Evaluating the Efficacy of Shared-use Vehicles for Reducing Greenhouse Gas Emissions: A U.S. Case Study of Grocery Delivery

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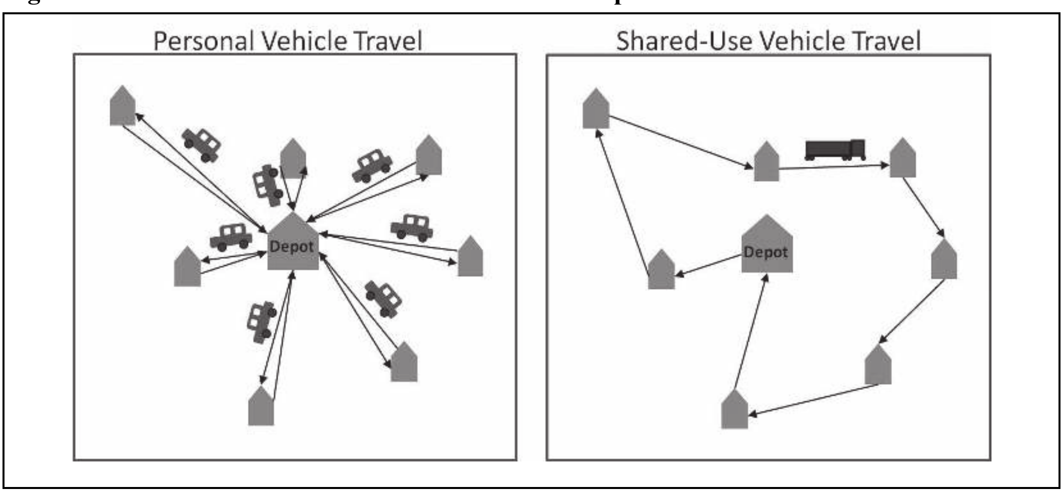
This paper compares the CO_2 emissions from the use of personal vehicles to shared-use vehicles for grocery shopping in Seattle, Washington. The research builds on existing literature by considering the importance of modeling the logistical details of routing and scheduling, and by comparing the results of an American case study to existing European case studies. We find the US and European case studies to provide consistent results, that low customer density provides greater opportunities for emissions reductions, and that logistical efficiencies can account for approximately 50% of CO_2 reductions.

INTRODUCTION

Under agreement of the Kyoto Protocol (United Nations 1998), governments worldwide are attempting to reduce greenhouse gas emissions. Efforts to address this concern are generally siloed – focusing on addressing the impacts of a particular contributing activity (*A Wedge Analysis of the U.S. Transportation Sector* (Simon et al. 2007) is one example which allocates necessary reductions to flatten emissions to each transportation source). This paper examines one way to consider the overall impact of transportation by relating freight activity and passenger travel. Further, the delivery services evaluated are immediately implementable and, thus, can begin addressing environmental concerns quickly.

Shared-use vehicle transportation services provide for the movement of passengers and goods and may offer opportunities for reducing the environmental footprint of these activities when compared to individuals using personal vehicles (Figure 1). For example, some large employers have developed their own shared-ride services and many municipalities provide both garbage and school bus services.

Figure 1: Illustration of Personal Vehicle Travel Compared to Shared-Use Vehicle Travel



These services reduce individual employee trips to the workplace, household trips to the transfer station, and household trips to schools by collecting passengers and goods into one vehicle and reducing vehicle miles travelled (VMT) (Cairns 2005). While the literature shows these services require fewer vehicle miles of travel, the vehicles they rely on have greater emissions of greenhouse gasses per mile. Thus, the net results from these services are unclear – does the more efficient routing outweigh the impacts from the higher-emission producing vehicles?

Research into the benefits of shared-use vehicles has generally focused on VMT but has not sufficiently considered the influence of spatio-temporal customer density, routing, and scheduling on the outcomes. Some services, like waste collection, third-party logistics, and school buses, dictate when customers are served and are able to serve proximate customers with the same vehicle, reducing VMT per customer. Other services, including many commercial services such as appliance, furniture, and grocery delivery, are dedicated to customer service or have low customer density, and they must create truck routes based on customer demands, which require serving a more spatially-random set of households. These services would typically have a higher VMT per customer. This paper investigates the potential CO_2 emissions savings for these two bounding cases – when customers are selected randomly or are assigned by location. This provides insight into the magnitude of the effect of logistical decisions on the emissions from a shared-use vehicle service, and under what circumstances these services can provide most benefit over individual-use vehicles. The results of this work will identify a potential method of reducing greenhouse gas emissions and will inform the practicality of addressing such questions as "How can the use of these services be encouraged?"

Much of the research comparing personal vehicle travel to shared-use vehicles has been completed in Europe. While Europe is comparable to the United States in many regards including relative economic strength and development, in general, Europe has higher levels of population density and differing transportation patterns. Newman and Kenworthy (1999) compare data from selected cities in Europe and the United States and illustrate U.S. cities on average use 2.5 times more energy for transportation per capita than European cities on average. European metropolitan areas have 3.5 more people per hectare and 3.8 more jobs per hectare than American ones on average. There may be other relevant differences between American and European cities, including roadway design. Given these differences, the research in Europe may not translate to American cities.

The research described in this paper uses grocery store shopping in Seattle, Washington, as a case study to quantify and compare the CO_2 emissions due to personal versus shared-use travel. Grocery shopping is a regular activity for most households, and is highly regional (most shoppers visit a proximate store). Due to its regularity, grocery shopping has potentially greater environmental impacts than more sporadic shopping trips (e.g., for electronics). Additionally, most grocery shopping is currently done in a traditional retail environment, in which consumers drive personal vehicles to and from supermarkets. While separate fields examine the behavioral issues associated with delivery services (see Tanskanen et al. 2002, for one example) and the financial viability of these types of services (Punakivi et al. 2001, is an example), this research complements that work by focusing on operational impacts and does not consider the financial viability, adoption levels, or willingness to pay considerations. The analysis indicates whether shared-use vehicles can show significant benefit to the environment over personal vehicles, if results from a United States' city are consistent with findings from Europe, and the extent to which logistical details influence the magnitude of benefit.

LITERATURE REVIEW

Evaluations of Environmental Impact of Shared-Use Vehicles

Few researchers have compared the environmental impact of replacing passenger travel with freight travel. Stefan et al. (2005), Hunt and Stefan (2007), Quak and de Koster (2007, 2009), Palmer (2007), Wygonik and Goodchild (2011), and Gebresenbet et al. (2011) have examined environmental impacts of urban commercial vehicles but not in contrast to personal vehicle use. Dessouky et al. (2003) consider trade-offs between cost, service, and environmental performance for a demand-responsive transit operation, but also do not compare these gains to the environmental impact of the personal vehicle trips the transit service might replace.

The American Public Transportation Association Transit Fact Book (2010) and Shapiro, et al. (2002) look at emissions per passenger mile for different vehicle types, using fleet averages, to show the benefits of public transit. Barth et al. (1996) examined the emissions implications of replacing personal travel with public rail service, finding rail produced fewer of certain emissions and personal travel produced fewer of others, but they did not examine CO_2 emissions, and their calculations relied on approximated average trip length and speed information. Delucchi et al. (2002) examined a number of cases for a handful of U.S. cities comparing personal travel to various forms of transit, finding transit generally produced fewer emissions, but factors including occupancy, electricity source, and access mode can significantly alter the results. Vincent and Jarram (2006) completed a strategic analysis using average travel patterns and emission factors to compare the CO_2 emissions associated with passenger travel, light rail transit, and bus rapid transit (BRT), finding both light rail and BRT systems would have significant reductions in CO_2 emissions over passenger travel, with the BRT reductions more than double the light rail reductions.

For cases where delivery vehicles replace personal travel, Matthews et al. (2001) compare the environmental impacts of traditional retail storefronts and e-commerce sales of books. Their analysis provides sketch-level bounds on the two cases and includes returning unsold books, personal travel, freight travel, production, and packaging impacts. Their results show e-commerce has lower environmental impacts between their two studied cases, but changing the parameters of each case will yield different outcomes. For example, while their evaluation conservatively assumes all e-commerce books travel via air for a portion of their trip, if the distance traveled by air increases by less than 10% the two sales methods have comparable environmental impacts. Kim et al. (2008) compare traditional shopping, e-commerce, and delivery to centralized drop-off locations, finding both e-commerce and delivering to centralized locations have significantly lower CO_2 emissions. McKinnon and Edwards (2009) compared shopping trips with home delivery of small, non-food items and found delivery services almost always result in fewer grams of CO_2 emissions, even when accounting for additional trips demanded from returns and redelivery needs, and adjusting consumer trip impacts to account for bus use and trip chaining. McKinnon and Woodburn (1994) suggest the CO_2 emissions associated with the final transport from the grocery store to homes via personal automobiles are significantly greater than the CO_2 emissions with the earlier steps in the supply chain. Edwards, et al. (2010) reconfirmed that for non-food items, delivery services have fewer CO_2 emissions than personal travel unless very large numbers of goods are purchased in trips made by personal vehicle.

The literature indicates a potential for CO_2 emissions reductions associated with certain mode shifts, but few papers have examined replacement of personal vehicles with shared-use vehicles on a detailed level. All papers that do compare this replacement rely on approximations of impacts, even when considering detailed logistics.

Evaluations of Environmental Impact of Grocery Delivery

The impact of substitution of personal grocery store travel by a delivery vehicle is a particularly well-studied example. The environmental impacts of grocery delivery services have received increasing attention in recent years as the availability of these services has risen, governments and consumers are increasingly concerned with climate change, and environmental evaluations of transportation has became more common. The literature to date indicates vehicle miles travelled (VMT) and CO_2 emissions are reduced when replacing personal travel for grocery shopping with delivery service. Most of this work has been done in Europe, and nearly all has occurred outside the United States. In addition, only one paper to date has explicitly examined the influence of routing and scheduling on environmental performance.

Cairns published a number of papers in the late 1990s illustrating significant VMT reductions over passenger travel associated with grocery delivery. Her work was based in the United Kingdom and examined different methods for calculating VMT impacts of grocery delivery services using approximations, bounding equations, and empirical models. Her empirical model (Cairns 1998) found VMT savings of up to 77% when 39 households are served by delivery vehicles with capacity to carry orders from eight households (a small delivery vehicle). Cairns (1997) found similar results, with at least 60% reductions in VMT estimated in every case, with many cases showing reductions on the order of 70%-80%. Cairns (1998) considered the number of customers served, finding increasing VMT savings were possible with an increasing number of customers. Her work did not consider environmental impacts, did not capture the impact of logistics decisions, and was based in Europe.

A Finnish research team has explored the logistics influences on VMT reductions potential (Punakivi and Saranen 2001, Siikavirta et al. 2002). This group has focused on how the interaction with the customer and the expected service parameters influence impacts, considering deliveries attended and unattended by customers, service time windows, and the mechanism for unattended deliveries. This work considers the financial implications of various methods as well as the transportation impacts. Their early work observed case studies with reductions in VMT between 50% and 93% over personal travel, depending on time window size. Siikavirta et al. (2002) took the evaluation a step further, adjusting VMT by emissions factors from the Finnish emissions model, LIISA, to illustrate an 18%-87% CO_2 emissions reduction potential when traditional grocery shopping was replaced by several different delivery service designs. Siikavirta et al.'s case studies (2002) resulted in estimates of CO_2 equivalent reductions of 76% with eight-hour time window services serving randomly-selected customers, and were able to increase these savings to 87% when the customers were organized by postal code (similar to the proximity-assigned analysis presented in this paper). Siikavirta et al.'s work (2002) is most similar to that presented here. Their research considers the CO_2 emissions impacts of routing and scheduling within an urban delivery system and provides an excellent point of comparison to the American case study presented here.

More recently, Tehrani and Karbassi (2005) used average emission factors (from Tehran's Air Quality Control Company) and trip lengths (from survey data) and focused on a busy, growing shopping district in Tehran, Iran. They found significant reductions in fuel use (88%) and emissions (25%) if all personal travel for grocery shopping was replaced with a delivery service. Tehrani and Karbassi's work provides insight into this problem in a non-Western context but is a strategic analysis that does not consider detailed impacts of density or routing.

As illustrated by the literature, significant mileage savings are possible when delivery service replaces personal travel. Further, one study (Siikavirta et al. 2002) examined the impact on CO_2 of replacing passenger travel with delivery service, and found significant CO_2 savings were also possible. These studies are summarized in Table 1.

Table 1: Summary of Literature Evaluating Mileage and CO_2 Emissions Reduction Potential for Grocery Delivery

	Analysis Unit	Savings	Scale	Method	Role of Logistics in Evaluation
Cairns 1997	VMT	≥ 60%, as much as 70-80%	Considers low adoption levels, small vehicles Truck capacity 5, 10, 15, 20	TransCAD routing, simple mathematical model	Fleet characteristics, load levels
Cairns 1998	VMT	≤77%	39 households Trucks capacity: 8 households	Empirical model in Excel, some data from TransCAD	Fleet characteristics, load levels
Punakivi and Saranen 2001	Km/order	54-93%	1450 households (1.63% market share) Truck capacity: 60 orders, 3000 litres	RoutePro simulations	Attended deliveries, unattended deliveries, delivery to centralized drop-off locations
Siikavirta et al. 2002	CO_2	18-87% 76% w/8-hour time window 87% proximity-assigned	1450 households (1.63% market share) Truck capacity: 60 orders, 3000 litres	RoutePro simulations, adjusted km by LIISA emissions factors	Time window size, proximity grouping
Tehrani & Karbassi 2005	Fuel use Emissions	88% 25%	2450 cars/day Average truck load: 30 orders, evenly distributed	Average emissions factors and trip lengths	none

METHODS

Network Dataset

The base network is from the ESRI StreetMap North America dataset (2006). These files include geographically accurate representations of the road network for North America, and include information regarding speed limit, functional class, street name, and street number range. The dataset was trimmed to only include road segments in the study area to reduce processing time, and the length in feet of each road segment was calculated and appended to the data table. Travel time was calculated using the segment length and these estimated speeds and also appended to the data table. Finally, information regarding the CO_2 emissions associated with each road segment for each vehicle type was also appended to the data table, based on the MOVES emissions factors, the roadway speed limit, the roadway functional class, the roadway length, and the vehicle type.

Emissions Factors

This research analyzes CO_2 tailpipe emissions and uses emissions factors obtained from the 2010 MOVES model (version MOVES2010) (US EPA 2010). This analysis assumed uncongested conditions, so speed limit data from the StreetMap North America dataset were used as the default flow speed for each road segment. Running exhaust emissions are tracked, since this problem involves less than one-hour stops. Based on EPA standards, an engine with its catalytic convertor in a hot state will pass to a cold state after this amount of time and will require accounting for hot- and cold-start emissions. However, stops in most residential urban pickup-and-delivery systems do not exceed this one-hour threshold. Data provided by a local carrier indicate the typical stop is less than five minutes.

Personal travel is represented by the emissions factors for personal cars using gasoline. A weighted average of the previous 15 years of data was used according to the distribution reported in the *Transportation Energy Data Book* (Davis and Diegel 2002). The delivery vehicle travel uses emissions factors for single-unit short haul trucks with diesel fuel, averaging emissions factors for 2007-2010 model years because the real-world fleet modelled here relies on a fleet of trucks less than three years old. In addition, the effects of refrigeration on emissions were not included since the fleet does not use refrigerated trucks.

Emission factors were selected for an analysis year of 2010. Hourly kilograms of CO_2 equivalents per mile were extracted and averaged over each hour of the day, for weekdays, throughout the year for the King County, Washington, region. All roadways in the region are urban. Roadways with speeds of 5, 20, 25, and 35 miles per hour are local or arterial roadways with frequent intersections and qualify as "unrestricted" roadways within MOVES. As such, these roadways were evaluated with MOVES' urban unrestricted roadtype emissions factors. Likewise, roadways with speeds of 45 and 55 miles per hour are limited-access highways, qualifying as "restricted" roadways, and therefore are evaluated with MOVES' urban restricted roadtype emissions factors (Table 2).

Table 2: Emissions Factors (Kilograms of CO_2 Equivalents per Mile) from EPA's MOVES Model

Speed	Road Type	Passenger Cars	Single-Unit Short Haul Truck
5	Urban Unrestricted	1.070268	3.713213
20	Urban Unrestricted	0.449884	1.441101
25	Urban Unrestricted	0.400271	1.272039
35	Urban Unrestricted	0.336501	1.014241
45	Urban Restricted	0.316466	0.865594
55	Urban Restricted	0.299489	0.739326

Grocery Store Locations

Puget Sound Regional Council provided a shapefile with the locations of the major grocery stores within King, Kitsap, and Snohomish counties. These locations were trimmed to those within one mile of Seattle. Stores within 1,000 feet of another store were eliminated, since they serve the same service area with competing brands. The resulting database included 42 grocery stores. The service areas of each of the remaining stores were calculated (using the Service Area tool within ArcGIS Network Analyst), and households were assigned to their appropriate service area.

This analysis considers replacing one roundtrip by a household to its nearest grocery store with delivery from that store. Cairns (1995) summarizes the results from six surveys to describe the typical grocery shopping patterns in the United Kingdom. She cites a 1993 survey showing nearly two-thirds of housewives grocery shop less than two miles from home and a survey by Telephone Survey LTD, which indicated "62% of car shoppers use the nearest store to their home 'of its type' for main food shopping" (Cairns 1995, pg. 412). Her summary also indicated the vast majority of households with a car (99.6%) in the UK use a car for shopping, though in certain districts that percentage is somewhat lower (Cairns 1995). Siikvavirta et al. (2002) indicate in Finland only 55% of households use a car to grocery shop. Similarly, detailed data are not available in the United States, where the National Household Travel Survey (US DOT 2003) consolidates all shopping into one category. Analysis of the 2001 NHTS by Pucher and Renne (2003) indicates 91.5% of all shopping trips in the U.S. were made by personal automobile. Market research by the Nielsen Company indicates value is the primary consideration for 60% of U.S. shoppers when choosing a grocery store, followed by goods selection (28%) and closest store (23%) (2007). While value is considered more important than proximity for more Americans, the survey report did not indicate secondary and tertiary considerations. For this analysis, assigning customers to their nearest store is reasonable and provides a baseline for comparisons between personal travel and delivery vehicles.

Household Data

Geographic data regarding households and parcels were gathered from the Washington State Geospatial Data Archive (WAGDA) and the Urban Ecology Lab at the University of Washington. This effort required joining the WAGDA King County parcels file (containing address data) to the Urban Ecology Lab King County parcels file (containing the number of residential units data) to geocode the parcels with residential units information, and selecting out the residential parcels.

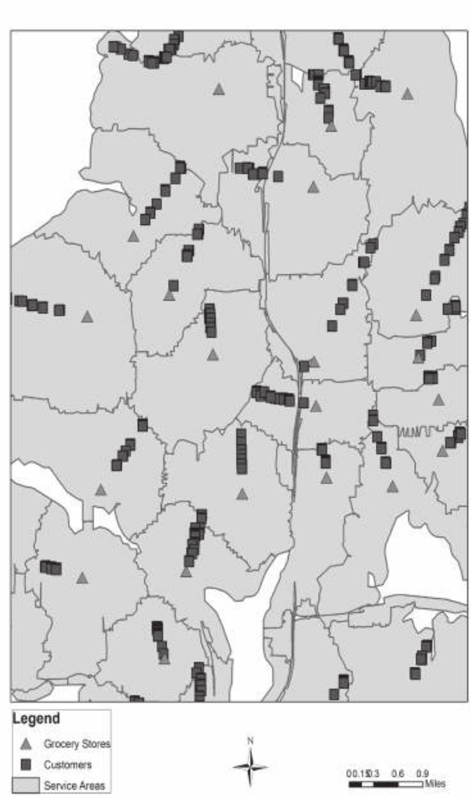
Calculating shared-use distance traveled is influenced by the logistical details of the service. Delivery service schedules dictated by customer preference have households distributed throughout the service area, while delivery service schedules dictated by the service provider have households geographically organized to obtain logistical efficiencies. Customer-directed service was estimated by random sampling of the households within the service area. Provider-directed service was estimated with proximity-assigned samples of the households. These two methods of selecting customers reflect best-case and worst-case scenarios in terms of logistical efficiency. Although a customer-directed service would allow customers to dictate their delivery time, a delivery service would assign customers to routes as efficiently as possible given fleet size and time constraints, so this worst case does not reflect the expected outcome in all cases. The provider-dictated service represents a best case for logistical efficiency with customers highly concentrated spatially.

Wygonik and Goodchild (2011) found truck size must be carefully calibrated to the customer volume to optimize cost and CO_2 emissions. As personal communication with local delivery providers indicate, each truck can hold approximately 35 households worth of orders, 35-household samples are used here. Because the sampling was done without replacement and the number of households in certain service areas was limited, five samples for each design were used, and their results averaged to provide the final values.

To sample the households randomly, the number of trucks (n) required to serve that service area was calculated by dividing the number of households in the service area (h) by the capacity of each truck (c=35). Because the base household parcel files were random, within each service area, every *n*th household was selected, for a total sample size of approximately 35 (minor variations resulted due to rounding). Each set included [i, n+i, 2n+i,…, xn+i] with i from 1 to 5.

To select a proximate sample of households, the households were ordered by their angle from the depot and then their distance from the depot. Households were then assigned to groups of 35 based on a modified greedy algorithm in which the next closest household was added to the sample until the desired sample size was achieved. Figure 2 illustrates the difference between the random sampling (Figure 2A) and proximity assignment (Figure 2B) for a set of service areas.

Figure 2: Illustrations of Sampling Techniques

A: Random Selection	B: Proximity Assignment
	

Vehicle Travel

To estimate the distances traveled and the associated CO_2 emissions, routing tools within ArcGIS Network Analyst were used. These tools can optimize on any metric provided within the network, most frequently distance, time, or cost. Here they are extended to account for CO_2 emissions. While the exact details of the heuristic used in the ArcGIS software is proprietary, their help manual (ESRI 2010) indicates shortest paths are identified with Dijkstra's algorithm (Dijkstra 1959) and order sequencing is completed with a tabu search heuristic (Glover 1986). These solutions are well regarded for quickly producing reasonable results.

To complete the routing estimates, the Network Analyst Closest Facility tool was used to calculate the distance travelled to each grocery store for each household in the sample. Output from Network Analyst includes the one-way distance travelled for each residential unit and the one-way CO_2 emissions associated with each residential unit's grocery store trip when the trip is optimized for shortest time. These outputs were doubled, to reflect round trip distances and CO_2 emissions.

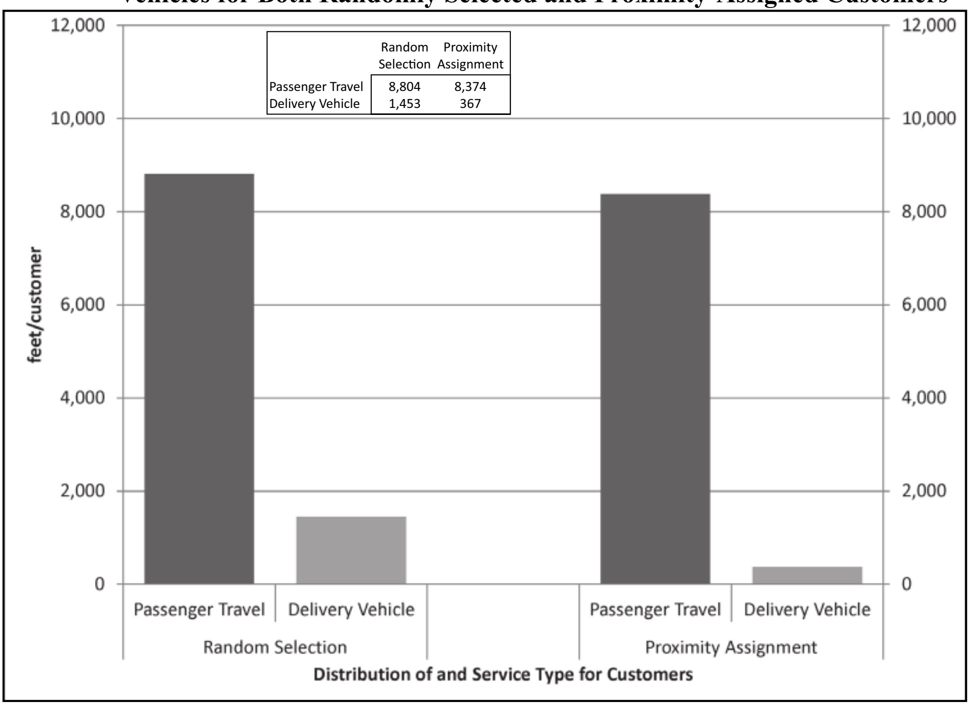
To complete the routing estimates, the Network Analyst Routing tool was used to calculate the distance travelled by a delivery vehicle starting and ending at the study grocery store and serving a sample of 35 households. Network Analyst was run to identify the fastest path to serve the given households. The analysis reordered the stops to identify the fastest route, but kept the first and last stops (the grocery store serving as the depot) constant. Output from Network Analyst includes the distance travelled for each delivery vehicle and CO_2 emissions associated with each tour, with the route optimized for shortest time. These values were averaged across the five samples to develop the total delivery vehicle miles traveled by the delivery vehicle for each service area.

RESULTS

Distance Traveled

The delivery vehicle routing, as expected, is shorter than the distance traveled by personal vehicles (see the table in Figure 3). The reductions in VMT of 85% to 95% are slightly higher than Cairns' (1997, 1998) observations between 60% and 80% and comparable to the upper bound of the Punakivi team findings of 54% to 93% (Punakivi and Saranen 2001, Siikavirta et al. 2002). While the distance traveled by the two subsets of personal vehicles (random selection versus proximity assignment) are reasonably similar, the distance traveled by the two subsets of delivery vehicles (random selection versus proximity assignment) are significantly different. Figure 3 illustrates this comparison, considering the variation across service areas.

Figure 3: Comparison of Distance Traveled per Customer for Personal and Shared-Use Vehicles for Both Randomly Selected and Proximity-Assigned Customers

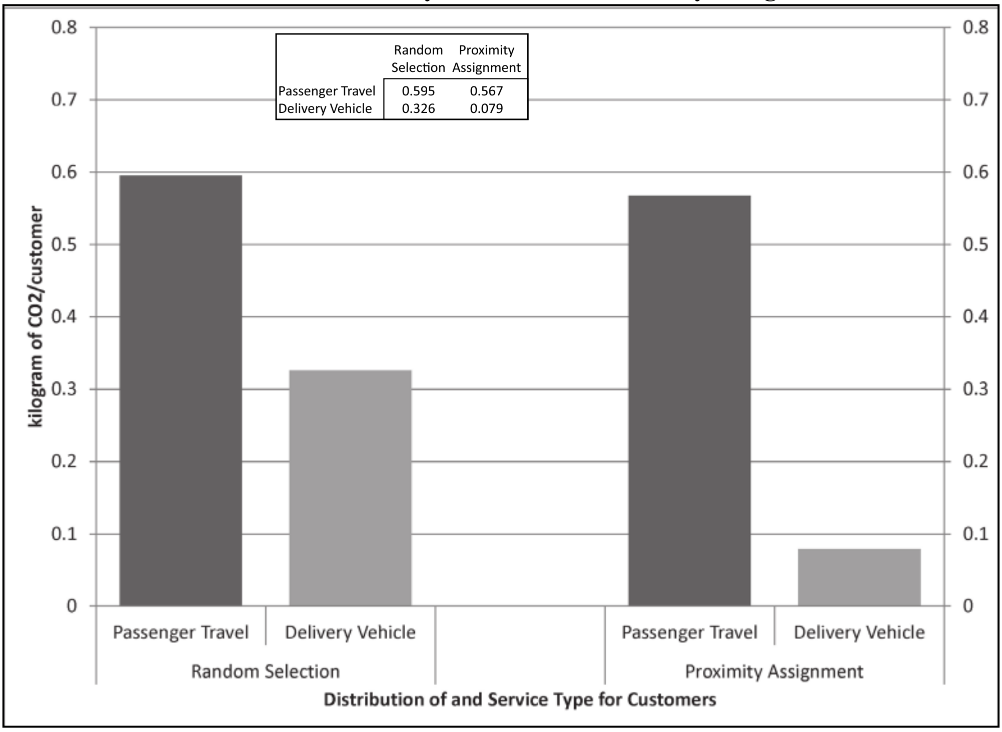


	Random Selection	Proximity Assignment
Passenger Travel	8,804	8,374
Delivery Vehicle	1,453	367

CO_2 Emissions Comparison

Also, as expected, the CO_2 emissions associated with the delivery vehicles are significantly fewer than those associated with personal travel (Figure 4). Large reductions in CO_2 emissions are observed when passenger travel is replaced by a delivery vehicle, and the results are comparable to Siikavirta et al.'s (2002) findings. However, these reductions are notably smaller than the reductions in distance traveled due to the larger CO_2 emissions associated with the delivery vehicles as compared with the passenger cars. As with distance traveled, the CO_2 emissions associated with personal travel do not vary significantly between the two sample types, but the CO_2 emissions associated with delivery travel do.

Figure 4: Comparison of Kilogrms of CO_2 per Customer for Personal and Shared-Use Vehicles for Both Randomly Selected and Proximity-Assigned Customers



The results illustrated in Figure 4 are presented as the upper and lower bounds of the benefit from a delivery service. Random selection represents a less efficient system, one in which customers select their service times. Even in this situation, delivery vehicles show significant reductions in CO_2 emissions over personal travel. In contrast, the proximity assignment selection represents a more efficient system, one in which the provider mandates service times, or can otherwise achieve significant customer density. The results from these two samples illustrate the influence logistics strategies have on the performance of a shared-use service. Appliance delivery with a small set of customers served on a given day is likely to roughly approximate a random sampling and is shown to have significant environmental savings. Grocery delivery services relying on a larger customer base and larger fleets will see reductions between these bounds, and services like garbage collection, in which customer service windows are frequently assigned by the provider and roughly approximate a proximity-assignment system, are shown to have higher environmental savings. This also demonstrates the importance of considering logistical strategies when estimating environmental impacts.

Influence of Service Area Size

While the above results support the findings from European research that significant VMT and CO_2 emissions reductions are possible when replacing personal travel with delivery service, given the vastly differing densities between European and American cities, the results were examined to determine if a relationship exists between CO_2 reduction and customer density. Given the fixed capacity of a delivery truck, the service area size represents the relative density of a service area. About half the variation in CO_2 emissions can be explained by service area for all but the randomly selected customers with delivery service. For all cases, a larger service area is associated with higher CO_2 emissions per customer.

Because of the higher CO_2 emissions associated with serving customers in a larger area, the CO_2 emissions savings associated with replacing personal travel with delivery service are higher as the service area increases (Figure 5a). This suggests the benefits of using a shared use vehicle are higher in less dense environments such as the U.S. Finally, comparing the service area size to the percentage reductions in CO_2 emissions (Figure 5b) illustrates the reductions associated with proximity assignment are consistent, between 80% and 90% (with one outlier of 70% savings). This result indicates density does not significantly affect the percentage reduction in CO_2 emissions and further indicates European and American results for proximity-assigned service should be consistent. Comparing these findings with Siikavirta et al.'s (2002) work, the values are similar (87% to the 80% to 90% observed here). The reductions associated with random assignment do increase with increasing service area, but also vary more, ranging from savings of 17.5% to 75%.

Overall, clear benefits are shown when personal travel is replaced by delivery service in all cases. This benefit is heightened when customers are grouped by location and when the service area is large. These results indicate density and urban form will influence the degree to which CO_2 emissions are reduced, but reductions should be expected in all situations where delivery trucks can be filled to capacity. Further study should examine the capacity level required to achieve a reduction in CO_2 emissions as most services are not expected to operate at full capacity at all times.

These savings assume households make round trips to the grocery store using a car. Other modes (for example walking, biking, or bus) are used and other destinations are included in grocery trips. Thus, a number of influencing factors, including trip chaining, mode choice, depot location, purchase/order size, congestion, and time of day, remain to be considered in the future.

CONCLUSION

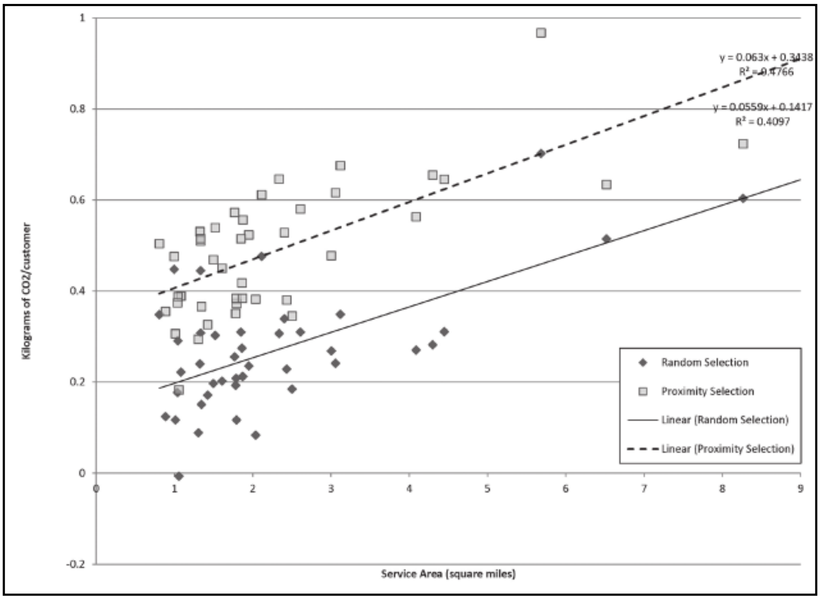
The analysis of grocery delivery demonstrates that a significant reduction in vehicle miles traveled and CO_2 emissions is possible when personal vehicle travel is replaced by delivery service. We demonstrate that routing and scheduling strategy plays a significant role in this trade-off. These reductions are largest when the delivery service serves a proximity-assigned set of customers. In this case, delivery service can reduce CO_2 emissions by 80%-90%, compared with 17%-75% reductions when customers are randomly assigned. The results from this case study are consistent with Siikavirta et al.'s (2002) case study, which found CO_2 emissions reductions potential between 18% and 87%. Their largest reduction (87%) corresponded to the case in which customers were proximity-assigned, and is a very similar result to the 80% to 90% reduction observed here. This analysis considered the relationship between personal vehicle travel replaced by one delivery vehicle. This unit of analysis allows for scaling according to adoption level – even a small number of customers (35), if served by one truck, could result in reduced greenhouse gas emissions. It also reflects the efficiencies gained by larger customer populations served by a fleet of delivery vehicles. With an increasing number of customers, providers can serve customers with larger fleets (or larger vehicles), can improve logistical efficiency, and can reduce VMT per customer, such that the routes may emulate a provider-controlled, proximity-assignment service. In these situations, reductions in CO_2 emissions are expected to fall between the randomly-selected and proximity-assigned cases, since customers within a self-selected delivery window can be grouped by the provider into proximity-based routes.

While all cases demonstrated reductions in CO_2 emissions, the largest savings in CO_2 emissions are associated with larger service areas. The profitability of delivery service is thought to correlate with dense locations, and larger service areas can be limited practically by service window size. However, emissions benefits are larger with less density. Pickup and delivery services could be incentivized in more rural locations to achieve environmental benefits, especially as alternative modes like transit, walking, and bicycle travel are less practical in more rural areas. In addition, these results indicate some differences can be expected due to the density difference in Europe and the United States, but overall, these services should prove beneficial in both places.

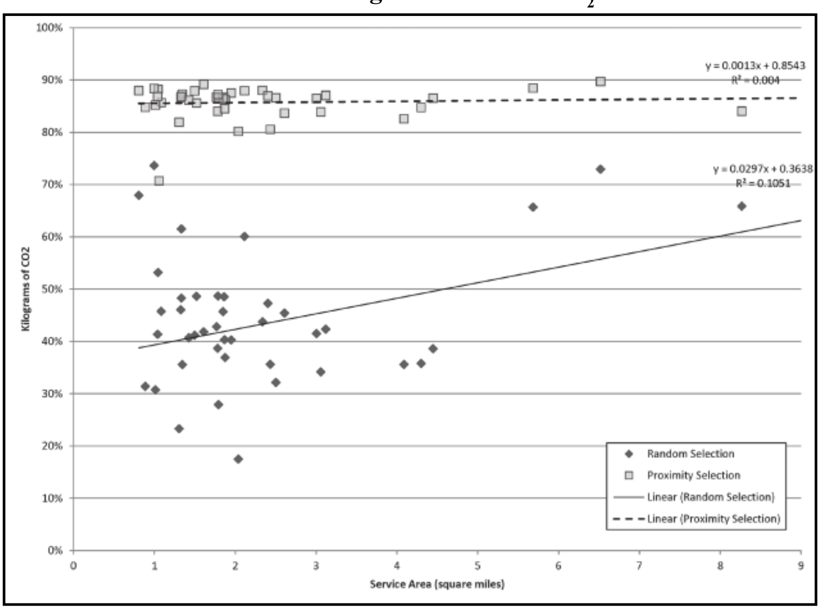
Significant greenhouse gas reductions are estimated through these cases, which provide initial bounds on expected gains from actualized service. The gains identified should be refined with further work to account for the reduction in impacts from personal travel associated with trip chaining, and the reduced benefit of delivery services when they operate at less than full capacity.

Figure 5: Comparison of Service Area to CO_2 Emissions Savings and Percentage Reduction, for Randomly-Selected and Proximity-Assigned Customers

A: Service Area Versus CO_2 Emissions Savings



B: Service Area Versus Percentage Reduction inCO_2 Emissions



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