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Household food waste collection: Building service networks through neighborhood expansion

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ABSTRACT

In this paper we develop a residential food waste collection analysis and modeling framework that captures transportation costs faced by service providers in their initial stages of service provision. With this framework and model, we gain insights into network transportation costs and investigate possible service expansion scenarios faced by these organizations. We solve a vehicle routing problem (VRP) formulated for the residential neighborhood context using a heuristic approach developed. The scenarios considered follow a narrative where service providers start with an initial neighborhood or community and expands to incorporate other communities and their households. The results indicate that increasing household participation, decreases the travel time and cost per household, up to a critical threshold, beyond which we see marginal time and cost improvements. Additionally, the results indicate different outcomes in expansion scenarios depending on the household density of incorporated neighborhoods. As household participation and density increases, the travel time per household in the network decreases. However, at approximately 10–20 households per km^2, the decrease in travel time per household is marginal, suggesting a lowerbound household density threshold. Finally, we show in food waste collection, networks share common scaling effects with respect to travel time and costs, regardless of the number of nodes and links.

1. Introduction

Food waste collection and recycling is an important issue in waste management that has gained interest in recent years due to the environmental impacts of food degradation in landfills (Edwards et al., 2017; Laurent et al., 2014). The United States (US) generated 63 million tons of food waste in 2015, of which approximately 40% originates from consumer-facing businesses and 43% from residences (ReFED, 2017). However, implementation of programs to recycle this food waste is slow due to high transportation costs and the relatively low market value of products created from current recycling processes (ReFED, 2017). States including Massachusetts, Connecticut, and Rhode Island have passed legislation to speed up program development by mandating diversion of food waste to recycling facilities from larger consumer-facing businesses (Manson, 2017), but residential food waste diversion has been ignored in state-level policy and legislation. This lack of interest in diverting residential food waste from landfills is problematic if states wish to continue reducing the environmental impact of their waste management systems.

As of 2014, only 200 municipalities in the US have some form of residential food waste collection in place through municipal mandates or private waste collection businesses (Yepsen, 2015). Increased costs for the addition of curbside food waste collection brings considerable challenges that have mostly been overcome by political will (Yepsen, 2014), which is unsustainable from a long-term economic perspective. In order to reduce waste collection program costs, economies of scale are critical (Bohm et al., 2010). Achieving these economies of scale may be difficult for food waste collection due to lower generation rates compared to municipal solid waste (MSW) and recyclable material (New York State Department of Environmental Conservation, 2010).

A main focus of previous waste collection models in the literature is to increase collection efficiency by optimizing routing and scheduling for networks at the urban scale (Arribas et al., 2010; Or and Curi, 1993). Urban residential waste collection poses significant methodological challenges due to the large number of individual waste bins to be collected. Also, these models neglect food waste generated by suburban areas. Larger regional networks that encompass both urban and suburban areas include many logistic dimensions such as transfer stations, time constraints, and bin types (Das and Bhattacharyya, 2015; Nuortio et al., 2006; Son and Louati, 2016). Some studies focus on specific waste materials,

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such as recyclables, to understand the dynamics that specific waste types confer to the collection system (Bing et al., 2014; Rousta et al., 2015). This practice may parallel dynamics seen in the food waste collection system.

Relatively few studies focus specifically on the collection of source-separated household food waste. Franchetti and Dellinger (2014) and Edwards et al. (2016) study the economic and environmental effects that an additional waste collection stream will have on the collection system. However, these studies each examine large, mature collection networks and systems, assuming all households participate in the collection service. Realistically, households in communities have varying values regarding recycling of food waste; therefore, not everyone is willing to participate in or pay for the additional service. National surveys in the US focusing on household attitudes toward food waste indicate that the majority of people still throw away food even though they feel guilty about their actions (Neff et al., 2015; Qi and Roe, 2016). Therefore, understanding the effects of participant spatial density on service cost is important for implementing collection services sustainably.

The overarching objective of this study is to provide system-level insights for expanding food waste collection. This objective is twofold. First, improvements to transportation costs for small start-up scale networks and the implications as service grows and more households incorporated in the network are examined. Second, the feasibility of expanding small scale residential food waste collection services is assessed by calculating travel and collections costs associated with adding new communities. As communities join the collection network, travel time and cost per household are expected to decrease, indicating positive returns to scale.

2. Analysis and modeling framework

2.1. Analysis framework: decision-making for service expansion

The analysis and modeling framework developed reflects the decision-making process faced by start-up food waste collection services early in development. The problem is approached by developing a model and analysis framework that solves for the vehicle routing problem (VRP) given an a priori set of households and their spatial locations over participation levels that reflect expansion scenarios. A new solution to the VRP for each network expansion level (a new collection route) is obtained as more households and communities join.

The VRP is solved using the cluster first, route second heuristic (Laporte, 2009), which helps address the high computational resources required of large networks. Under this approach, destination nodes are clustered first based on their spatial proximity and the VRP is solved for each cluster. A second VRP is performed on the network of centroids of each cluster. For this study, the clusters are determined (a priori) based on pre-defined neighborhood boundaries, precluding the need for a clustering algorithm. The motivation behind this assumption is behavioral. Social interaction within communities or neighborhoods likely contribute more towards behaviors such as adoption of curbside composting services (Hopper and Nielsen, 1991; McMillan and Chavis, 1986).

The framework consists of two routing layers: (1) an intra-neighborhood vehicle routing and (2) inter-neighborhood vehicle routing. Fig. 1 illustrates this framework.

Each neighborhood represents a community seeking collection service. The first layer solves a VRP for a given neighborhood between households randomly selected to represent different levels of collection program participation. The collection vehicle must stop at each household and requires a set time duration for collecting the food waste. A solution to the first stage VRP will indicate the sequence of household stops, network links traversed, total traversal time, and quantity of collected waste is produced.

In the second layer, an inter-neighborhood VRP is solved for a network of centroids of the neighborhoods. Associated with each neighborhood centroid is a total waste collected at that neighborhood and travel time determined previously in the first (intra-neighborhood) layer. Similarly, the output to the inter-neighborhood VRP includes a collection route that indicates the sequence of stops and network link traversed between neighborhoods. This layer also produces the total time of the collection route and total quantity of food waste collected by the vehicle.

2.2. Vehicle routing problem (VRP) formulation

The VRP is formulated as a mixed-integer mathematical program and solved using the cluster first and route second heuristic (Laporte, 2009). The neighborhood residential waste collection problem is formulated as a capacitated VRP where the decision variables are:

x_{hij}^k – The shortest path travel times nodes h, i, and j for collection truck k.
y_i^k – The total quantity of food waste in the collection truck k including node i.
w_j^k – Mass of waste delivered to recycling facility j by collection truck k.
v_j – The total mass of food waste delivered to recycling facility j.

The formulation has the following objective function:

$$Min = \sum_{i\in(D,N)} \sum_{j\in(D',N)} \sum_{k\in K} c_{ij} x_{ij}^k + \sum_{j\in N} m_j \tag{1}$$

The objective function (1) minimizes the truck travel time between pickup $i \in D, N$ and drop-off $j \in D', N$ nodes over the set of vehicles $k \in K$ mobilized in the collection network by summing the travel time c_{ij} on each traversed link x_{ij}^k and the collection time at each pickup node m_j.

Subject to the constraints:

$$\sum_{h\in D}\sum_{i\in N} x_{hi}^k = 1 \ \forall k \in K \tag{2}$$

$$\sum_{i\in N} x_{hi}^k = \sum_{j\in N} x_{jh'}^k \ \forall k \in K, \ h \in D, \ h' \in D' \tag{3}$$

$$\sum_{h\in(D,N)} x_{hi}^k = \sum_{j\in(N,D')} x_{ij}^k \ \forall k \in K, \ i \in N \tag{4}$$

$$\sum_{i\in N} x_{ij}^k = \sum_{h'\in D'} x_{jh'}^k \ \forall k \in K \tag{5}$$

$$\sum_{k\in K}\sum_{j\in(N,F)} x_{ij}^k = 1 \ \forall i \in N \tag{6}$$

Constraints (2-6) provide the minimum cost flow constraints that simulate the behavior of the collection truck. The truck can only leave the depot once, all households or neighborhoods must be visited by only one truck, food waste must dropped off at the recycling facility, and the truck must return to the vehicle depot.

$$y_i^k \geqslant y_h^k + (q_i + Q)x_{hi}^k - Q \ \forall h \in (N,D), \ i \in N, \ k \in K \tag{7}$$

$$w_j^k \geqslant y_i^k - Q(1 - x_{ij}^k) \ \forall k \in K, \ i \in N, \ j \in D' \tag{8}$$

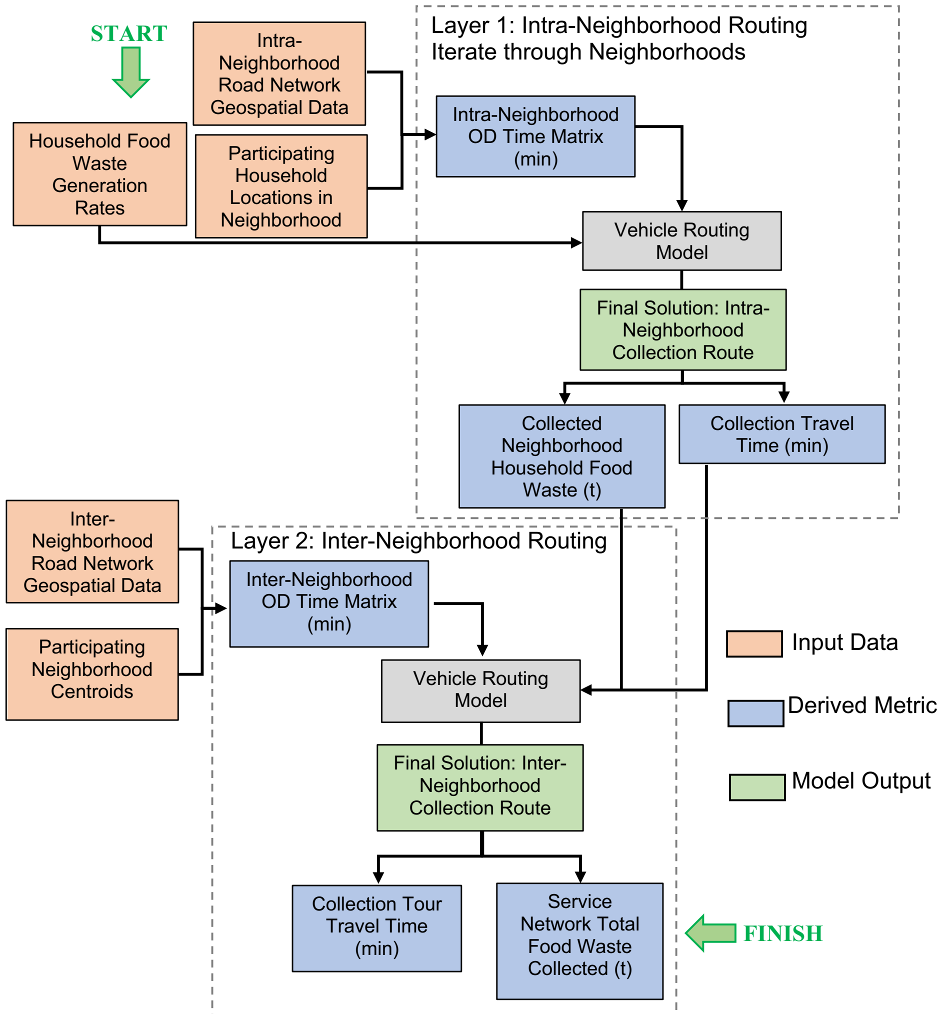

Fig. 1. Modelling framework.

Constraints (7), (8) are modeled after the Miller-Tucker-Zemlin constraints to prevent subtours for collection vehicles (Miller et al., 1960). These constraints track the total food waste in the collection truck at each stop, ensuring that the sum of the current quantity of food waste in the truck and quantity picked up at the household q_i do exceed truck capacity Q.

$$\sum_{j \in F} w_j^k \leqslant Q \;\; \forall k \in K \tag{9}$$

$$\sum_{j \in F} \sum_{k \in K} w_j^k = \sum_{i \in N} q_i \tag{10}$$

Constraint (9) ensures the capacity of the collection truck is not violated. Constraint (10) ensures waste dropped off equals the total amount of waste collected.

$$v_j = \sum_{k \in K} w_j^k \;\; \forall j \in F \tag{11}$$

$$P_j^{quo} \leqslant v_j \leqslant P_j^{cap} \;\; \forall j \in F \tag{12, 13}$$

Constraint (11) tracks the total amount of food waste delivered to the recycling facility $j \in F$, and Constraint (12,13) ensure that recycling facility quotas P_j^{quo} are met and capacities P_j^{cap} are not violated.

$$\sum_{i \in (D,N)} \sum_{j \in (N,D')} c_{ij} x_{ij}^k + m_j = B^k \;\; \forall k \in K \tag{14}$$

$$B^k \leqslant B^{k,Lim} \;\; \forall k \in K \tag{15}$$

Constraint (14) equates the travel time between nodes and the pickup time at each node to the total travel time for the collection route B^k. Constraint (15) ensures that the total travel time does not exceed the maximum travel time set $B^{k,Lim}$.

All VRPs across scenarios considered in this study were solved using the IBM CPLEX solution algorithms with a MATLAB interface.

2.3. Model assumptions, data sources, and limitations

Assumptions regarding collection and transportation time, household food waste generation rates, and operational costs are summarized in Table 1 and discussed.

Road network links, nodes and signed speed limits are obtained from the transportation network data available at the New York State Geographic Information Systems Clearinghouse (NYS Office of Information Technology Services, 2017). ESRI ArcMap is to compute the shortest path travel times between nodes, constituting the travel time matrix used in the VRP formulation. Other parameters such as vehicle acceleration and stopping times at intersections were not considered. Thus, the results may underestimate the travel time and costs per household.

In 2010, a residential and commercial solid waste audit was performed in Monroe county, NY and included in their Local Solid Waste Management Plan Update (Barton & Loguidice. D.P.C., 2015).

Table 1
Assumed model parameters.

Item	Value	Unit	Description	Reference
Collection time for food waste bins	0.5	Min	Time taken to collect food waste bins at households	Model baseline
Travel Speed	Variable/Speed Limit	km/h	Time taken to travel along road segments	Speed limits from road network information. NYS GIS clearinghouse
Food waste generation				
Low Generation (LG)	.002	t/week		
High Generation (HG)	.007	t/week		
Vehicle operating cost				
Low Cost (LC)	60	$USD/h		
High Cost (HC)	100	$USD/h		

An average MSW generation rate of 26 kg per household per week was identified by this waste audit, with a 6.8% fraction of that MSW identified as food waste equating to approximately 2 kg of food waste generated per household per week. Conversely, the New York State Department of Environmental Conservation has estimated that food waste generation rates are higher, at 20% of the MSW generated by households, equating to 5.2 kg of food waste per week based on total waste generated found in the regional waste audit. However, an upper bound of 7 kg of food waste per household per week is used to represent increases or spikes in food waste generation during the holiday or summer seasons (Lebersorger and Schneider, 2014). All households are assumed to generate the same quantity of food waste in each scenario. Food waste generation rates vary across households weekly because estimating actual household generation rates poses additional challenges not considered in this study.

Transportation costs are estimated in $USD per hour, which is the industry standard (personal communications with Waste Management, Inc. and Natural Upcycling). True operation costs will vary with fuel prices, weather, salary, and other vehicle maintenance costs not considered in this study. To account for some cost variability, upper and lower costs are derived from correspondence with two local waste collection companies. The current model only comprehends a homogeneous vehicle fleets with pre-defined capacities. If preliminary routing solutions indicate that smaller vehicles may be more desirable than larger vehicles due to time constraints rather than capacity, those parameters must be changed manually. Realistically, some collection vehicles are more suited to residences that produce only a few kilograms of food waste a week, while others can pick up larger quantities of food waste from multi-family households.

2.4. Study area

The study area is the Town of Penfield, a municipality located near Rochester, NY. Regional data for Penfield was used for this study, including geocoded household locations and traffic road network links. Only single-family households are considered for analysis, constituting 98% of the total residential parcels in Penfield. The collection vehicle starting depot and drop-off are the same facility located just south of the City of Rochester. A map of neighborhoods considered within Penfield is shown in Fig. 2 and characteristics of the study area are shown in Table 2.

2.5. Evaluation steps

First, participation from Neighborhood 7 (NH7) and Neighborhood 15 (NH15) are evaluated independently to understand characteristics from each neighborhood. Participation levels from 5 to 50 households per neighborhood are considered for each neighborhood. Second, NH7 and NH15 are combined to create the base service network for the collection program. The time for the collection routes for participating households in NH7 are evaluated from 5 to 50 participants. Then, more participating households from NH15 are added to the network and collection times are evaluated. Third, households from NH9 and NH34 are independently added to the base network and the collection route times are compared. Comparing the addition of NH9 to the addition of NH34 indicates how adding neighborhoods with different spatial characteristics effect the collection route time. Finally, high/low operational costs in conjunction with high/low waste generation rates are applied to the collection service network route solutions to assess potential collection costs per ton of material (see Table 1).

3. Results

3.1. Travel time in individual neighborhoods

Comparing the final objective function (Eq. (1)) values at convergence from NH7 to NH15 show an increase in total route time and intra-neighborhood time as households are added to the network.

Fig. 3 suggests that increasing the number of participating households increases intra-neighborhood travel times. The total travel time experienced (intra and inter neighborhood travel times) also increases with more participating households. The similarity in mean travel time (min/HH) increase between total and intra-household travel times suggests that the rate of increase for total travel time is due largely to adding more participants to the network. This is illustrated also in Fig. 4.

Fig. 4 points to economies of scale as program participation increases. The intra-neighborhood route time per household remains relatively constant, while the inter-neighborhood travel time per household (not shown) decreases, subsequently decreasing total travel time. Each neighborhood is a static defined area with fixed boundaries; therefore, as program participation continues to increase in any given neighborhood, the participation density also increases. Fig. 5 considers the impact of increasing participant density on travel time per household.

Graphing the travel time per household against household density in neighborhoods, a similar trend emerges indicating reduction in travel time per household as participation increases and households are added to service network. Variations in the trend are due to the different road networks and collection routes for each scenario. A drastic decrease in travel time per household is seen increasing from 0 to 10 participants per km^2, showing a "knee" in the curve between 10 and 20 participants per km^2. Including additional participants beyond 20 per km^2 marginally reduces the travel time per participating household in the neighborhood. Collection trucks require a minimal time for waste collection at destinations and therefore are only able to improve route travel times up to that limit, which is 30 s in this study.

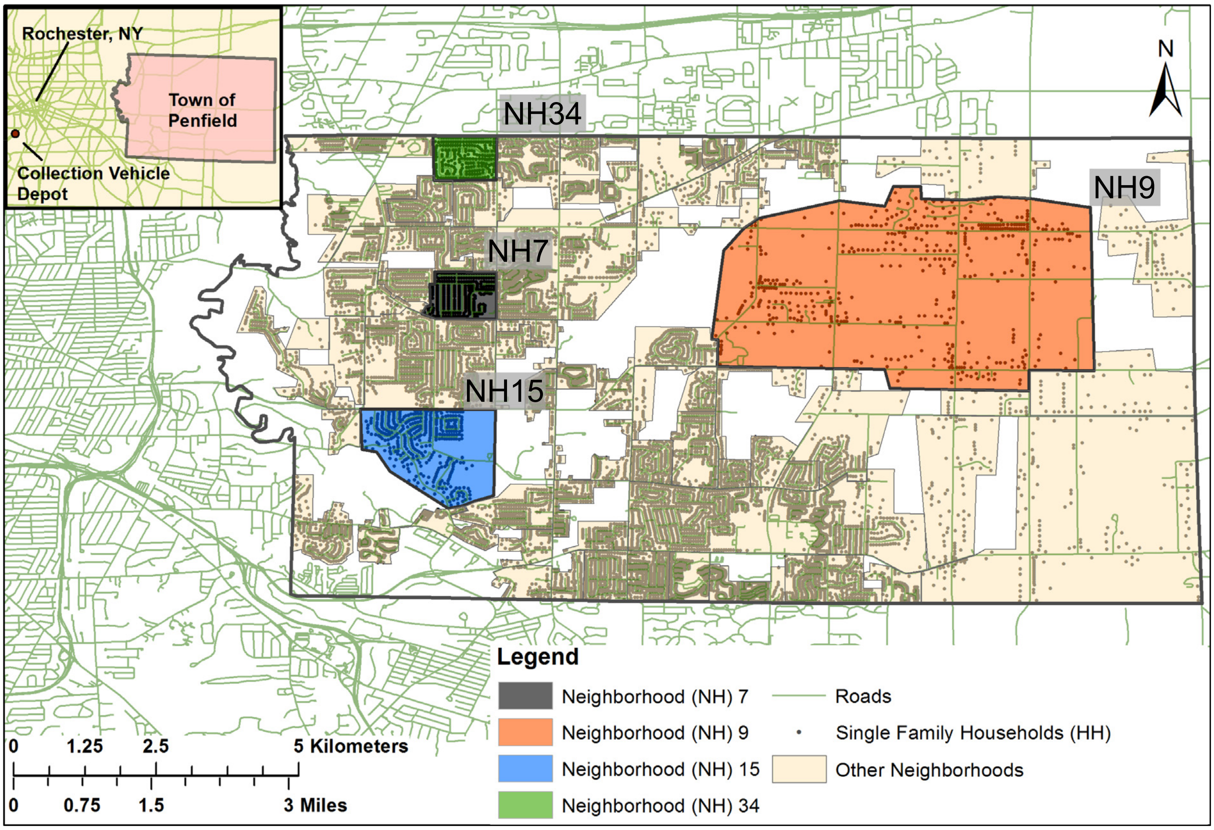

Fig. 2. Study area - Penfield, NY.

Table 2
Neighborhood characteristics.

Name	Area (km^2)	Total households	50 randomly selected HH (% Total)	Depot to centroid TT (min)
Penfield, NY	97	12,450	N/A	N/A
Neighborhood 7	0.70	280	17.9%	17.4
Neighborhood 9	14.53	469	10.7%	24.53
Neighborhood 15	1.95	386	13.0%	14.74
Neighborhood 34	0.62	221	22.6%	17.94

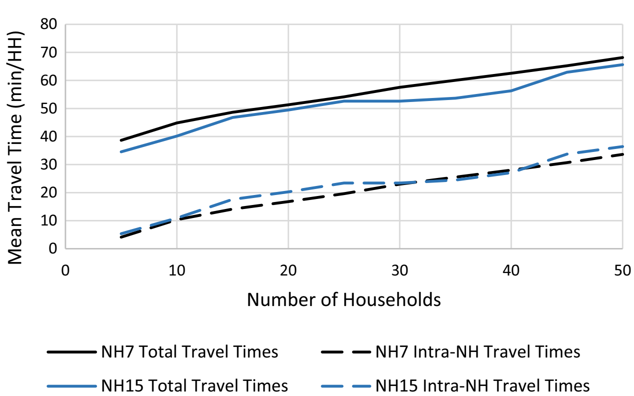

Fig. 3. Comparison of total route times for NH7 and NH15.

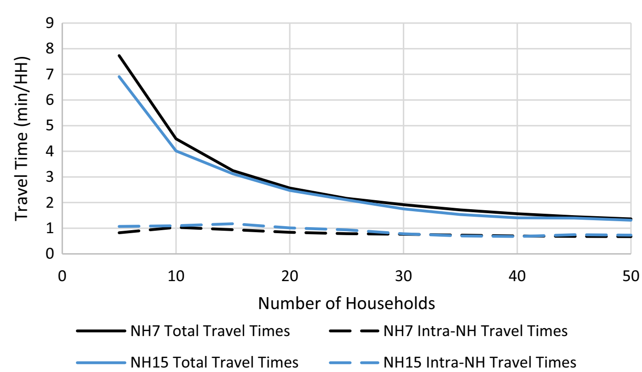

Fig. 4. Comparison of per household route times for NH7 and NH15.

3.2. Travel times in expanding service networks

Although assessing the travel times for single neighborhood networks independently yield insights into neighborhood routing performance characteristics, waste collection services consider networks of neighborhoods jointly, building out through an expansion process. To represent and model this expansion, once NH7 reaches 50 participants, 50 participants from NH15 are introduced to the network incrementally. This expansion scenario continues the trends in for increasing overall travel times (Fig. 6), but reducing travel time per participant (Fig. 7).

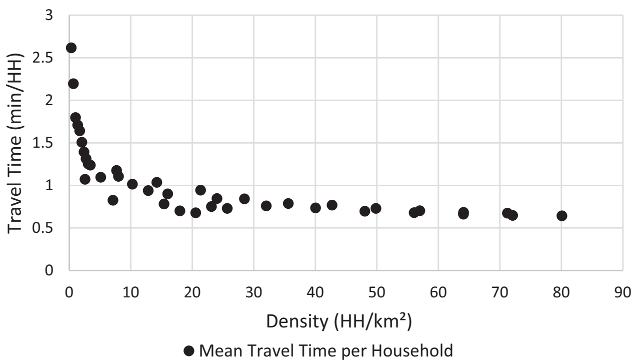

Fig. 5. Travel time vs household density.

The total travel time of the collection vehicle per participant decreases and the intra-neighborhood travel time per participant remains consistent as participating households from NH15 are added to the service network. The decrease in total travel time per participant indicates economies of scale that continue as participants are added from NH15 and consistence in intra-neighborhood travel time suggests a uniformity in the distribution of households within each neighborhood.

As the food waste collection service grows, these services will consider including more neighborhoods. Deciding which neighborhood routes to incorporate into the service may have a large impact on the total travel time for collection, ultimately affecting route travel time and subsequently operation cost. Densely populated neighborhoods closer to the existing network are more desirable for expansion relative to neighborhoods where travel time between houses is larger and the neighborhood center is further away from the existing service area. However, advantages of considering these different additions is unclear if potential participants are willing to pay the cost for the collection service. A comparison of adding NH9 and NH34 to the base service network are compared for total travel time and mean travel time per participating household.

The addition of NH9 or NH34 to the network have very different effects on both total and per participant travel times for the final routes. Spikes in total travel time are shown when NH9 and NH34 are initially added to the network. The spike for NH9 is larger than NH34 because it is a further distance from the base service network. The rate of increase for collection time increase for NH9 is also higher than NH34 due to the lower density of households in NH9 causing increased travel times between households.

Adding NH9 initially increases travel time per participant, due to the longer distances traveled by the collection truck to the neighborhood, then slowly decreases with the addition of participants. After an addition of 50 households, the travel time per household does not return to the previous level of pre-NH9 addition. Alternatively, adding NH34 to the collection network continues the travel time reduction trends seen previously. After the addition of approximately 20 participants from NH34, travel times per participant are equivalent to pre-NH34 addition, and more participants lead to further route time reductions. Figs. 8 and 9 shows that it is possible to temper the initial shocks of adding new neighborhood service areas by recruiting more households into the program to justify the longer distance traveled.

3.3. Cost assessment

Collection cost is also important to assess from a feasibility standpoint, especially when considering potential participants'

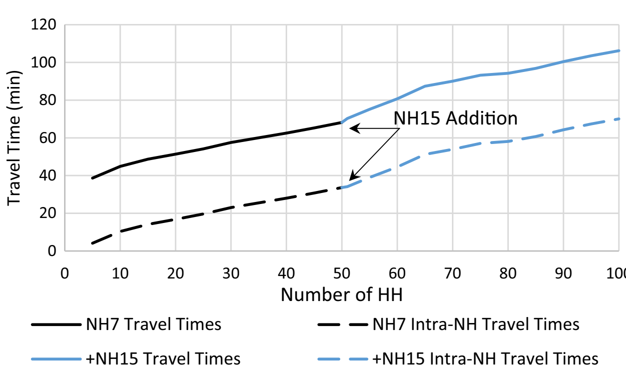

Fig. 6. Collection route times for the NH7 and NH15 collection network.

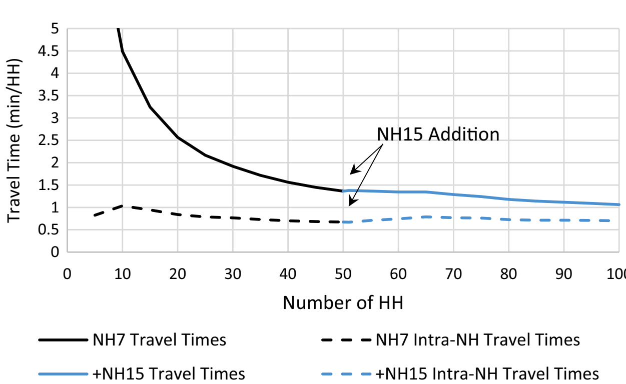

Fig. 7. Mean collection route times for the NH7 and NH15 collection network per participating household.

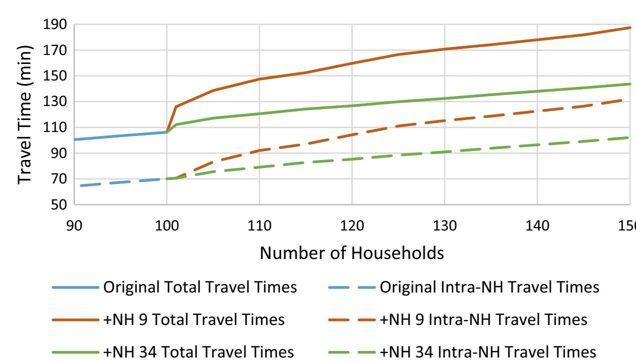

Fig. 8. Total collection route times of the expanded NH9 and NH34 collection network.

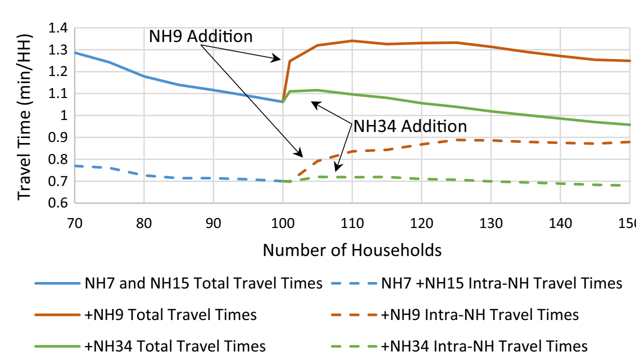

Fig. 9. Mean collection route times of the expanded NH9 and NH34 collection network per participating household.

willingness to pay for service. However, the variability of food waste generation and operational costs present barriers to generalizing costs per ton to a specific value. Therefore, upper and lower bounds for generation and operational costs are considered to encompass a range of variability in food waste generation and operational costs (Table 2). The high-cost scenario combines the high operation cost parameter with the low food waste generation parameter, producing the highest cost per ton of food waste collected. The low-cost scenario combines low operation cost with high food waste generation, producing the lowest cost per ton of collected food waste. Low cost/low generation and high cost/high generation parameter combinations are omitted because the cost per ton of food waste collected are intermediate to the evaluated high and low-cost scenarios. Regardless of the values of cost and generation parameters, collection costs per ton of material are expected to follow decreasing trends as the number of participants in the network increase (Fig. 10).

Trends in collection costs per ton of material ($/t) are shown to decrease similarly to reductions in mean per participant travel times in the network for NH7 and NH15 but show the wide range in potential collection costs. These high and low cost scenarios are extended to 50 more households from NH9 or NH34 to show how the addition of these neighborhoods effect total cost (Table 3).

Even under the best scenarios of high food waste generation and low operating costs, inclusion of NH9 in the collection network increases the collections cost per ton. However, the marginal cost of providing service will continue to decrease as participants are added. Alternatively, the inclusion of NH34 in the collection network decreases the total collection costs in each scenario. Under higher cost scenario, the additional cost or savings are more pronounced in the additional neighborhoods than the lower cost scenario. Therefore, if operating costs and food waste generation rates are unfavorable, the company can capitalize on potential savings by extending service to neighborhoods that are close and dense to reduce the overall collection costs. Inversely, demand for service in a more rural neighborhood will increase overall costs, but these increases can be minimized with low operation costs and high food waste generation.

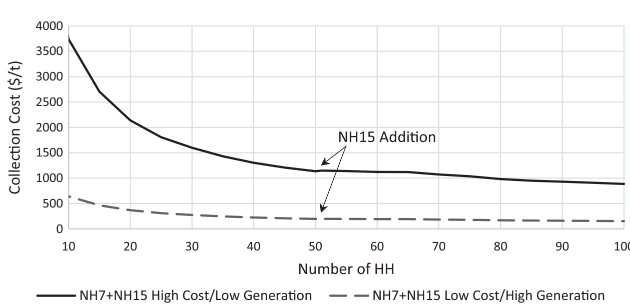

Fig. 10. Transportation costs for the NH7 and NH15 network.

4. Discussion

4.1. Effects of household density of neighborhoods

Results indicate a relationship between the decreases in travel time per household in collection routes with increasing household density in neighborhoods. Although this relationship is intuitive, there are two interesting insights revealed.

First, there is a clear trend in the decrease in travel time per households as more households are added to the collection route within a given neighborhood. More extensive modeling and study is required to further corroborate this result. However, if future work finds consistency across similar networks, the relationship can be used to estimate the cost of waste collection without solving a VRP for large-scale network with many nodes, which is computationally prohibitive. Additionally, the estimation method could be applied to other food waste collection scenarios, most notably to a commercial facilities context. Current policy reports that quantify the cost of performing food waste collection from large commercial sources considers only the cumulative cost of traveling from each individual generator of waste to the final depot (Manson, 2017). This method both models unrealistic waste management behavior and overestimates the cost of transportation. Clustering generators together as we did in this study and applying a travel time relationship to estimate costs is an approximation, but it is more accurate than transportation costs estimated in reports like Manson (2017).

Secondly, reductions in travel time per household are significant up to a critical threshold as participants are added to the collection route. At this threshold of participant density, the improvements in cost reductions are only marginal compared to the initial growth of the service. In the scenarios presented in this paper, the threshold of participant density appears to be between 10 and 20 households per km^2. After that, decreases in travel time per participant show diminishing returns, approaching a stable travel time per participant.

4.2. Effects of spatial separation between neighborhoods in a service area

In the scenarios presented, a system shock occurs as neighborhoods are added to the collection network. When initially adding neighborhoods with a few households to the collection network, the total travel time and cost per household will spike. The distance of the newly added neighborhood from the base network influences the magnitude of the spike, and the density of potential customers in the neighborhood influences how quickly the system recovers. Moreover, this model reveals a critical mass of participating households that are needed before the collection times and costs will return to pre-shock levels. Customers added after this critical mass is reached will only continue to reduce the travel time per participant in the network, hypothetically reducing the collection costs for all participants in the program.

Identifying the critical mass of new participants in each neighborhood will help inform program expansion decisions. A company

Table 3
Cost scenario values for expansion to NH9 or NH34 network.

Cost Scenarios	100 HH from base network	+50 HH from NH9		+50 HH from NH34	
($/t)	Total ($/t)	Total ($/t)	Change ($/t)	Total ($/t)	Change ($/t)
(HC,LG)	708	832	+124	638	−70
(LC,HG)	142	167	+25	128	−14

could administer a survey to a neighborhood community, and if participation interest reaches the critical mass identified by the routing trends, then it would be economical to provide service in that area. After the participant mass is reached, revenue generated per customer from additional participants will remain relatively stable. The stability allows a startup company to decide if it is worth spending resources on attracting new participants in the same neighborhood or focusing on service expansion to other neighborhoods

5. Conclusion

While past studies have examined residential waste collection and variants of this pick-up and deliver problem, none to the knowledge of the authors have considered the network build-out of these systems. This study presents a residential food waste collection model focusing on the impacts of expanding and growing the network both in terms of additional households and additional communities for a service provider in the early stages of its development and growth.

The increases in the overall collection time are most affected by the increases in household participation within neighborhoods rather than travel time between neighborhood clusters. Increases in household participation lead to an increase in spatial density of participants, subsequently reducing the collection time per participant if distributed equally. When household density is low (less than 10 households/km^2), addition of more participants quickly reduces the per household travel time. At higher participant densities, the rate of travel time decreases less quickly, indicating diminishing returns on collection time after approximately 10 households/km^2.

Economies of scale are clearly visible as participants are added to the collection network of individual and multiple neighborhoods. Decreases in travel time as well as decreases in program cost are visible as more households participate and more food waste is collected. This trend should be leveraged by start-up collection programs to assess how economic feasibility will be maintained while satisfying service demands from customers.

Since food waste constitutes a fraction of residential solid waste generation and voluntary participation is limited, collection methods will be different compared to municipal solid waste. This paper focused on spatial properties of small collection programs, but there are other unanswered questions that should be addressed in future research. The optimal size of collection vehicles for food waste programs should be studied because smaller collection vehicles might be more suitable for food waste collection due to decreased operation costs and environmental impacts. Ultimately, the goal of residential food waste recovery is to reduce the environmental impacts of food waste degradation in landfills by diverting food waste to other recycling facilities. However, the energy, emissions, and economic balance that includes in-depth transportation modeling should be researched to understand these balances more completely.

Acknowledgements

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