = R_n h_n$, we can express $\xi = \tau^2\{\int_0^{\bar{d}_n}(\int_0^{\bar{d}_n}([\Delta(y) - 2\Delta(z)]A(y) + (\partial_{v_n}R_n + R_n\partial_{v_n}\frac{var[T(Q_n)]}{E[T(Q_n)]})D(y))dy + [\Delta(\bar{d}_n) - 2\Delta(z))]B)D(z)dz\}$. For $v_n = p_n$, A, $B \le 0$, $D \ge 0$ and $\partial_z\Delta(z) = (\partial_{Q_n}\Delta)\partial_z Q_n > 0$ ($\partial_{Q_n}\Delta > 0$ and $\partial_z Q_n > 0$, $\partial_{p_n}\frac{var[CT(Q_n)]}{E[CT(Q_n)]} > 0$ as per Lemmas 5 and 1). As a result, $\xi > 0$ and $\partial_{p_n}c_{vn} > 0$, whereas the sign of $\partial_{\beta_n}c_{vn}$ is again ambiguous as $\partial_{\beta_n}R_n, \partial_{\beta_n}(var\,[T(Q_n)]\,E\,[T(Q_n)]^{-1}) < 0$ and $\partial_{\beta_n}h_n, \partial_{\beta_n}\bar{d}_n \ge 0$.

D.4. **Proof of Lemma 4.** Equations 5.2 and 5.3 are the first-order conditions for the respective optimization problems.

D.5. **Proof of Theorem 1.** We first establish the direct (access) effect of higher store density on consumer waste W_c, $\partial_N W_c = \int_0^{\bar{d}} w(z)(h_n + N\partial_N h_n)dz + Nw(\bar{d})h_n(\bar{d})\partial_N\bar{d}$. Here, $\partial_N h_n = 0$ and $\partial_N\bar{d} = -\frac{1}{2}\frac{1}{N}\bar{d} < 0$. With this, $\partial_N W_H = 8\rho[\int_0^{\bar{d}} w(z)zdz - \frac{1}{2}\bar{d}w(\bar{d})\bar{d}]$, $\partial_N W_H = 8\rho[\int_0^{\bar{d}}\{w(z)z - w(\bar{d})\frac{1}{2}\bar{d}\}dz]$. As $w(z) \le w(\bar{d})$ for all $z \in [0, \bar{d}]$, we obtain $\partial_N W_H < 0$. Using $\int_0^{\bar{d}} w(z)zdz \equiv w(\underline{d})\frac{1}{2}\bar{d}^2$, we obtain $\partial_N W_H = -N^{-1}(w(\bar{d}) - w(\underline{d}))A\rho$.

Using the implicit function theorem, $\frac{dp^*}{dN} = \wp\partial_N\mathbb{P}(p^*)$, $\wp = -(\partial_{p^*}^2\pi_n(p^*))^{-1}$. Given concavity at the optimum ($\partial_{p^*}^2\pi_n(p^*) < 0$), to ensure that equilibrium price is decreasing with higher density we only need to ensure $\mathcal{P}(p^*) \equiv -\partial_N\mathbb{P}(p^*) > 0$ and we obtain $\frac{dp^*}{dN} = -\wp\mathcal{P}(p^*) < 0$. In derivation of expression for $\mathcal{P}(p^*)$, we used $\partial_{s_n}\xi_m^{ss} = \frac{\phi(s_n)}{\Phi(s_n)}\frac{\bar{\beta}_n}{\Phi(s_n)}$ and $\partial_{s_n}\xi_\sigma^{ss} = \frac{\phi(s_n)}{\Phi(s_n)}\frac{\bar{\beta}_n}{\Phi(s_n)}\frac{1}{c_{vn}}$, $\partial_N c_{vn} = \frac{1}{m_n}[\partial_N\sigma_n - c_{vn}(\partial_N m_n)]$ and $\frac{dc_{vn}}{dp_n} = \frac{1}{m_n}[\frac{d\sigma_n}{dp_n} - c_{vn}\frac{dm_n}{dp_n}]$, $\partial_N s_n = \frac{\bar{\beta}_n}{\Phi(s_n)}\frac{\partial_N c_{vn}}{c_{vn}^2}$. Further $\frac{dW_c}{dp^*} = N\int_0^{\bar{d}}(\partial_{p^*}Q^*(z)\partial_Q w(z))h(z)dz \equiv -\xi_{p^*}^{wc}$, as $\partial_{p^*}h_n = 0$ (due to symmetry of equilibrium) and $\partial_{p^*}\bar{d} = 0$. $\partial_Q w(z) = \beta_n\frac{1}{\mu E[T]^2}\{\beta_n\sum_{k=0}^{Q} k\psi_k + \bar{\beta}_n qP\} > 0$; since $\partial_{p^*}Q^* < 0$ we obtain $\frac{dW_c}{dp^*} \equiv -\xi_{p^*}^{wc} < 0$.

Finally, condition 6.2 is obtained from: $\frac{dW_c}{dN} = \frac{\partial W_c}{\partial N} + \frac{dW_c}{dp^*}\frac{dp^*}{dN} = -N^{-1}(w(\bar{d}) - w(\underline{d}))A\rho + \wp\mathcal{P}(p^*)\,\xi_{p^*}^{wc} < 0$.

As for the individual components of $\mathcal{P}(p^*)$ we have: $\partial_N m_n = \tau[\int_0^{\bar{d}}(\partial_N R_n)h_n dz + \int_0^{\bar{d}} R_n(\partial_N h_n)dz + R(\bar{d})h_n(\bar{d})\partial_N\bar{d}]$, where $h_n(z; p_n, \beta_n, \{p_n\}, \{\beta_n\}) = 8\rho z$, due to symmetry of the equilibrium. Here, $\partial_N R_n = 0$, $\partial_N h_n = 0$ and $\partial_N\bar{d} < 0$. This establishes $\partial_N m_n < 0$. Similarly, $\partial_N\sigma_n^2 = \tau\delta_n(\bar{d})h_n(\bar{d})\partial_N\bar{d} < 0$, $\delta_n(z) = R(z, p^*)\,\Delta(z)$, $\Delta(z) = R(z, p^*)\,\frac{var[T(Q^*(z,p^*))]}{E[T(Q^*(z,p^*))]}$, $\partial_N c_{vn} = (2\sigma_n m_n^2)^{-1}\xi$, $\xi \equiv m_n\partial_N\sigma_n^2 - 2\sigma_n^2\partial_N m_n$ $=[\int_0^{\bar{d}_n}(\Delta(\bar{d}) - 2\Delta(z))R_n h_n dz]\tau^2 R(\bar{d})h_n(\bar{d})\partial_N\bar{d}$. With, $\int_0^{\bar{d}_n}(\Delta(\bar{d}) - 2\Delta(z))R_n h_n dz < 0$ and $\partial_N\bar{d} < 0$ we establish $\partial_N c_{vn} > 0$.

Finally, for $\partial_N\partial_{v_n}m_n=\tau[\int_0^{\bar d}(\partial_{v_n}R_n)(\partial_N h_n)+R_n(\partial_N\partial_{v_n}h_n)dz+[\partial_{v_n}R_n|_{z=\bar d}h_n(\bar d)+R_n(\bar d)(\partial_{v_n}h_n)|_{z=\bar d}]\partial_N\bar d$, and $2\sigma\partial_N\partial_{v_n}\sigma_n=-\sigma_n^{-1}\partial_N\sigma_n+\tau[\int_0^{\bar d}(\partial_{v_n}\delta)(\partial_N h_n)+\delta(\partial_N\partial_{v_n}h_n)dz+[(\partial_{v_n}\delta|_{z=\bar d})h_n+\delta(\bar d_n)(\partial_{v_n}h_n)|_{z=\bar d}]\partial_N\bar d$, here $\partial_N h_n=0$, $\partial_{v_n}R_n,\partial_N\bar d,\partial_{p_n}h_n$, $\partial_{v_n}\delta\le 0$ and $\partial_N\partial_{p_n}h_n\ge 0$, this establishes $\partial_N\partial_{p_n}m_n,\partial_N\partial_{p_n}\sigma_n>0$.

D.6. **Proof of Theorem 2.** We now establish the direct effect of higher store density on retail waste W_r. Using implicit expression for $\sigma_n s_n$: $\sigma_n s_n=-\sigma_n\bar\Phi(s_n)^{-1}\int_{-\infty}^{s_n}z\phi(z)dz-\bar\Phi(s_n)^{-1}m_n\bar\beta_n$, we obtain $\partial_N W_r=\tau^{-1}\{\xi_\sigma^{ss}\partial_N(N\sigma_n)-\xi_m^{wr}\partial_N(Nm_n)\}$, as we show next $-\partial_N(Nm_n),\partial_N(N\sigma_n)>0$ and we obtain $\partial_N W_r>0$. Now, $\partial_N(Nm_n)=m_n+N\partial_N(m_n)=8\rho[\int_0^{\bar d}(zR(z)-\frac{1}{2}\bar d_n R(\bar d_n))dz]$. As $R(z)\le R(\bar d)$ for all $z\in[0,\bar d]$, we obtain $\partial_N(Nm_n)<0$. Now, $\partial_N(N\sigma_n)=\frac{1}{2\sigma_n}(2\sigma_n^2+N\partial_N\sigma_n^2)=8\rho\frac{1}{2\sigma_n}[\int_0^{\bar d}(2z\delta(z)-\frac{1}{2}\bar d\delta(\bar d))dz]>0$ if $2\delta(\beta_\delta\bar d)>\delta(\bar d)$, here $8\rho[\int_0^{\bar d}2z\delta(z)dz]\equiv 8\rho\frac{1}{2}\bar d^2 2\delta(\beta_\delta\bar d)$.

We next sign $\frac{dW_r}{dp^*}\frac{dp^*}{dN}$. From proof of Theorem 1 we know $\frac{dp^*}{dN}=-\wp\mathcal{P}(p^*)$, we next obtain expression for $\frac{dW_r}{dp^*}$. Following similar procedure to obtaining $\partial_N W_r$ we get $\tau\frac{dW_r}{dp^*}=\xi_\sigma^{ss}\frac{d}{dp^*}(N\sigma_n)-\xi_m^{wr}\frac{d}{dp^*}(Nm_n)=N(\xi_\sigma^{ss}\frac{d\sigma_n}{dp^*}-\xi_m^{wr}\frac{dm_n}{dp^*})$, from Lemmas 2 and 3 $\frac{dm_n}{dp^*}$, $\frac{d\sigma_n}{dp_n}<0$ and in general the sign of $\frac{dW_r}{dp^*}$ is ambiguous. Retail waste increases with price iff $\xi_{p^*}^{wr}>0$. Thus, lower equilibrium price ($\mathcal{P}(p^*)>0$) leads to retail waste decrease iff $\frac{dW_r}{dp^*}\frac{dp^*}{dN}=-\tau^{-1}\wp\mathcal{P}(p^*)\xi_{p^*}^{wr}<0\iff\mathcal{P}(p^*)\xi_{p^*}^{wr}>0$ as $\tau,\wp>0$. Condition of part (ii) now follows.

Altogether, retail waste is higher with higher store density iff $\frac{dW_r}{dN}=\frac{\partial W_r}{\partial N}+\frac{dW_r}{dp^*}\frac{dp^*}{dN}>0$, condition 6.5 now also follows.

D.7. **Proof of Theorem 3.** We first establish existence and uniqueness of $\hat N$. We show $\partial_N W=A\rho N^{-1}(*)+(**)$, here $(**)\equiv\tau^{-1}\xi_\sigma^{ss}\partial_N(N\sigma_n)>0$, $(*)$ crosses zero only once and that as long as $(*)<0$ market waste W is convex in N ($\partial_N^2W>0$), existence and uniqueness of $\hat N$ then follows. Using $w(z)=\frac{\beta_nQ(z)+\bar\beta_nq}{E[T(z)]}-\mu$, $\bar x=\beta_n-\xi_m^{wr}$, $A_\xi(z)=\frac{\bar xQ(z)+\bar\beta_nq}{E[T(z)]}$ we can express $(*)\equiv A_\xi(\hat z)-A_\xi(\bar d)$, $\hat z\in[0,\bar d]$. From $(*)<0\Leftrightarrow A_\xi(\bar d)>A_\xi(\hat z)$ it follows $\partial_zA_\xi(z)|_{\bar d}>0$, as $\partial_zA_\xi(z)=\partial_zQ\frac{\mu^{-1}}{E[T]^2}B$ crosses zero only once ($\partial_zQ\frac{\mu^{-1}}{E[T]^2}>0$ and $B=\bar x\beta_n\sum_{k=0}^{Q}k\cdot\psi_k+\bar\beta_nq[\bar x-\beta_n\bar P]$, $\partial_zB=\partial_zQ\bar x\beta_nQ\cdot\psi_Q>0$) and it has to cross zero at $z<\bar d$ because $A_\xi(\bar d)>A_\xi(\hat z)$ and $\bar d>\hat z$. Further, $\partial_N^2W\equiv(1)+(2)+(3)$, where $(1)\equiv 2\rho\frac{1}{N}\bar d^3\partial_zA_\xi(z)|_{\bar d}$, $(2)\equiv\frac{1}{\tau}\bar\beta_n^2\bar\Phi(s_n)^{-2}N(\frac{m_n}{\sigma_n}\partial_N\sigma_n-\partial_Nm_n)^2\phi(s_n)\bar\Phi(s_n)^{-1}\sigma_n^{-1}$, $(3)\equiv 4\rho\bar d^2y(-\partial_N\frac{\delta(\bar d)}{2\sigma_n})$. Here, $(1)>0$ as $\partial_zA(z)|_{\bar d}>0$; $(2)>0$ as each term is positive, and $(3)>0$ as $-\partial_N\frac{\delta(\bar d)}{2\sigma_n}>0$.

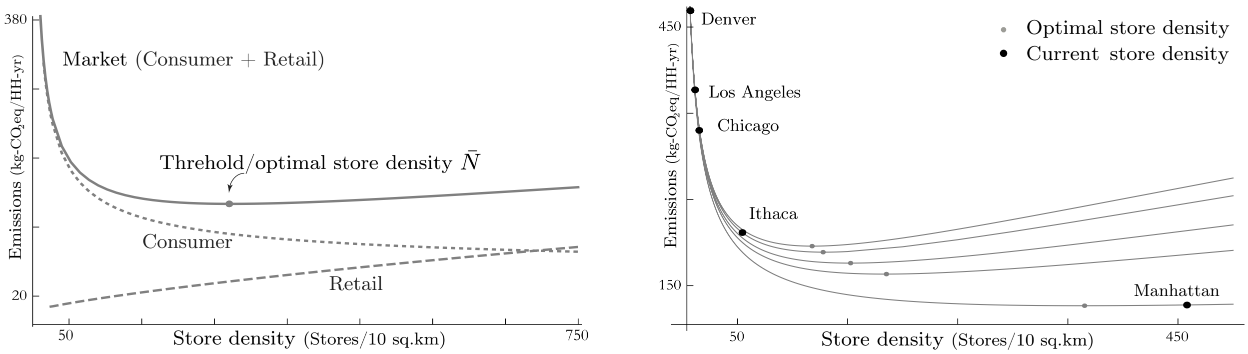
Only expression for $\hat N$ remains. It solves $\partial_NW=\partial_NW_c+\partial_NW_r=0$; $\partial_NW_c=-[w(\bar d)-w(\underline{d})]A\rho N^{-1}$ (Theorem 1) and $\partial_NW_r=\tau^{-1}\{\xi_\sigma^{ss}\partial_N(N\sigma_n)-\xi_m^{wr}\partial_N(Nm_n)\}$ (Theorem 2). We can express $-\tau^{-1}\partial_N(Nm_n)=N^{-1}[R(\bar d)-R(\underline{d}_R)]A\rho$, $\underline{d}_R$ is defined from $8\rho\int_0^{\bar d}R_nzdz=N^{-1}R(\underline{d}_R)A\rho$; and $\tau^{-1}\partial_N(N\sigma_n)=\sqrt{N^{-1}}\aleph(N)\sqrt{A\rho}$, $\aleph(N)=\sqrt{\delta_n(\underline{d}_\delta)}-\delta_n(\bar d)/\sqrt{4\delta_n(\underline{d}_\delta)}$, $\underline{d}_\delta$ is defined from $8\rho\int_0^{\bar d}\delta_nzdz=N^{-1}\delta_n(\underline{d}_\delta)A\rho$. Thus, $\partial_NW_r=N^{-1}[R(\bar d)-R(\underline{d}_R)]\xi_m^{wr}A\rho+\sqrt{N^{-1}}\aleph(N)\sqrt{A\rho}\xi_\sigma^{ss}$.

We now show that when prices are lower with higher store density ($\frac{dp^*}{dN}<0$), market waste is increasing $\frac{dp^*}{dN}\frac{dW}{dp^*}>0$. To establish this we only need to show $\frac{dW}{dp^*}<0$. After a series of manipulations, using $\delta_n(z)=R^2(z,p^*)\frac{var[T(Q^*(z,p^*))]}{E[T(Q^*(z,p^*))]}$, we obtain $\frac{dW}{dp^*}=N\int_0^{\bar d}\partial_{p^*}Q^*(z)(\partial_QA_\xi(z)+y(2\sigma_n)^{-1}\partial_Q\delta_n(z))h(z)dz<0$, as $\partial_{p^*}Q^*(z)<0$ and $\partial_QA_\xi(z)+y(2\sigma_n)^{-1}\partial_Q\delta_n(z)>0$. This establishes part (ii) of the theorem.

Finally combining parts (i) and (ii) of the theorem we obtain the expression for $\bar N$. It is defined from $\frac{dW}{dN}=\partial_NW+\frac{dp^*}{dN}\frac{dW}{dp^*}=0$. Note, $\underline{d}_\xi$ solves $N\int_0^{\bar d}\partial_{p^*}Q^*(z)(\partial_QA_\xi(z)+y(2\sigma_n)^{-1}\partial_Q\delta_n(z))h(z)dz=A\rho\xi_{p^*}^{w}$. With this $\frac{dp^*}{dN}\frac{dW}{dp^*}=-\wp\mathcal{P}(p^*)A\rho\xi_{p^*}^{w}$ and expression for $\bar N$ follows. Since, $\frac{dp^*}{dN}\frac{dW}{dp^*}>0$ it follows that $\bar N<\hat N$.

Appendix E. Service setting

Figure E.1 shows the per-capita annual carbon emissions associated with food waste for varying levels of store density in the service setting case. It closely resembles its counterpart in the price setting (see Figure 8.1).



Parameter values as per Table 1 (baseline), unless specified otherwise. Right Panel: Lines represent areas with different *population* densities (top to bottom: 1550 (Denver), 1900 (Ithaca), 2836 (Los Angeles), 4447 (Chicago), 24137 (New York) /sq. km).

Figure E.1. Emissions Associated with Food Waste: Service Setting