

**Changing Retail Business Models and the Impact on CO₂ Emissions
from Transport:
E-commerce Deliveries in Urban and Rural Areas**

FINAL PROJECT REPORT

by

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In cooperation with US Department of Transportation-Research and Innovative Technology
Administration (RITA)



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Technical Report Documentation Page

1. Report No. 2013-S-UW-0023	2. Government Accession No. 01547301	3. Recipient's Catalog No.	
4. Title and Subtitle Changing Retail Business Models and the Impact on CO2 Emissions from Transport: E-commerce Deliveries in Urban and Rural Areas		5. Report Date 10/31/2014	
		6. Performing Organization Code	
7. Author(s) Anne Goodchild, Erica Wygonik		8. Performing Organization Report No. 23-626637	
9. Performing Organization Name and Address PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 121E Seattle, WA 98195-2700		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTRT12-UTC10	
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		13. Type of Report and Period Covered Research 7/1/2013-10/31/2014	
		14. Sponsoring Agency Code	
15. Supplementary Notes Report uploaded at www.pacTrans.org			
16. Abstract While researchers have found relationships between passenger vehicle travel and smart growth development patterns, similar relationships have not been extensively studied between urban form and goods movement trip making patterns. In rural areas, where shopping choice is more limited, goods movement delivery has the potential to be relatively more important than in more urban areas. As such, this work examines the relationships between certain development pattern characteristics including density and distance from warehousing. This work models the amount of CO2, NOx, and PM10 generated by personal travel and delivery vehicles in a number of different scenarios, including various warehouse locations. Linear models were estimated via regression modeling for each dependent variable for each goods movement strategy. Parsimonious models maintained nearly all of the explanatory power of more complex models and relied on one or two variables – a measure of road density and a measure of distance to the warehouse. Increasing road density or decreasing the distance to the warehouse reduces the impacts as measured in the dependent variables (VMT, CO2, NOx, and PM10). We find that delivery services offer relatively more CO2 reduction benefit in rural areas when compared to CO2 urban areas, and that in all cases delivery services offer significant VMT reductions. Delivery services in both urban and rural areas, however, increase NO _x and PM10 emissions.			
17. Key Words Emissions, delivery, CO2 footprint, land use		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages	22. Price NA

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Abstract

While researchers have found relationships between passenger vehicle travel and smart growth development patterns, similar relationships have not been extensively studied between urban form and goods movement trip making patterns. In rural areas, where shopping choice is more limited, goods movement delivery has the potential to be relatively more important than in more urban areas. As such, this work examines the relationships between certain development pattern characteristics including density and distance from warehousing. This work models the amount of CO₂, NO_x, and PM₁₀ generated by personal travel and delivery vehicles in a number of different scenarios, including various warehouse locations. Linear models were estimated via regression modeling for each dependent variable for each goods movement strategy.

Parsimonious models maintained nearly all of the explanatory power of more complex models and relied on one or two variables – a measure of road density and a measure of distance to the warehouse. Increasing road density or decreasing the distance to the warehouse reduces the impacts as measured in the dependent variables (VMT, CO₂, NO_x, and PM₁₀). We find that delivery services offer relatively more CO₂ reduction benefit in rural areas when compared to CO₂ urban areas, and that in all cases delivery services offer significant VMT reductions. Delivery services in both urban and rural areas, however, increase NO_x and PM₁₀ emissions.

Executive Summary

Worldwide, awareness has been raised about the dangers of growing greenhouse gas emissions. In the United States, transportation is a key contributor to greenhouse gas emissions. American and European researchers have identified a potential to reduce greenhouse gas emissions by replacing passenger vehicle travel with delivery service. These reductions are possible because, while delivery vehicles have higher rates of greenhouse gas emissions than private light-duty vehicles, the routing of delivery vehicles to customers is far more efficient than those customers traveling independently. In addition to lowering travel-associated greenhouse gas emissions, because of their more efficient routing and tendency to occur during off-peak hours, delivery services have the potential to reduce congestion. Thus, replacing passenger vehicle travel with delivery service provides opportunity to address global concerns - greenhouse gas emissions and congestion.

While addressing the impact of transportation on greenhouse gas emissions is critical, transportation also produces significant levels of criteria pollutants, which impact the health of those in the immediate area. These impacts are of particular concern in urban areas, which due to their constrained land availability increase proximity of residents to the roadway network. In the United States, heavy vehicles (those typically used for deliveries) produce a disproportionate amount of NO_x and particulate matter – heavy vehicles represent roughly 9% of vehicle miles travelled but produce nearly 50% of the NO_x and PM₁₀ from transportation.

Researchers have noted that urban policies designed to address local concerns including air quality impacts and noise pollution – like time and size restrictions – have a tendency to increase global impacts, by increasing the number of vehicles on the road, by increasing the total VMT required, or by increasing the amount of CO₂ generated. The work presented here is designed to determine whether replacing passenger vehicle travel with delivery service can address both concerns simultaneously. In other words, can replacing passenger travel with delivery service reduce congestion and CO₂ emissions as well as

selected criteria pollutants? Further, does the design of the delivery service impacts the results? Lastly, how do these impacts differ in rural versus urban land use patterns?

This work models the amount of VMT, CO₂, NO_x, and PM₁₀ generated by personal travel and delivery vehicles in a number of different development patterns and in a number of different scenarios, including various warehouse locations. In all scenarios, VMT is reduced through the use of delivery service, and in all scenarios, NO_x and PM₁₀ are lowest when passenger vehicles are used for the last mile of travel. The goods movement scheme that results in the lowest generation of CO₂, however, varies by municipality.

Regression models for each goods movement scheme and models that compare sets of goods movement schemes were developed. The most influential variables in all models were measures of roadway density and proximity of a service area to the regional warehouse.

These results allow for a comparison of the impacts of greenhouse gas emissions in the form of CO₂ to local criteria pollutants (NO_x and PM₁₀) for each scenario. These efforts will contribute to increased integration of goods movement in urban planning, inform policies designed to mitigate the impacts of goods movement vehicles, and provide insights into achieving sustainability targets, especially as online shopping and goods delivery becomes more prevalent.

Chapter 1 Introduction

Worldwide, awareness has been raised about the dangers of growing greenhouse gas emissions. In the United States, transportation is a key contributor to greenhouse gas emissions (US EPA 2008). American and European researchers have identified a potential to reduce greenhouse gas emissions by replacing passenger vehicle travel with delivery service (see Wygonik & Goodchild 2012 and Siikivirta et al. 2002). These reductions are possible because, while delivery vehicles have higher rates of greenhouse gas emissions than private light-duty vehicles, the routing of delivery vehicles to customers is far more efficient than those customers travelling independently. In addition to lowering travel-associated greenhouse gas emissions, because of their more efficient routing and tendency to occur during off-peak hours, delivery services have the potential to reduce congestion. Thus, replacing passenger vehicle travel with delivery service provides opportunity to address global concerns - greenhouse gas emissions and congestion.

While addressing the impact of transportation on greenhouse gas emissions is critical, transportation also produces significant levels of criteria pollutants, which impact the health of those in the immediate area (US EPA 2013b, US EPA 2013c). These impacts are of particular concern in urban areas, which due to their constrained land availability increase proximity of residents to the roadway network. In the United States, heavy vehicles (those typically used for deliveries) produce a disproportionate amount of NO_x and particulate matter – heavy vehicles represent roughly 9% of vehicle miles travelled but produce nearly 50% of the NO_x and PM₁₀ from transportation (US EPA 2008, Davis et al. 2013) (see fig. 1.1).

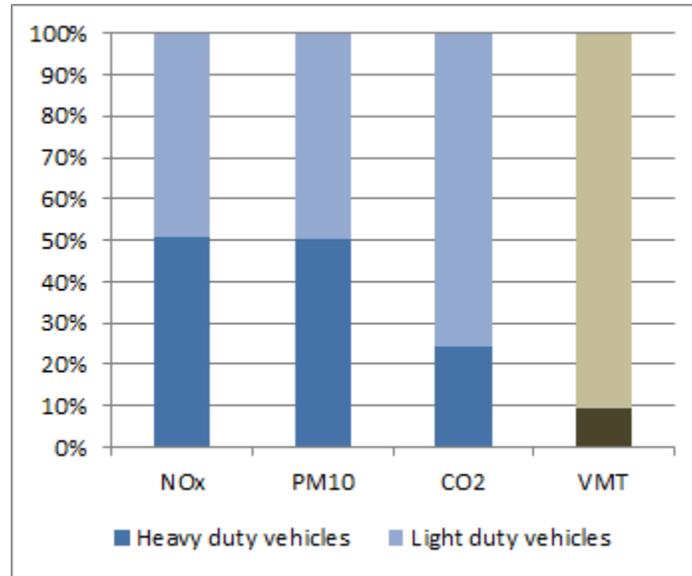


Figure 1.1 Emissions and Vehicle Miles Traveled by Source Type

Researchers have noted that urban policies designed to address local concerns including air quality impacts and noise pollution – like time and size restrictions – have a tendency to increase global impacts, by increasing the number of vehicles on the road, by increasing the total VMT required, or by increasing the amount of CO₂ generated (Wygonik and Goodchild 2011, Siikavirta et al. 2002, Quak and de Koster 2007 and 2009, Allen et al. 2003, van Rooijen et al. 2008, Holguin-Veras 2013). The work presented here is designed to determine whether replacing passenger vehicle travel with delivery service can address both concerns simultaneously. In other words, can replacing passenger travel with delivery service reduce congestion and CO₂ emissions as well as selected criteria pollutants? Further, does the design of the delivery service impacts the results?

In addition, while researchers have found relationships between passenger vehicle travel and smart growth development patterns, similar relationships have not been extensively studied between urban form and goods movement trip making patterns. In rural areas, where shopping choice is more limited, goods movement delivery has the potential to be relatively more important than in more urban areas. As such, this work also aims to examine the relationships between certain development pattern characteristics

including density and distance from warehousing. That is, do goods movement strategy impacts differ by urban form characteristics?

This work models the amount of CO₂, NO_x, and PM₁₀ generated by personal travel and delivery vehicles in a number of different scenarios, including various warehouse locations. The results allow for a comparison of the impacts of greenhouse gas emissions in the form of CO₂ to local criteria pollutants (NO_x and PM₁₀) for each scenario. These efforts will contribute to increased integration of goods movement in urban planning, inform policies designed to mitigate the impacts of goods movement vehicles, and provide insights into achieving sustainability targets, especially as online shopping and goods delivery becomes more prevalent.

Chapter 2 Literature Review

2.1 Reductions in externalities with delivery systems

A sizable body of research has indicated replacement of personal travel to grocery stores with grocery delivery services has significant potential to reduce VMT. Cairns (1997, 1998, 2005) observed reductions in vehicle miles travelled (VMT) between 60 and 80 percent when delivery systems replaced personal travel. The Punakivi team found reductions in VMT as high as 50 to 93 percent (Punakivi and Saranen, 2001; Punakivi et al., 2001; Punakivi and Tanskanen, 2002; Siikavirta et al., 2002). Wygonik and Goodchild (2012) saw reductions of 70-95%.

Both Siikavirta et al. (2002) and Wygonik & Goodchild (2012) examined the impact on CO2 emissions for passenger travel replacement for grocery shopping. Wygonik & Goodchild observed reductions in CO2 emissions between 20 and 75 percent when delivery systems served randomly selected customers and reductions 80-90% when delivery systems served clustered customers. These are comparable to the results observed by Siikavirta et al. (2002).

Hesse (2002) points out limitations in evaluations which directly replace passenger travel with delivery service as other changes to the logistics system are likely. He further comments on the likelihood for e-commerce to encourage more distal warehouse locations. The evaluation presented here attempts to address some of these concerns by incorporating the entire supply chain from regional warehouse to end consumer. Recent growth by Amazon (Wenger 2013) shows at least some retailers are not moving their warehouses further away, but instead are moving them closer to population centers.

While some research has indicated replacement of personal travel to grocery stores with grocery delivery services has significant potential to reduce VMT, these articles have not addressed criteria pollutants, which are associated with significant health impacts (EPA 2013b, EPA 2013c).

2.2 Warehouse locations

Since warehouses (including storage and distribution centers) are frequently an end point for commercial trips, their location can significantly influence the distances travelled by goods movement vehicles. Research about the optimal locations for warehouses is common. Crainic et al. (2004) found that the use of ‘satellite’ warehouses to coordinate movements of multiple shippers and carriers into smaller vehicles reduced the vehicle miles traveled of heavy trucks in the urban center but increased the total mileage and number of vehicles moving goods within the urban center. This research illustrates the close relationship between warehouse location and the vehicle choice. Likewise Dablan and Rakotonarivo (2010) found terminal locations have moved further from the city center over the past 30 years resulting in an estimated increase in CO₂ of 15,000 tonnes per year. They compare this with estimated gains from smaller consolidation centers located close to city centers and found the increase in CO₂ from the relocated terminals was 30 times greater than the savings from the smaller consolidation centers. Filippi et al. (2010) found greater potential environmental savings through urban distribution centers than through changes to the vehicle fleet, though both were successful.

In contrast, Allen and Browne (2010) found that locating distribution facilities closer to urban centers would reduce the average length of haul and total vehicle kilometers travelled by freight vehicles in and to urban centers, and Andreoli et al. (2010) found that mega-distribution centers, located to serve multiple regions, increased the distance travelled between the distribution center and the final outlet.

While this area of the literature is well-studied, clear consensus about the CO₂ impacts of warehouse location has not been reached and little research exists on the impacts of warehouse location on criteria pollutants. This research examines the results of shifting shopping behavior from personal travel to delivery service and examines the influence on warehouse structure on those results. It also provides insight into the trade-offs between local impacts (criteria pollutants – NO_x and PM₁₀) and global ones (VMT and CO₂).

2.3 Influence of urban form

An extensive literature has examined the role of density and urban form on automobile travel. Dense development, strong road connectivity, and a mix of land uses are three of the key features of Smart Growth development (Smart Growth Network 2011, Moudon et al. 2003). These features are associated with reduction in travel cost (Porter et al. 2005), trip making, trip length (Cervero 1989; Cervero 1996; Cervero and Landis 1997), total VMT (Frank et al. 2007; Frank et al. 2006; Ewing et al. 2002; Ewing and Cervero 2001; Handy et al. 2005; Porter et al. 2005), and emissions (TRB 2009). While there is reasonable consensus about the household travel benefits of dense development patterns, only a few studies have touched on the impact of density on freight vehicle impacts and those studies are not conclusive. Klastorin et al. (1995) found demand for truck trips is increased in urban areas, but Wygonik and Goodchild (2011) found the cost and environmental impact per delivery order to be less in denser areas.

Daganzo (2010) in discussing the traveling salesman problem (TSP), proposes an approximation summarized in equation 2.1. The approximate travel length for a single delivery vehicle serving a set of customers is a function of the number of customers and service area size (or customer density) along with a factor for the type of road network connectivity (straight line paths – Euclidean/L2 or grid connections – Manhattan/L1). Daganzo's (2010) TRP approximation is:

$$L^* \sim k \sqrt{AN} = kN / \sqrt{\delta} \quad (2.1)$$

where L: travel length

k : network constant (k = 0.72 for L2 (Euclidean), .92 for L1 (grid))

A : service area

N : number of customers

δ : customer density.

He extends that approximation for the vehicle routing problem (VRP) (in which more than one vehicle serves a set of customers) in equation 2.2. Here in addition to the number of customers and service area, he includes the capacity of the vehicle and the distance from the depot to the service area centroid. Daganzo's (2010) VRP approximation is:

$$L_{vrp} \leq L_{tsp} + 2Dr/v_m \quad (2.2)$$

where L_{vrp} : travel length for the vehicle routing problem estimation

L_{tsp} : travel length for the traveling salesman problem estimation

r : distance from depot to center of tour area

D : total demand (units)

v_m : vehicle capacity.

The findings from these studies indicate that customer density, road network density and connectivity, service area size, the mix of land uses, and the distance from the warehouse or depot to the service area centroid all may influence VMT and, thus, emissions associated with goods movement.

Chapter 3 Study Data

3.1 Network Data Set

The base network is pulled from the ESRI StreetMap North America data set (ESRI 2006) and was modified in a number of ways. First, the data set was trimmed to only include road segments in King County, Washington to reduce processing time. Next, 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 the speed limit information and appended to the data table. Finally, information regarding the CO₂, NO_x, and PM₁₀ 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.

Once the data were added to the StreetMap layer, it was built as a Network for use in the Network Analyst tool set in ArcGIS.

While this evaluation considers link-level travel speeds, it does not include various real-time travel components, including congestion and queuing. These factors may affect the results but are outside the scope of this analysis.

3.2 Emissions Factors

Emissions factors were obtained from the 2010b MOVES model (EPA 2013a). EPA's MOVES model was used to identify emissions rates as it is the most current emissions model supported by the United States government. The factors in MOVES are sensitive to a number of different parameters considered within this analysis, including speed and vehicle type. This analysis assumed uncongested conditions, so speed limit data from the StreetMap North America data set was used as the default flow speed for each road segment. Running exhaust emissions are tracked.

Personal travel is represented by the emissions factors for personal cars using gasoline. The home delivery vehicle travel uses emissions factors for single-unit short haul trucks with diesel fuel, and the emissions rates for the vehicles used to move goods from the warehouse to stores relies on data for combination short-haul trucks and diesel fuel. A weighted average of the previous 15 years of data was used according to the vehicle age distribution reported in the Transportation Energy Data Book (Davis et al. 2013) for passenger cars and trucks, respectively. Because of data restrictions, the distribution of the previous 15 years data is only released as of 2001. This distribution is applied to 2014.

Emission factors were selected for an analysis year of 2014. Hourly kilograms per mile of CO₂ equivalents, NO_x, and PM₁₀ were extracted and averaged over each hour of the day, for weekdays, throughout the year for the King County, Washington region. Roadways with speeds of 5, 20, 25, and 35 miles per hour used urban unrestricted roadtype emissions factors, and roadways with speeds of 45 and 55 miles per hour used urban restricted roadtype emissions factors (see table 3.1). Since the trucks work with hot engines due to their short stopping time, only running exhaust emissions are tracked.

Table 3.1 Emissions factors (kilograms per mile of CO₂ Equivalents, NO_x, and PM₁₀) from EPA’s MOVES model (EPA 2013a)

		Urban Unrestricted				Urban Restricted	
		5	20	25	35	45	55
Passenger Cars	CO ₂	1.05917	0.41817	0.37320	0.33967	0.30813	0.29773
	NO _x	0.0004980	0.0002969	0.0002943	0.0003189	0.0003020	0.0003128
	PM ₁₀	0.00002615	0.00000865	0.00000842	0.00001183	0.00000736	0.00000720
Single Unit Short Haul	CO ₂	3.8027	1.4837	1.3319	1.1308	0.8667	0.7403
	NO _x	0.016566	0.005898	0.005196	0.004357	0.003390	0.002950
	PM ₁₀	0.0007268	0.0002548	0.0002240	0.0001876	0.0001566	0.0001448
Combination Short Haul	CO ₂	4.8386	2.5148	2.3542	1.9788	1.9175	1.7228
	NO _x	0.023531	0.010781	0.009821	0.008475	0.008198	0.007719
	PM ₁₀	0.0010048	0.0005433	0.0005058	0.0003797	0.0003296	0.0002410

3.3 Selected Municipalities

To consider the impact of urban form and density on delivery impacts, a set of municipalities was selected to reflect a range of development patterns. To maintain consistent data, the municipalities within King County, Washington were evaluated. Earlier work focused on Seattle, which is a large urban area. To enable comparison with the earlier work, Seattle was included here. To select the additional locations, the number of addresses, road length, and municipal area for each municipality in King County were calculated in ArcGIS. These values were used to calculate the address density (number of addresses per square mile) and the road density (linear feet per square feet) for each municipality (see fig. 3.1).

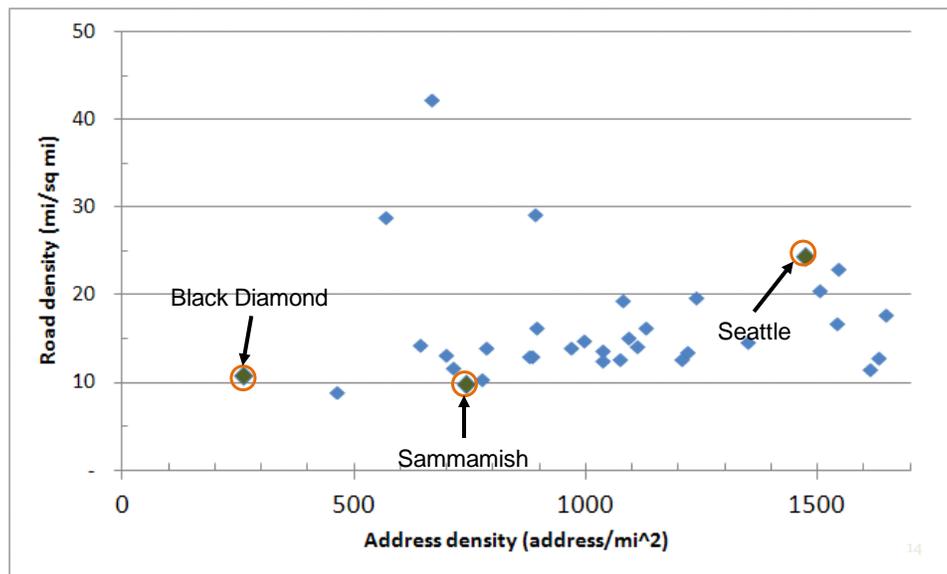


Figure 3.1 Address density and road density of municipalities in King County, Washington

As illustrated in figure 3.1 Seattle has relatively high address density and moderate road density. After eliminating outliers and places with fewer than 1000 residents, Black Diamond and Sammamish were selected as two of the most contrasting locations, with low address and road densities. Their relative locations, sizes, and road densities are illustrated in figure 3.2. Table 3.2 illustrates the descriptive statistics for each municipality.

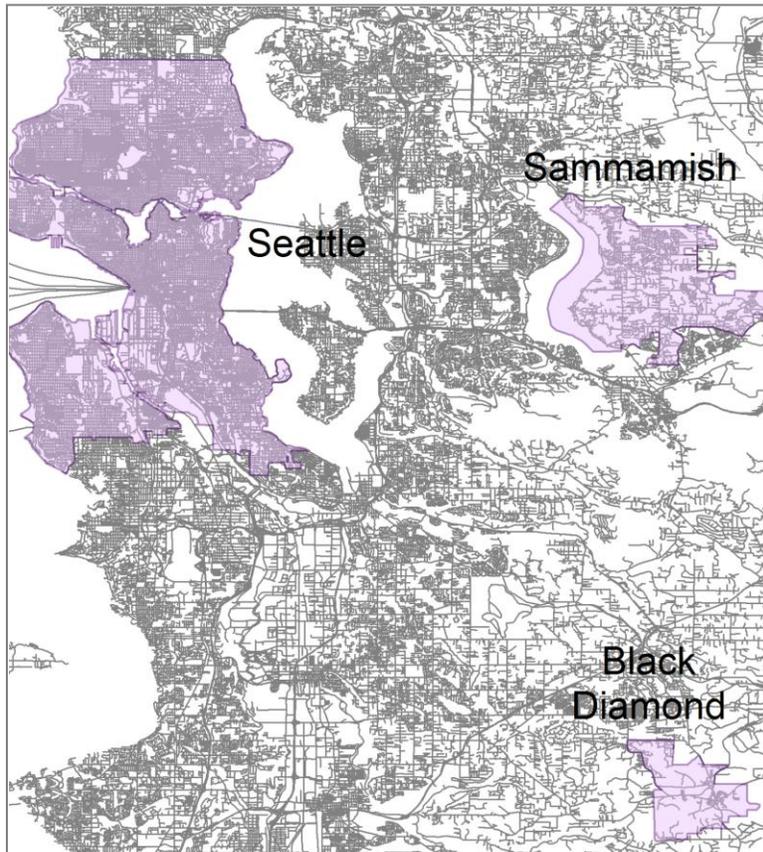


Figure 3.2 Map of selected municipalities – Seattle, Black Diamond, and Sammamish – illustrating relative locations, sizes, and road densities

Table 3.2 Descriptive statistics for selected municipalities – Seattle, Black Diamond, and Sammamish

	Seattle	Black Diamond	Sammamish
Area (sq mi)	143.4	7.2	22.0
Average depot service area (sq mi)	28.7	7.2	22.0
Linear Road Miles	2017	78	215
Number of Addresses	211,501	1,881	16,339
Address Density (addresses/ sq mi)	1,475	261	742
Customer Density (customers/sq mi)	1.2	4.9	1.6
Est. Market Share	0.1%	1.9%	0.2%
Stores in City Limit	42	0	2
Stores Serving Customers	42	1	6
Depots	5	1	1
Avg. Miles to Warehouse from Depots	19.5	12.5	25.2

3.4 Depot Locations

Delivery services are generally clustered into two primary types – ones that rely on existing brick-and-mortar retail locations for depots and those that use warehouses as depots. While other models exist, this research compares these two main types: a brick-and-mortar storefront depot with a warehouse-based model. This analysis considers replacing one roundtrip by an address to its nearest grocery store with delivery from a local store-based delivery service or service from a regional warehouse. Earlier work by the authors (Wygonik and Goodchild 2012) used one service area for personal travel and delivery service, and this work is designed to develop a more realistic model of the delivery service. For companies operating a delivery service out of a store-front, they are unlikely to operate that company out of every store front. Rather, they would likely pick a small subset of available options which would serve as depots for different quadrants of the city. This change reflects more realistic catchment areas for retail stores versus a delivery depot.

Puget Sound Regional Council provided a shapefile with the locations of the major grocery stores within King, Kitsap, and Snohomish counties. The service areas of the stores were calculated (using the Service Area tool within ArcGIS Network Analyst) and addresses were assigned to their closest store's service area for the personal travel calculations. 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.

One in 5 stores throughout King County were selected to serve as local depots. This value compares with the roughly 1 in 3 stores Tesco.com uses as local depots in the UK (Punakivi and Tanskanen, 2002). As a result, a subset of five stores was selected to serve as depots for the store-based delivery service in Seattle. These stores are distributed throughout Seattle and are illustrated in figure 3.3. Black Diamond and Sammamish are each served by one local depot. In Black Diamond that depot is outside the city limits. One existing warehouse location in Kent, Washington was selected to serve as the

depot location for the warehouse-based delivery service, as well as the warehouse serving the grocery stores themselves (fig. 3.4).

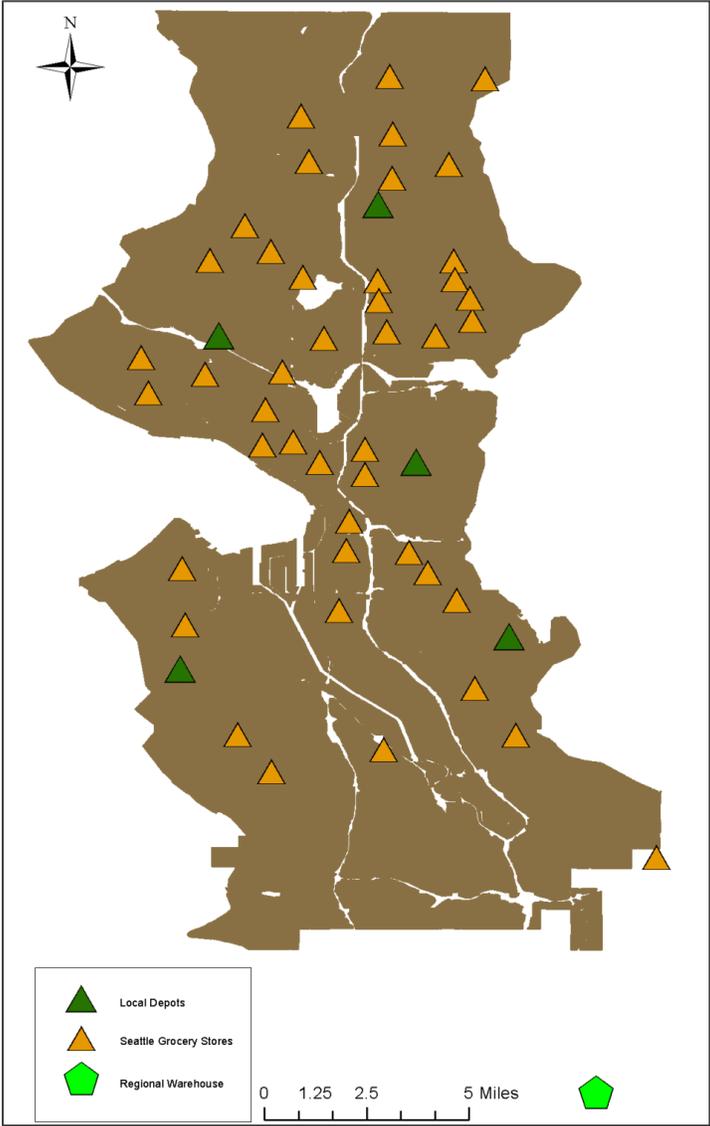


Figure 3.3 Warehouse, depot, and store locations in Seattle

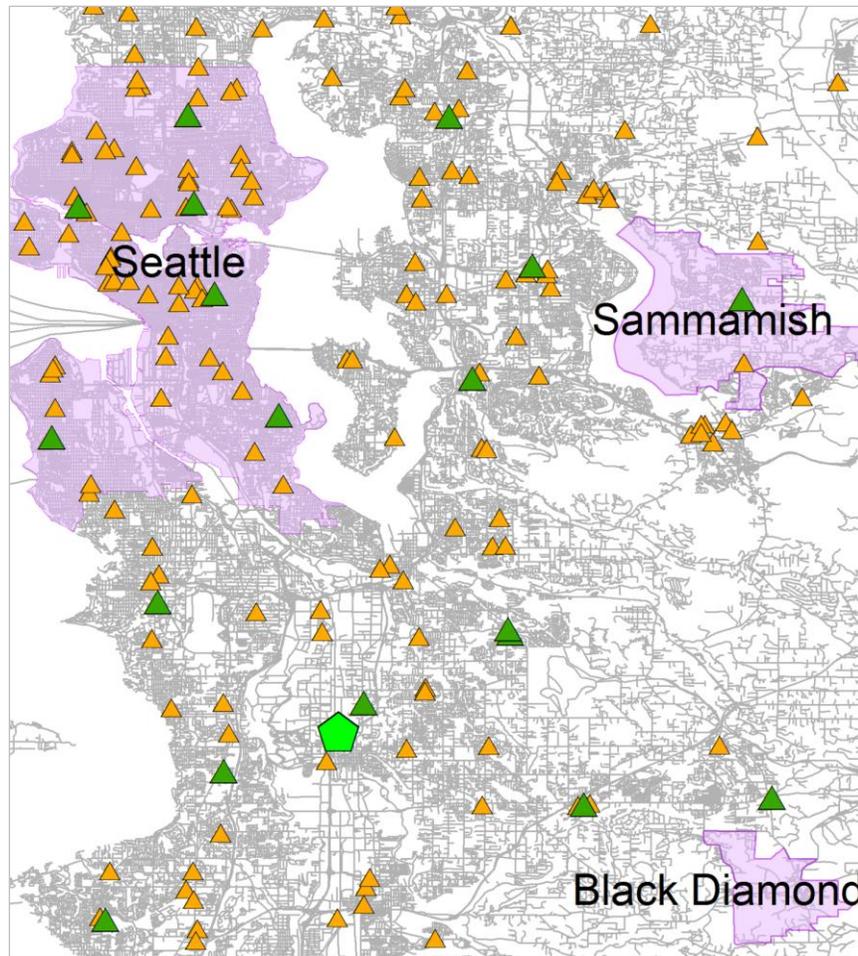


Figure 3.4 Warehouse, depot, and store locations for the three studied municipalities

3.5 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. To maintain consistency with prior work, in Seattle only household location were selected. That effort required joining the WAGDA King County parcels file (containing address data) to the Urban Ecology Lab King County parcels file (containing the residential units data) to geocode the parcels with residential units information, and selecting out the residential parcels. For Black Diamond and Sammamish, all addresses were used as potential customers, reflecting that both households and businesses receive delivery services.

As personal communication with local delivery providers indicate each truck can hold approximately 35 households worth of orders, 35-household samples are used here. A total of 25 samples for each municipality were gathered, as that ensured adequate statistical power while providing reasonable computation time. For Seattle, 5 samples were gathered for each of the 5 local depot service areas. For Black Diamond and Sammamish, 25 samples were gathered for the local depot service area. These samples were used for all three travel types – household travel to their proximate store, delivery service from their assigned store-based depot, and delivery service from the regional warehouse – enabling direct comparison between each. The sampling was conducted randomly, with replacement, from all available customers in the local depot service area. To evaluate the impacts of personal travel, the sampled customers were then assigned to their closest store.

Chapter 4 Method

4.1 Scenarios

Three scenarios were considered in this evaluation:

- 1) The baseline scenario, Passenger Vehicles, represents a common form of travel for grocery shopping. A large, combination truck stocks the grocery stores from the regional warehouse. Individual customers use passenger vehicles to complete roundtrips from their addresses to their closest grocery store and back.
- 2) The second scenario, Local Depot Delivery, provides delivery service from selected grocery retail locations distributed throughout the region. In this scenario, the local depots are stocked from the regional warehouse using large, combination trucks. Then smaller box trucks complete delivery via a milk-run starting and ending at the select stores and stopping at the sampled customers along the way.
- 3) The third scenario, Regional Warehouse Delivery, provides delivery service directly from the regional warehouse using small, box trucks. The routes start and end at the regional warehouse and stop at the sampled customers along the way.

These scenarios are illustrated in figure 4.1.

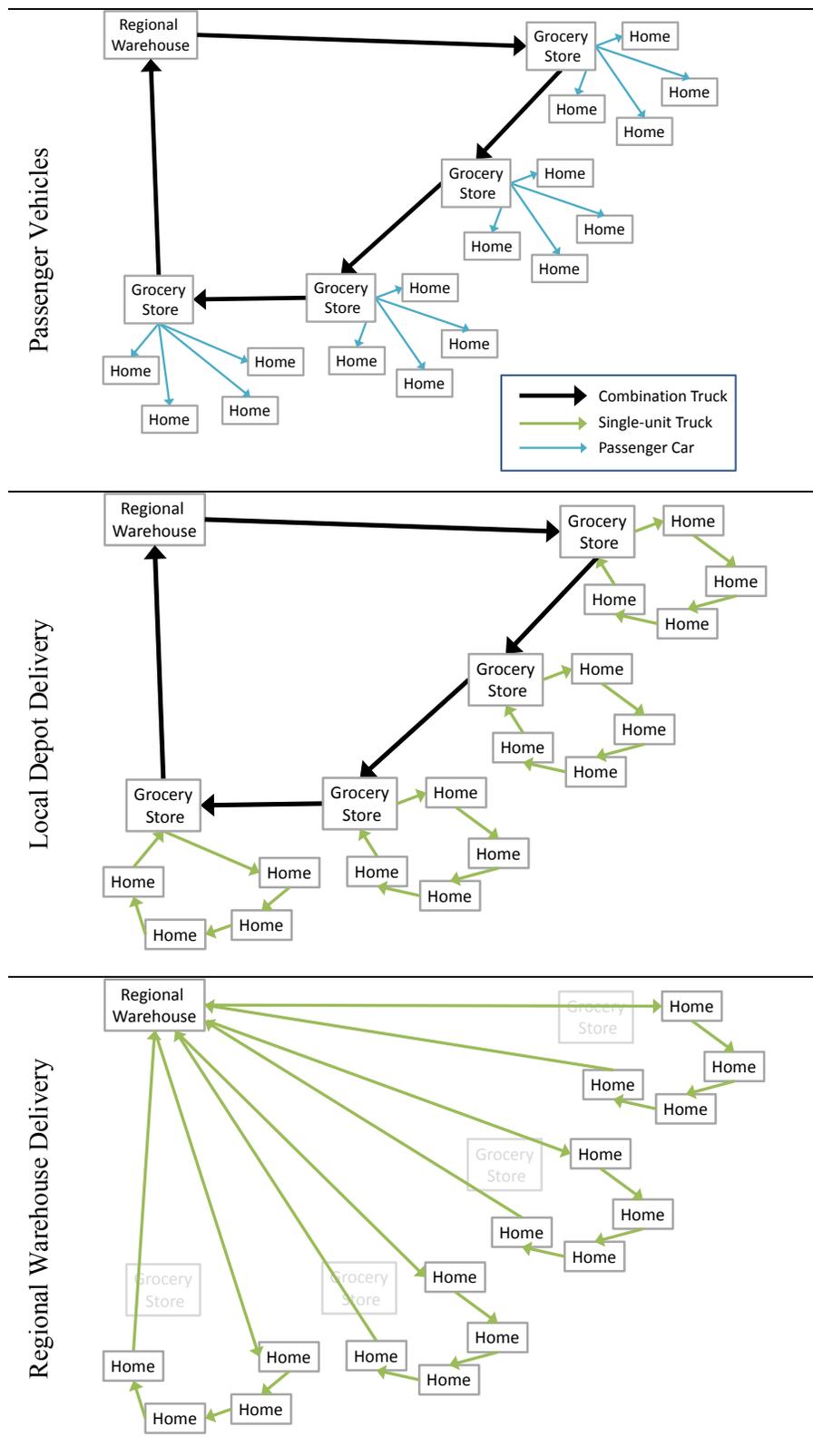


Figure 4.1 System bounds and vehicle types for three scenarios

4.2 Vehicle travel

To estimate the distances traveled and the associated emissions, routing tools within ArcGIS Network Analyst were used.

To complete the routing estimates, the Network Analyst Closest Facility tool was used to calculate the distance traveled to each grocery store for each household in the sample for the Passenger Vehicle scenario. The StreetMap network was loaded for use with Network Analyst. Output from Network Analyst includes the one-way distance traveled for each residential unit and the one-way 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 emissions. Using round trips for the Passenger Vehicle scenario represents a simplification, as some grocery shopping does occur within chained trips. However, the available data do indicate most grocery shopping occurs via passenger vehicle making exclusive trips (as discussed above and outlined in Wygonik and Goodchild 2012). Not all trips would be replaced by this type of service, but it is a reasonable estimation of the impact of replacing main household stocking trips.

To complete the routing estimates, the Network Analyst Routing tool was used to calculate the distance traveled by a delivery vehicle starting and ending at the depots and serving a sample of 35 households. The StreetMap network was loaded for use with Network Analyst. 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 depot) constant. Output from Network Analyst includes the distance traveled for each delivery vehicle and emissions associated with each tour, with the route optimized for shortest time.

Vehicle travel to stock the grocery stores from the regional warehouse was also included to maintain a constant system boundary for all scenarios. For the personal travel, 10 tractor trailers were

required to stock the 49 grocery store locations proximate to Seattle. The Network Analyst Routing tool was used to calculate the distance traveled and emissions for 10 tractor trailers leaving the regional warehouse and each serving 5 stores (one served 4). The results were then divided by 10 to represent the average values for one truck. For Black Diamond, the 5 stores closest to the one serving Black Diamond were selected and served by a tractor trailer. For Sammamish, the 10 closest stores were selected and served by two tractor trailers for stocking runs.

For the scenario involving the local, store-based depots, the Network Analyst Routing tool was used to calculate the distance traveled and emissions for one tractor trailer serving the 5 store-based depots in Seattle and the closest 5 depots to Black Diamond and Sammamish. Figure 4.1 above illustrates the 3 scenarios.

4.3 Assumptions

A number of assumptions were required within the modeling system. First, all optimizations used hard time windows, guaranteeing that promised delivery times would be met. The problem is also simplified to an urban delivery system, disregarding pickup. The model does not consider real-time routing changes. It is a planning tool and is not intended to provide dynamic routing information. In addition, this model currently assumes uncongested conditions.

4.4 Regression modeling

The regression modeling was conducted using the R statistical package. This evaluation relied on the same set of sampled addresses used above, but in this case each address represented a data point with information about VMT and CO₂, PM₁₀, and NO_x emissions associated with each of the three goods movement scenarios along with descriptive data about an addresses associated land use environment (address density, distance to the warehouse, etc.). As a result, the regression estimates were conducted on the entire set of sampled addresses, with a sample size of 2625 (25 addresses, sampled 35 times, in 3 municipalities). Because of the sampling with replacement initially conducted, a small subset of the

sampled addresses may be included more than once. This value is expected to be small enough to not affect the outcome.

To estimate the models, a modified forward selection was conducted on the likely variables. Each variable was tested for fit, and the variable with the highest explanatory power that was also significant was added to the model. This new model was tested with each of the remaining variables. If any of those remaining variables were significant, the model with the new highest predictive power was selected as the current active model. This process was repeated until either all variables were added to the model or new variables were not significant.

Two difference sets of models were developed. The first set of models represented the Best Fit models, and these models included all variables that tested significant within the model estimation. The second set of models represent the Parsimonious models. These models include only the variables that meaningfully improve the explanatory power.

Models for each dependent variable (VMT, CO₂, NO_x, and PM₁₀) were developed for each goods movement structure, for a total of 12 models in each of the two sets.

The variables selected in these models were then tested for influence in the comparative relationships between goods movement strategies. The two sets of models were again developed for each dependent variable, but this time a subset of models was created representing the differences between passenger vehicle travel and local depot delivery, between passenger vehicle travel and warehouse-based delivery, and between local depot delivery and warehouse-based delivery. Again, a total of 24 models were estimated.

Based on the literature, the following variables were tested for each goods movement strategy. For Passenger Travel, the tested variables include:

- Address Density : the number of addresses in the store service area divided by the store service area size (units = 1/square mile)
- Store Service Area Size : the store service area size (square mile)

- Distance from the Warehouse to the Store : the on-road travelled distance between the warehouse and the assigned store (miles), calculated using Google maps and the location addresses
- Store Service Area Road Density : the linear feet of road in a store service area divided by the store service area size (feet/square feet)
- Store Service Area Junction Density : the number of junctions in a store service area divided by the store service area size (1/square feet)

A similar set of variables was tested for the Local Depot Delivery models, but these variables were standardized by the depot service area instead of the store service area.

- Customer Density : the number of customers in the depot service area divided by the depot service area size (units = 1/square mile)
- Depot Service Area Size : the store service area size (square mile)
- Distance from the Warehouse to the Depot : the on-road travelled distance between the warehouse and the assigned depot (miles) , calculated using Google maps and the location addresses
- Depot Service Area Road Density : the linear feet of road in a depot service area divided by the depot service area size (feet/square feet)
- Depot Service Area Junction Density : the number of junctions in a depot service area divided by the depot service area size (1/square feet)
- Distance from the Depot to the Depot Service Area Centroid : the on-road travelled distance between the depot and the geographic centroid of the depot service area (miles), calculated using Network Analyst tools in ArcGIS

The variables tested for Warehouse Delivery were the same as those tested for Local Depot delivery, except a different measure for travel distance from the warehouse was used.

- Customer Density
- Depot Service Area Size

- Depot Service Area Road Density
- Depot Service Area Junction Density
- Distance from the Warehouse to the Depot Service Area Centroid : the on-road travelled distance between the warehouse and the geographic centroid of the depot service area (miles) , calculated using Network Analyst tools in ArcGIS

Additional variables were developed for the goods movement strategy comparisons. These were ratios between like variables. For example, the passenger travel models were evaluated for the road density in the store service area, while the delivery models were evaluated for the road density in the depot service area. For the comparison models, an extra variable representing the ratio of store service area road density to depot service area road density was included.

Descriptive statistics for all evaluated variables are included in table 4.1. The correlation plot between these variables is illustrated in fig 4.2. As is shown, the different measures of distance among the warehouse, stores, depots, and centroids were highly correlated. The various measures of road and junction density were highly correlated.

Table 4.1 Descriptive statistics for evaluated independent variables

	Minimum Value	Mean	Maximum Value	Standard Deviation	Units
Store Service Area Road Density	6.0	15.6	37.5	7.81	miles/square mile
Distance: Warehouse to Store	10.8	19.2	29.4	6.31	miles
Address Density	20.5	1009.1	2886.5	760.56	1/square miles
Store Service Area Junction Density	56.6	179.9	637.0	116.88	1/square miles
Store Service Area Size	0.5	6.6	20.6	3.95	square miles
Customer Density	1.6	2.9	4.9	1.43	1/square miles
Depot Service Area Road Density	9.8	16.3	31.9	8.64	miles/square mile
Distance: Warehouse to Depot	12.5	19.1	25.7	5.80	miles
Depot Service Area Junction Density	70.3	204.8	530.0	146.49	1/square miles
Distance: Depot to Centroid	0.2	2.1	4.2	1.51	miles
Distance: Warehouse to Centroid	12.8	20.0	27.0	5.89	miles
Store:Depot Service Area Road Density	0.60	0.98	1.31	0.17	
Distance - Warehouse to Store: Warehouse to Centroid	0.72	0.96	1.25	0.09	
Distance - Warehouse to Centroid: Warehouse to Depot	0.93	1.05	1.14	0.08	
Distance - Warehouse to Store: Warehouse to Depot	0.67	1.00	1.19	0.07	

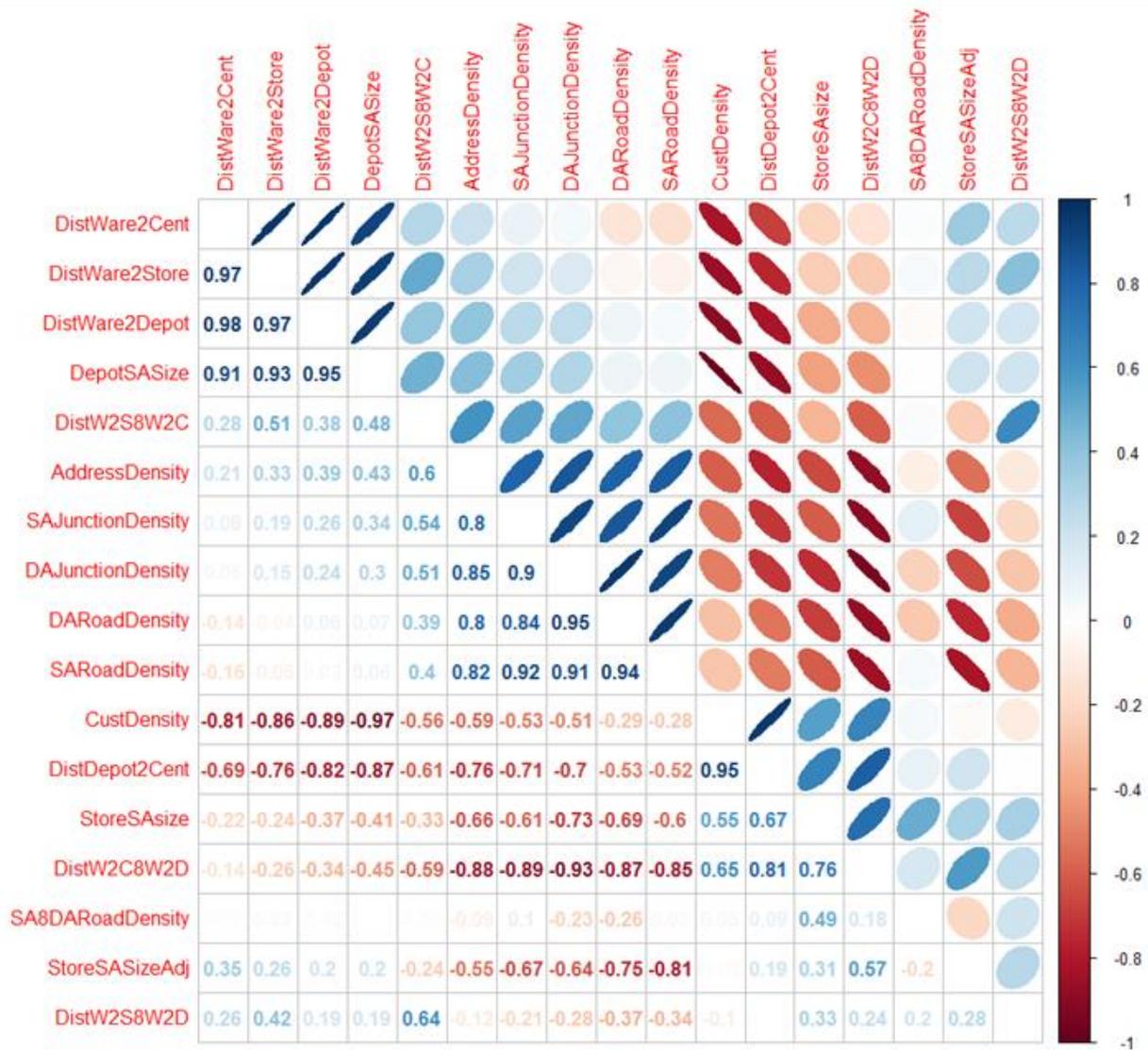


Figure 4.2 Correlations between evaluated independent variables

Chapter 5 Results

5.1 Evaluation of goods movement schemes by municipality

Figure 5.1 and figure 5.2 illustrate the service areas for the grocery stores and local depots. The 35-household samples were drawn from the households within each depot service area. One of the stocking routes used to supply the stores or local depots is shown in figure 5.1. One of the household samples and the associated routes for passenger travel and for local-depot-based delivery are shown in figure 5.2.

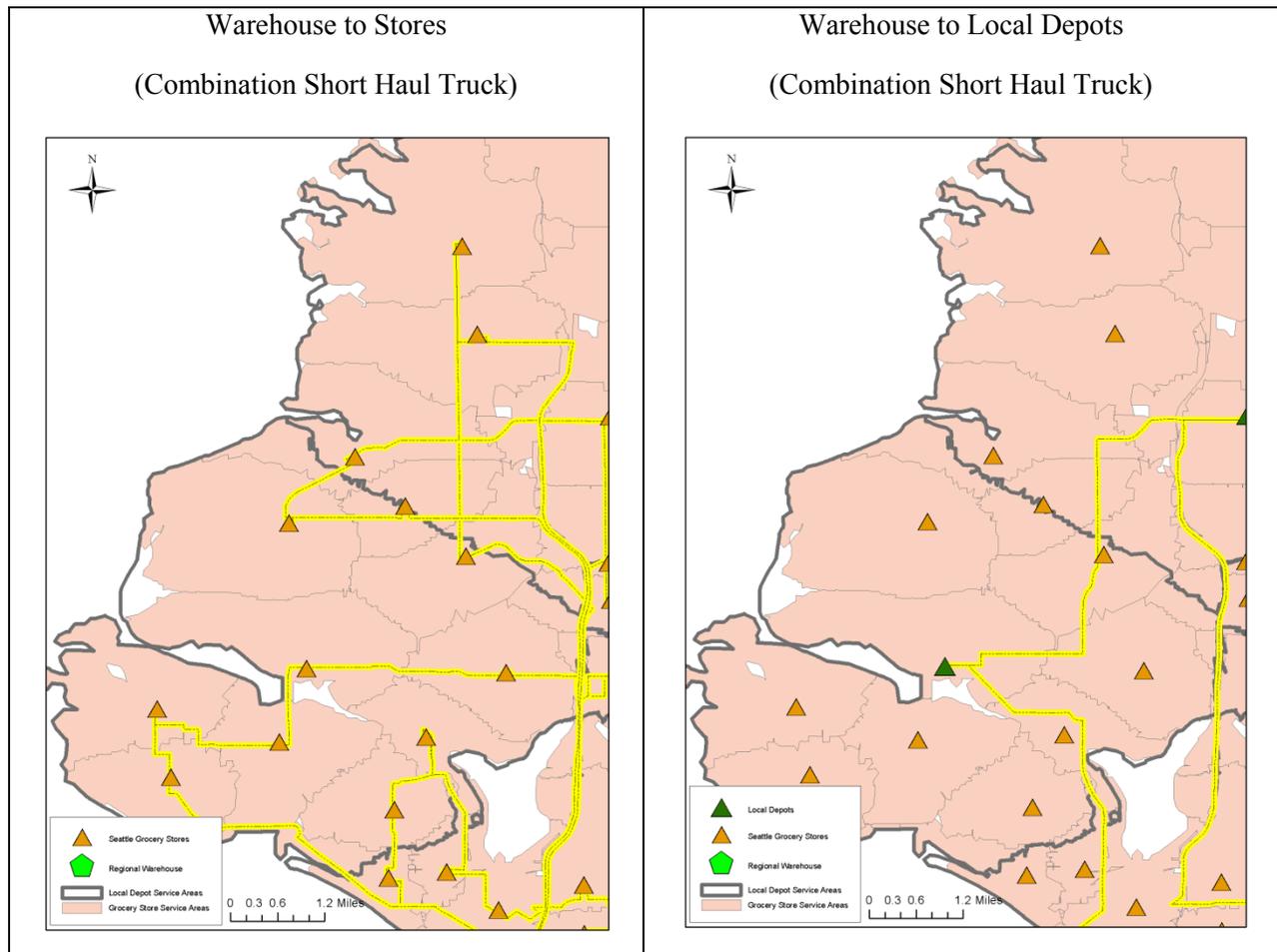


Figure 5.1 Illustrations of example stock routes

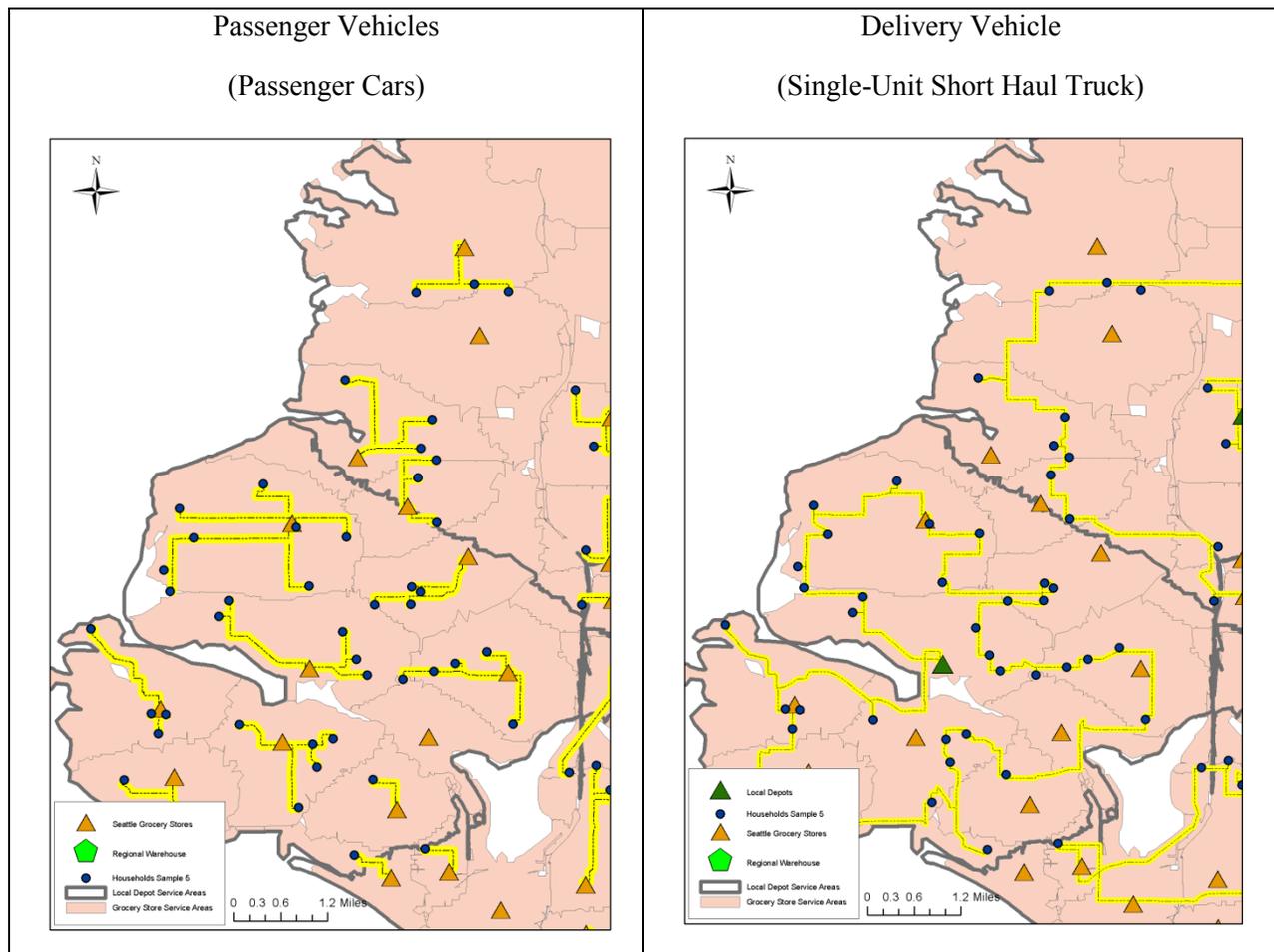
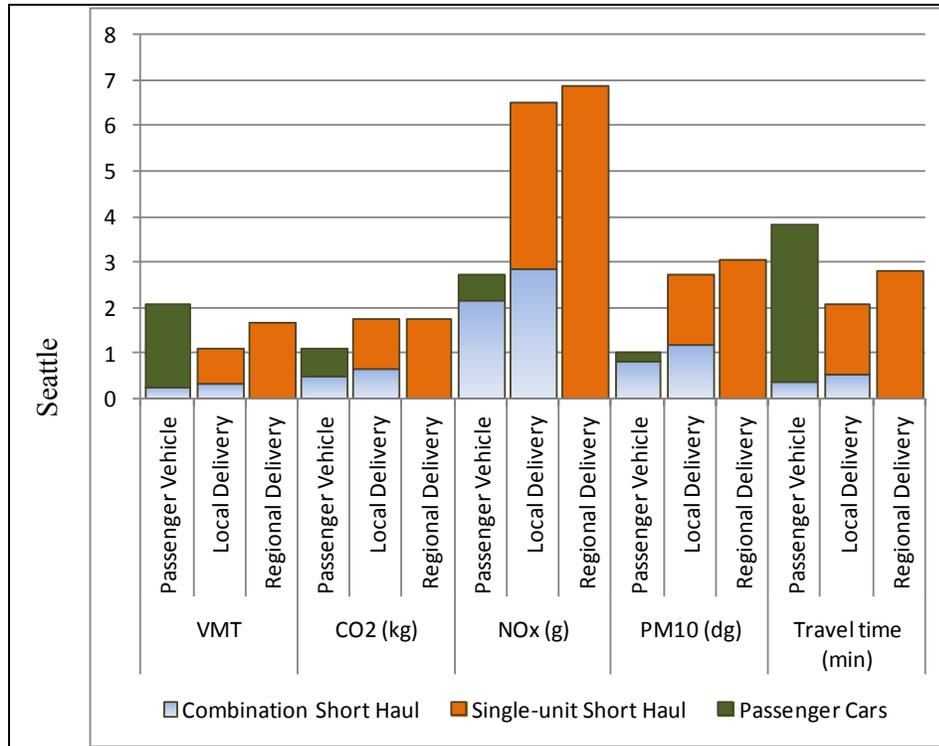


Figure 5.2 Illustrations of example final travel to homes

Looking at the results from the three different delivery structures (fig. 5.3), the relative contributions of the different legs of the supply chain become apparent. Personal travel requires the largest number of vehicle miles traveled but generates moderate levels of pollutants. Any use of a combination short haul truck within a supply chain involves significant emissions production, while the passenger cars contribute very small amounts of the studied emissions and practically no PM10. Combination short haul trucks have particularly high rates of NOx emissions, relatively. In Black Diamond, where the regional warehouse delivery system generates only slightly higher levels of VMT

than the local depot delivery system but fewer emissions of NOx and PM10, the relative impact of the combination short haul trucks is apparent.



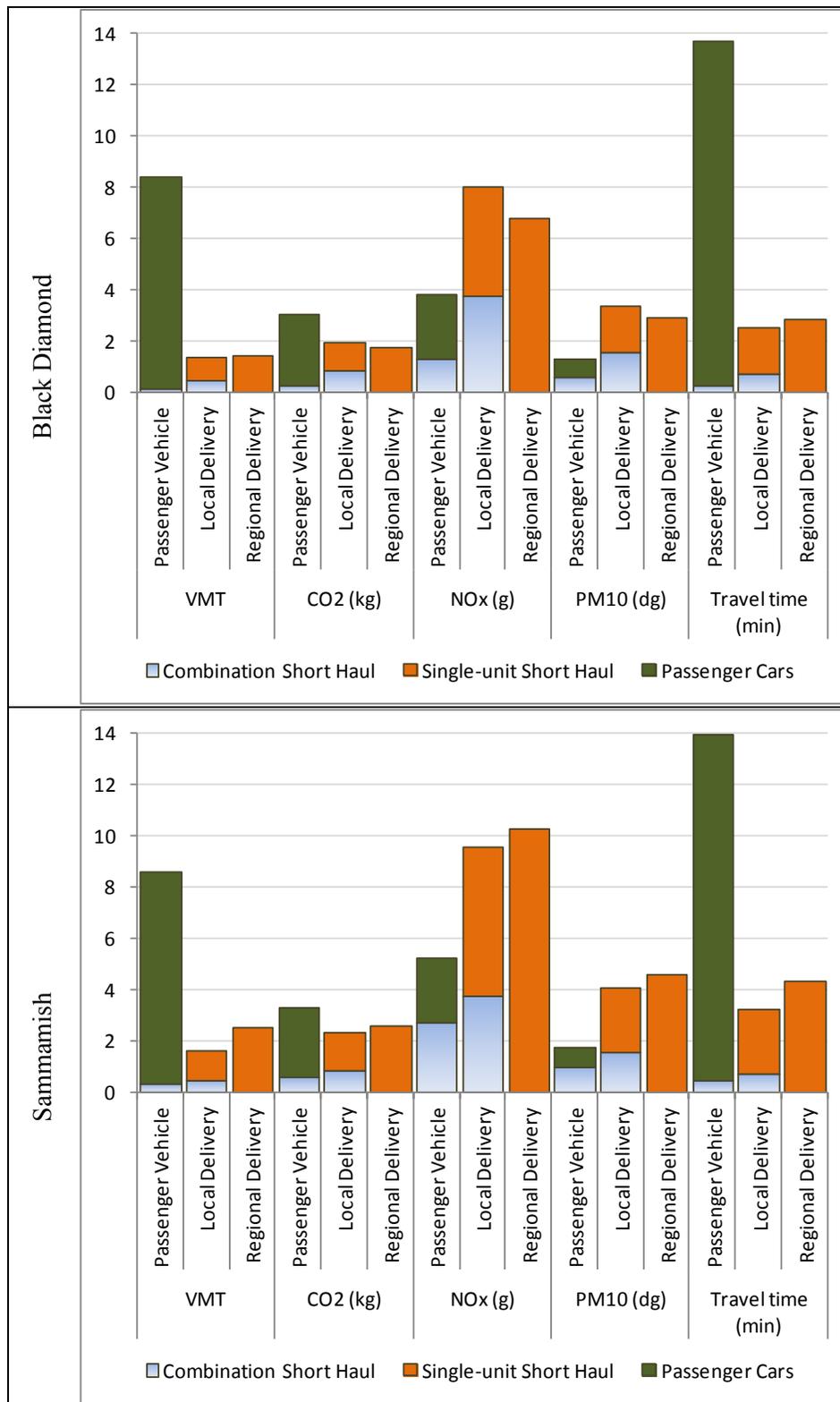


Figure 5.3 Results for each delivery structure, by vehicle type

Table 5.1 displays the data that supports figure 5.3. It includes averaged data about each leg of the supply chain for each scenario: the trip from warehouse to store or depot and the trip from the store or depot to the addresses or the trip directly from the warehouse to the addresses.

Local Depot Delivery service – where a single-unit short haul truck delivers to homes from a local depot stocked by a combination short haul truck – requires the lowest amount of VMT. The efficiency of delivery is highlighted by comparing the amount of VMT generated by passenger cars compared to the corresponding final-leg delivery vehicle. Even when the delivery vehicle is serving homes from a regional warehouse, it still requires fewer VMT than if individual homes travel directly to their closest grocery store.

The results in table 5.1 also highlight the benefit of delivering to stops that are clustered together. While the combination trucks all serve 5 stores or depots, the stores are clustered together in the routes. The depots are spread throughout the city or region and require more travel to serve from the warehouse. Further, the personal vehicles require twice as much travel to get from the homes to the stores as the delivery vehicle requires to serve those homes from a local depot even though the personal travel goes to the closest store and the local depot is serving an entire quadrant of the city.

By leveraging the efficiency of a delivery structure, local depot delivery directly has the lowest VMT any of the cases. A goods movement system relying on passenger vehicles for the last mile has the highest levels of VMT and the highest levels of CO₂ for two of the municipalities. It does, however, produce the lowest levels of the studied criteria pollutants (NO_x and PM₁₀) for the three municipalities. The goods movement system producing the lowest levels of CO₂ varies by municipality, with each of the three studied locations relying on a different goods movement structure to minimize carbon dioxide generation. The two delivery systems produce the highest criteria pollutants, but the least efficient system varies by municipality.

Table 5.1 Vehicle miles traveled, emissions, and travel time by supply chain leg and design

		VMT	CO2 (kg)	Nox (g)	PM10 (dg)	Travel time (min)		
Seattle	Last Mile Personal Travel	To stores	0.3	0.5	2.2	0.8	0.4	
		To addresses	1.8	0.6	0.6	0.2	3.5	
		Total	2.1	1.1	2.7	1.0	3.8	
	Local Depot Truck Delivery	To depots	0.3	0.7	2.8	1.2	0.5	
		To addresses	0.8	1.1	3.7	1.6	1.6	
		Total	1.1	1.7	6.5	2.8	2.1	
	Regional Truck Delivery	To addresses	1.7	1.8	6.9	3.1	2.8	
	Black Diamond	Last Mile Personal Travel	To 5 stores	0.2	0.3	1.3	0.6	0.3
			To addresses	8.3	2.7	2.5	0.7	13.5
			Total	8.4	3.0	3.8	1.3	13.8
Local Depot Truck Delivery		To 5 depots	0.5	0.9	3.8	1.6	0.7	
		To addresses	0.9	1.1	4.2	1.8	1.9	
		Total	1.4	2.0	8.0	3.4	2.6	
Regional Truck Delivery		To addresses	1.5	1.7	6.8	2.9	2.9	
Sammamish		Last Mile Personal Travel	To 10 stores	0.3	0.6	2.7	1.0	0.5
			To addresses	8.3	2.7	2.5	0.7	13.5
			Total	8.6	3.3	5.2	1.7	14.0
	Local Depot Truck Delivery	To 5 depots	0.5	0.9	3.8	1.6	0.7	
		To addresses	1.2	1.5	5.8	2.5	2.6	
		Total	1.6	2.4	9.6	4.1	3.3	
	Regional Truck Delivery	To addresses	2.5	2.6	10.3	4.6	4.3	

Table 5.2 summarizes the goods movement system that produces the highest and lowest levels of VMT, CO2, Nox, PM10, and Travel Time for each municipality.

Table 5.2 Summary of delivery structure impacts

		VMT	CO2 (kg)	Nox (g)	PM10 (g)	Travel time (min)
lowest	Seattle	1.1	1.1	2.7	0.10	2.1
	Black Diamond	1.4	1.7	3.8	0.13	2.6
	Sammamish	1.6	2.4	5.2	0.17	3.3
highest	Seattle	2.1	1.8	6.9	0.3	3.8
	Black Diamond	8.4	3.0	8.0	0.34	13.8
	Sammamish	8.6	3.3	10.3	0.46	14.0

Passenger Vehicles
Local Depot Delivery
Regional Warehouse Delivery

The results were also evaluated for significance using the two-tailed t-test. All comparisons were significantly different with p-values ($p \leq 0.001$), except for the difference in pollution generation between the two delivery systems in Seattle and the difference in VMT for the two delivery systems in Black Diamond. In Seattle, no significant difference between the two delivery systems was observed in the generation of CO2. The difference in NOx generation in Seattle between the two delivery systems was significant only at the $p \leq 0.1$ level, and the difference in PM10 generation was significant at the $p \leq 0.01$ level. The difference in VMT between the two delivery systems in Black Diamond was significant at the $p \leq 0.005$ level.

Detailed results of the t-tests are included in table 5.3 and illustrate that variations across samples are small compared to the variation between scenarios.

Table 5.3 t-test results

			VMT	CO2 (kg)	Nox (g)	PM10 (g)	Travel time (min)
Seattle	Passenger Vehicle vs Local Depot	t statistic	27.18	10.85	54.23	57.34	27.32
		d.f.	461	26	27	26	406
		p-value	0.000	0.000	0.000	0.000	0.000
	Passenger Vehicle vs Regional Warehouse	t statistic	5.42	11.53	19.27	19.84	10.07
		d.f.	36	26	24	24	52
		p-value	0.000	0.000	0.000	0.000	0.000
	Local Depot vs Regional Warehouse	t statistic	8.09	0.39	1.73	2.96	8.43
		d.f.	26	48	29	28	30
		p-value	0.000	0.701	0.094	0.006	0.000
			VMT	CO2 (kg)	Nox (kg)	PM10 (kg)	Travel time (min)
Black Diamond	Passenger Vehicle vs Local Depot	t statistic	95.08	26.70	32.88	38.24	78.89
		d.f.	680	56	25	24.88	560
		p-value	0.000	0.000	0.000	0.00	0.000
	Passenger Vehicle vs Regional Warehouse	t statistic	95.85	35.70	27.57	35.25	78.13
		d.f.	822	73	26	25.26	684
		p-value	0.000	0.000	0.000	0.00	0.000
	Local Depot vs Regional Warehouse	t statistic	3.11	5.04	7.49	6.75	4.49
		d.f.	46	47	47	46.51	47
		p-value	0.003	0.000	0.000	0.00	0.000
			VMT	CO2 (kg)	Nox (kg)	PM10 (kg)	Travel time (min)
Sammamish	Passenger Vehicle vs Local Depot	t statistic	95.80	27.95	42.24	52.71	77.60
		d.f.	817	80	27	26	735
		p-value	0.000	0.000	0.000	0.000	0.000
	Passenger Vehicle vs Regional Warehouse	t statistic	83.80	22.79	59.69	77.24	71.15
		d.f.	824	120	28	26	853
		p-value	0.000	0.000	0.000	0.000	0.000
	Local Depot vs Regional Warehouse	t statistic	30.51	7.81	5.55	9.98	19.17
		d.f.	48	46	46	47	45
		p-value	0.000	0.000	0.000	0.000	0.000

5.2 Developing regression models for each goods movement scheme

The results of the previous section indicate some aspects of urban form do influence the impacts of a goods movement system. In Seattle, a fairly dense urban area, passenger vehicle use resulted in the least of all three studied emissions, despite its overall high level of VMT generation. In the two more rural

municipalities – Black Diamond and Sammamish – delivery options were able to reduce CO2 emissions even if they could not reduce criteria pollutants. However, there are a number of differences among these places. They vary in terms of their customer density, network density, number of stores and depots, and their distance to the regional warehouse. To shed some light into the factors that influence VMT and emissions generation, regression models were developed for each of the three goods movement methods. As discussed in the Methods section, a modified forward selection was conducted to develop Best Fit and Parsimonious models. For this analysis, all of the delivery addresses for all three municipalities were combined into one data set to enable testing of the variables discussed above, resulting in a sample size of 2625 addresses. Table 5.4 illustrates the resulting models for each of 4 dependent variables for each of the three goods movement strategies.

Table 5.4 Best fit models for each goods movement strategy

Passenger Vehicle	r ²	Intercept	Store Service Area Road Density	Distance: Warehouse to Store	Address Density	Store Service Area Junction Density	Store Service Area Size
	VMT	0.686	10.990	-0.286	0.045	-0.001	
Co2	0.659	3.598	-0.088	0.031	-0.0003		
NOx	0.698	2.879	-0.034	0.111	-0.0003	-0.001	0.013
PM10	0.600	0.102	-0.001	0.003	-0.00001	-0.00003	0.0004

Local Depot Delivery	r ²	Intercept	Depot Service Area Road Density	Distance: Warehouse to Depot	Depot Service Area Junction Density	Distance: Depot to Centroid
	VMT	0.822	1.190	-0.028	0.024	0.001
Co2	0.647	1.833	-0.035	0.029	0.001	0.020
NOx	0.873	7.006	-0.181	0.135	0.004	0.229
PM10	0.871	0.294	-0.008	0.006	0.0002	0.010

Regional Warehouse Delivery	r ²	Intercept	Customer Density	Depot Service Area Road Density	Depot Service Area Junction Density	Distance: Warehouse to Centroid
	VMT	0.969	0.567	-0.008	-0.018	0.001
Co2	0.945	0.930	0.022	-0.028	0.001	0.067
NOx	0.948	3.602	0.075	-0.112	0.003	0.266
PM10	0.956	0.149	0.002	-0.005	0.0001	0.013

As seen in table 5.4, a relatively small number of variables influences each model. Further, the variables that influence the models for each delivery structure are consistent, with the same variables appearing in all four models across each of the local depot and regional warehouse delivery models. For the passenger vehicle structure, the models for VMT and CO2 result in the same set of selected variables, as do the models for NOx and PM10. The models shown here all explain at least 60 percent of the variation observed, with as much as 95 percent of the variation observed for regional warehouse delivery explained. All of the models rely on a form of road density and distance from the warehouse to some part of the service area. Junction density and customer or address density appear in a majority of the models.

Lastly, the coefficients have consistent signs across most of the models. Road density always has a negative influence (increased road density results in lower VMT, CO2, NOx, and PM10). An increased distance between the warehouse and service area always results in higher values for the dependent variables. Increased customer density results in lower VMT but higher CO2, NOx, and PM10 for the regional warehouse delivery. In contrast, increased address density for passenger vehicle travel results in lower VMT and lower CO2, NOx, and PM10 emissions. The junction density variables have consistent signs for the delivery models (increased junction density increases the VMT, CO2, NOx, and PM10), but those signs are opposite the signs for junction density in the passenger travel models for NOx and PM10.

While these models are explanatory, they have two primary limitations. First, simpler models explain much of the variation observed in the Best Fit models. Second, some of the independent variables

included in the Best Fit models covary. For example, the variables for junction density and road density are highly correlated. For these reasons, Parsimonious Models were developed. These models are seen in table 5.5.

Table 5.5 Parsimonious models for each goods movement strategy

Passenger Vehicle	r ²	Intercept	Store Service Area Road Density	Distance: Warehouse to Store
	VMT	0.677	12.127	-0.369
Co2	0.641	4.300	-0.114	
NOx	0.692	3.507	-0.081	0.094
PM10	0.596	0.118	-0.002	0.003

Local Depot Delivery	r ²	Intercept	Depot Service Area Road Density	Distance: Warehouse to Depot
	VMT	0.818	1.343	-0.021
Co2	0.643	1.876	-0.024	0.028
NOx	0.865	8.054	-0.129	0.109
PM10	0.864	0.034	-0.006	0.005

Regional Warehouse Delivery	r ²	Intercept	Depot Service Area Road Density	Distance: Warehouse to Centroid
	VMT	0.967	0.424	-0.009
Co2	0.942	0.980	-0.016	0.066
NOx	0.945	3.700	-0.062	0.266
PM10	0.953	0.149	-0.003	0.013

As seen in table 5.5, these models can be reduced to one or two variables: some measure of road density and some measure reflecting the distance from the warehouse to the service area. The r² values for the Best Fit models are no more than 0.018 better, and as little as 0.002 improvement is seen. In all of the Parsimonious Models, road density negatively influences the dependent variables, and the distance from the warehouse to the service area has a positive influence.

5.3 Developing regression models for goods movement scheme comparisons

The variables identified in the previous section, which influence the studied impacts of the three goods movement strategies, were used to focus evaluations of the comparative impacts of the strategies. Models were developed for each comparison (passenger vehicle travel vs. local depot delivery, passenger vehicle travel vs. regional warehouse delivery, and regional warehouse delivery vs. local depot delivery) for each of the studied impacts. The variables that appear in the Parsimonious models for the two goods movement strategies under consideration were included in the regression analysis. For example, when evaluating the variables that influence the relative impacts of passenger vehicle travel versus local depot delivery, Store Service Area Road Density, Depot Service Area Road Density, Distance from Warehouse to Store, and Distance from Warehouse to Depot were included. Further, ratios comparing Store Service Area Road Density to Depot Service Area Road Density and the two distances were also developed and included. This model therefore had six potential variables included. The results for the Best Fit models are shown in table 5.6.

Table 5.6 Best fit models for goods movement strategy comparisons

Passenger Vehicles vs. Local Depot Delivery	r ²	Intercept	Store Service Area Road Density	Distance: Warehouse to Store	Depot Service Area Road Density	Distance: Warehouse to Depot	Store:Depot Service Area Road Density
	VMT	0.699	9.084	-0.187	-0.017	-0.155	
Co2	0.556	1.455	-0.066		-0.023	-0.009	0.620
NOx	0.238	-5.050	-0.033		0.077		0.331
PM10	0.546	-0.230			0.004	-0.001	

Passenger Vehicles vs. Warehouse Delivery	r ²	Intercept	Store Service Area Road Density	Distance: Warehouse to Store	Depot Service Area Road Density	Distance: Warehouse to Centroid	Store:Depot Service Area Road Density	Distance Warehouse to Store: Warehouse to Centroid
	VMT	0.708	9.548	-0.198	-0.072	-0.151		1.895
Co2	0.609	3.723	-0.057	0.057	-0.033	-0.098	0.517	-1.545
NOx	0.653	-1.174	-0.067		0.055	-0.162	0.615	
PM10	0.838	-0.053	-0.002		0.003	-0.010	0.021	

	r ²	Intercept	Depot Service	Distance:	Distance:	Distance
			Area Road Density	Warehouse to Depot	Warehouse to Centroid	Warehouse to Centroid: Warehouse to Depot
VMT	0.979	-0.710	0.003	0.052	0.010	
Co2	0.644	-0.813	0.005		0.038	
NOx	0.953	-7.938	0.009	0.581	-0.403	4.469
PM10	0.966	-0.265	0.001	0.020	-0.011	0.106

Most of the Best Fit models were able to explain more than half the variation in the comparisons. However, once again, the Best Fit models included variables that covary and did not provide significantly more explanatory power than simpler models. Table 5.7 illustrates the resulting Parsimonious models.

Table 5.7 Parsimonious models for goods movement strategy comparisons

	r ²	Intercept	Depot Service	Distance:
			Area Road Density	Warehouse to Depot
VMT	0.691	10.252	-0.322	
Co2	0.544	1.840	-0.082	
NOx	0.235	-4.754	0.047	
PM10	0.546	-0.230	0.004	-0.001

	r ²	Intercept	Distance:	Depot Service	Distance:
			Warehouse to Store	Area Road Density	Warehouse to Centroid
VMT	0.701	11.086	-0.065	-0.328	
Co2	0.599	2.620	-0.040	-0.085	
NOx	0.644	-0.789			-0.158
PM10	0.835	-0.037		0.001	-0.010

Regional Warehouse vs.
Local Depot Delivery

	r ²	Intercept	Depot Service Area Road Density	Distance: Warehouse to Depot	Distance: Warehouse to Centroid
VMT	0.978	-0.662		0.062	
Co2	0.644	-0.813	0.005		0.038
NOx	0.949	-3.565	0.030	0.159	
PM10	0.965	-0.165	0.001	0.008	

As with the individual models, one or two variables was able to explain much of the variation observed. Variable selection for the parsimonious models relied only on direct measures of distance and road density, and none of the ratios were selected for these models. Further, once again the r² values are not substantially larger with the Best Fit models than the parsimonious models. Differences as little as 0.001 and not larger than 0.012 are observed between the r² values.

Using this information along with the differences observed in the estimated impacts for each municipality allows us to evaluate the tipping point for CO₂ reduction when replacing Passenger Vehicle travel. Solving for 0 with equation 5.1, indicates that when the road density in the depot service area is at least 22.43 miles/square mile, passenger travel will result in lower CO₂ emissions than local depot delivery. Black Diamond’s 78 linear miles of road represent 10 linear miles of road for every square mile, and Sammamish’s 215 linear miles of road represent about 9.7 linear miles of road for every square mile. In contrast, Seattle’s over 2000 linear miles of road represent more than 24 linear miles of road for every square mile of land – just above the threshold. The relationships between the studied municipalities and the identified threshold is illustrated in figure 5.4. The difference in CO₂ between passenger travel and local depot delivery is

$$CO_2 \text{ passenger travel-local depot delivery} = 1.840 - 0.082 * \delta \quad (5.1)$$

where δ : Depot Service Area Road Density.

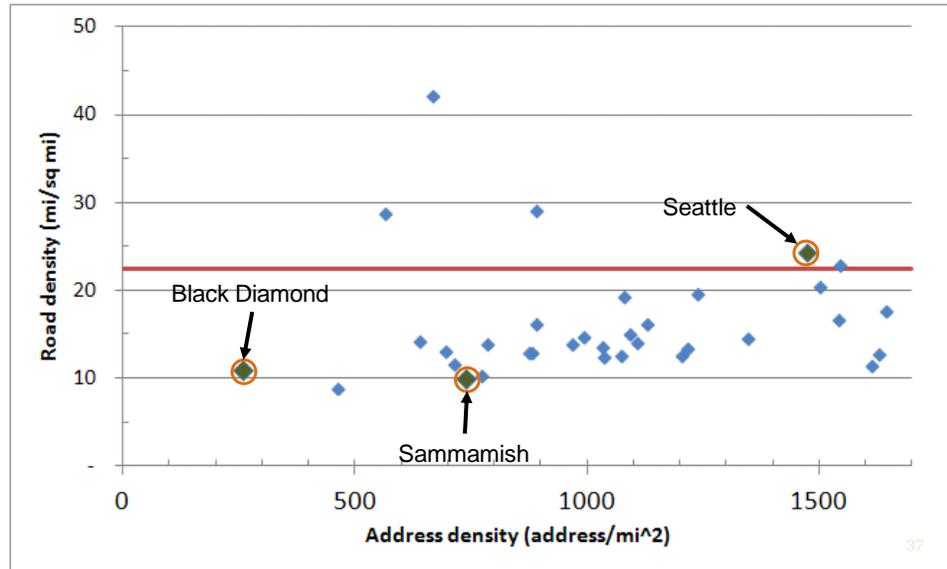


Figure 5.4 Studied municipalities and other King County, Washington municipalities

Because the parallel equation comparing passenger vehicle travel and warehouse delivery relies on two variables (equation 5.2) the tipping point cannot be solved. However, the graph below illustrates the sensitivity analysis for the two variables. Any point below the line is a scenario in which Warehouse-based Delivery is estimated to generate lower CO2 emissions than Passenger vehicle travel (see fig. 5.5). Figure 5.6 illustrates where the municipalities in King County, Washington – including the ones studied here – fall relative to that line. The difference in CO2 between passenger travel and warehouse-based delivery is

$$CO2_{\text{passenger travel-warehouse-based delivery}} = 2.620 - 0.04 * L - 0.085 * \delta \quad (5.2)$$

Where L : Distance from Warehouse to Store
 δ : Depot Service Area Road Density.



Figure 5.5 Sensitivity analysis threshold comparing influences on CO2 emissions between passenger vehicles and warehouse delivery goods movement schemes

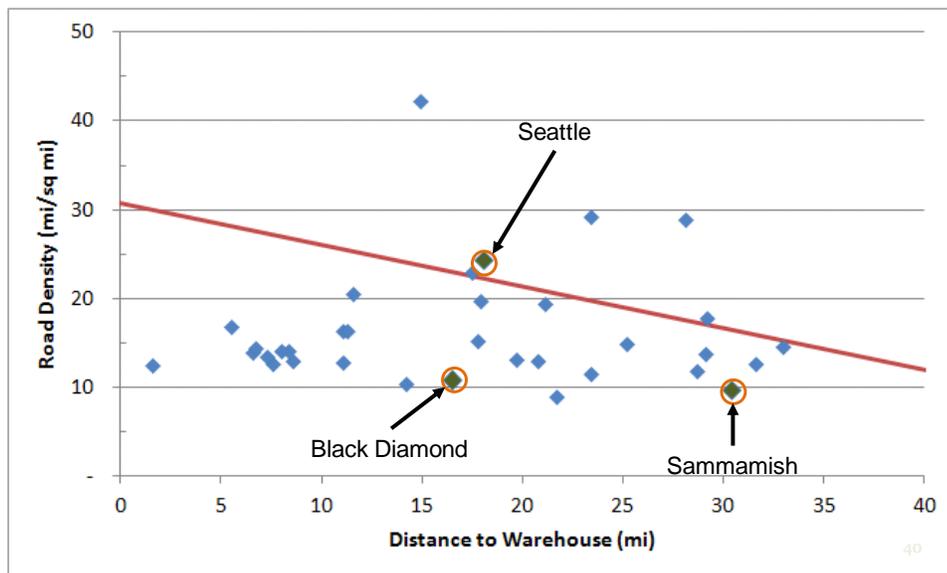


Figure 5.6 Studied Municipalities and Other King County, Washington Municipalities Compared to Distance to Warehouse and Road Density Thresholds between Passenger Travel and Regional Delivery for CO2 Emissions

Chapter 6 Discussion

These results show notable sensitivity to the structure of the depot, the depot location, routes traveled, and business model. Earlier work by Wygonik and Goodchild (2012) found delivery services reduced VMT and CO₂ emissions when used in lieu of passenger vehicle travel. These results conditionally support those findings. Understanding operational details and including them in modeling efforts is necessary to evaluate the efficacy of these services. On-going work should pursue the influence of customer density thresholds, depot density, regional warehouse location sensitivity, and engine technology. Delivery service is one method of addressing some of the externalities from transportation. Further research will inform how to best leverage this transportation strategy. Shopping travel represents 14.5 percent of household vehicle miles travelled. (Hu and Reuscher 2004) Finding methods to reduce VMT associated with shopping has significant potential to address total VMT and resulting emissions.

This analysis relied on data provided by a local supplier, in which 35-households are served from a regional warehouse using one single-unit truck within the necessary time constraints. Different regional land use patterns with higher levels of sprawl might require significantly more travel from the regional warehouse to the urban center and restrict the number of households that can be served by each truck. Alternatively, lower customer demand may alter the usage levels of the vehicles or higher customer demand may enable more tightly clustered customers. While this analysis did not show particular sensitivity to customer density, there is mathematical support for its influence. As such, testing the assumptions in this work with different customer sample sizes and different truck occupancy levels is suggested.

Distance to the warehouse was a significant variable in the models developed. However, the variation in distance was limited. In rural places that are not as proximate to a major urban center, these distances would be expected to be considerably longer. Further evaluation of the sensitivity of the models to this variable is suggested.

In structuring this work, the author had expected to find a relationship between an aspect of the store service area to an aspect of the delivery service area to explain the relative efficiency of the goods

movement strategies. This did not occur. Further, the author had anticipated customer density to be an important variables. This also did not occur. In practice, only direct measures – not comparative ones – informed the relative performance of the goods movement strategies. In addition, which density was important, it was the road density, not the customer density that influenced the results. Exploring other measures of transportation density and connectivity are therefore suggested.

A key aspect of this analysis is the assumed location of the local depots and the warehouse. Given the importance of distance and road density, the results may be highly sensitive to the locations chosen. Extensive random sampling of the households was conducted, but the depots were not similarly varied. The author suggests an evaluation in which the number and location of local depots are varied, in addition to the above suggestion to pursue a wider range of warehouse distances. Another aspect that may be highly influential are the assumptions made in this analysis regarding the number of depots and stores served by the stocking routes. As the relative contributions of the combination trucks are large, the results could be sensitive to variations in these assumptions. In addition, the efficiency of these stocking routes may vary with urban form – more distant and less dense areas may require less efficient stocking routes because of the additional time required to serve those locations.

Finally, this analysis relied on business-as-usual transportation methods: diesel-engine tractor trailers serving longer routes and bigger customers with single-unit diesel engine trucks or gasoline-engine passenger vehicles serving customers. Transportation methods that rely on lower emission technology (such as hybrid, electric, compressed natural gas or human-powered vehicles) or that involve more efficient operations (trip-training for passenger vehicles) will change the impacts observed.

6.1 Limitations

This work provided useful insight regarding the relationship between land use and VMT, and CO₂, PM₁₀, and NO_x emissions. However, a number of limitations remain.

This work relied on data from King County, Washington. While the selected municipalities reflected the range of densities observed in that county, it is not reflective of the entire range of densities observed across the United States or in other countries.

The work also assumed a roundtrip was conducted between addresses and stores and that roundtrip was replaced by a delivery service. While carpooling or using transit service to replace a commute trip would be purely substitutional, the same relationship is not guaranteed with shopping behavior. Personal shopping trips that are replaced by delivery service may be backfilled with other trips, including other shopping trips. Further, a replacement may occur between final purchase in store with an online purchase, but recent data indicates customers will still shop in the store to gather data before making their purchase, so-called showrooming. Lastly, while the evidence indicates most shopping transportation does occur with personal vehicles and does involve roundtrips, some shopping does occur using walking, biking or transit and some shopping is part of chained trips. In addition, this analysis assumed customers would travel to the closest store. While the available data indicates this assumption is mostly true (recall, customers were reported to shop at the closest store of its type), it is not strictly true and has the effect of underestimating the impacts of the personal travel scenario. Some minor error is introduced in that addresses but not individual units were sampled. Since zoning laws tend to focus multifamily homes and multiple-occupant commercial space toward central business districts and arterials, this sampling error has the potential to bias the results in the other direction – overestimating the impacts from personal travel. These units are, however, the most likely to take advantage of alternative modes to conduct shopping activities due to their proximity.

Another limitation to generalizing these results, reflects the number and location of the warehouses and depots. The results point to the influence of the distance to the warehouse on the measures. Because of the land use patterns and physical constraints in King County, Washington (due to bodies of water, mountains, and existing urban areas), the range of distances to the warehouse was relatively small. Less geographically-constrained regions of the country may have much longer distances to warehouses.

While some reductions in CO₂ emissions were estimated through the use of delivery service, this model is not able to include secondary benefits to CO₂ emissions from congestion reduction. This secondary effect will have the largest impact in urban areas which are already significantly impacted by high levels of congestion. The more dense areas are the places where reductions in CO₂ emissions are not observed directly by replacing personal travel with delivery service. While rural areas would be less impacted by secondary effects of congestion reduction, the significant reductions seen in CO₂ generation when personal travel is replaced by delivery service could be eliminated if some of the personal travel trips are not eliminated but are replaced by other travel.

Finally, this analysis assumed trucks would utilize existing diesel engine technology. Diesel engines generate high levels of the evaluated pollutants and will limit the potential advantage of VMT reductions. Leveraging other types of engine technology may allow delivery services to positively affect all evaluated measures and eliminate the observed trade-offs.

Chapter 7 Conclusions and Recommendations

This work supports earlier findings that VMT can be reduced by delivery schemes. Earlier efforts found VMT reduction between passenger travel and delivery vehicles to range from 50 to 95 percent (Cairns 1997, 1998, 2005; Punakivi and Saranen, 2001; Punakivi et al., 2001; Punakivi and Tanskanen, 2002; Siikavirta et al., 2002; Wygonik and Goodchild 2012). This work, which included both urban and more rural areas and more realistic comparisons between delivery service areas and retail customer sheds, found a wider range in the VMT reduction. In Seattle, reductions in VMT as small as 20% were observed when passenger vehicle travel was replaced by warehouse-based delivery service. However, in the more rural areas, where passenger vehicle trips are longer and the delivery service areas more closely resemble the retail store customer sheds, the reductions in VMT were between 70 and 85 percent. Likewise, the work here saw reductions in CO₂ only in the more rural areas, and observations of 20 to 45 percent were at the low end of the 20-90 percent reduction range observed in the earlier studies (Wygonik & Goodchild 2012, Siikavirta et al. 2002).

The results show there is some trade-off between VMT and pollutants. While the Local Depot Delivery has the lowest VMT levels, in some cases it generates the highest levels of criteria pollutants. Further, the passenger travel system generates the highest VMT but the lowest levels of criteria pollutants. Frequently, transportation policies and operating systems are designed to address VMT and congestion. If a region is also concerned with pollution, it will have to decide how to value the different impacts to decide how to shape policy. Combination trucks produce exceptionally high levels of NO_x and PM₁₀. These criteria pollutants have localized impacts. Policies that limit big trucks near population centers may increase VMT, but they may be worth it to ameliorate local health impacts from NO_x and PM₁₀.

Linear models were estimated via regression modeling for each dependent variable for each goods movement strategy and their comparisons. Parsimonious models maintained nearly all of the explanatory power of more complex models and relied on one or two variables – a measure of road density and a measure of distance to the warehouse. Increasing road density or decreasing the distance to

the warehouse reduces the impacts as measured in the dependent variables (VMT, CO₂, NO_x, and PM₁₀).

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