COST, EMISSIONS, AND CUSTOMER SERVICE TRADE-OFF ANALYSIS IN PICKUP DELIVERY SYSTEMS

Final Report

SR 500-330

Oregon Department of Transportation

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May 2011

Technical Report Documentation Page

1. Report No. OR-RD 11-13	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Cost, Emissions, and Customer Service Trade-Off Analysis In Pickup and Delivery Systems

5. Report Date
May 2011

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Oregon Department of Transportation
Research Section
200 Hawthorne Ave. SE, Suite B-240
Salem, OR 97301-5192

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
SR 500-330

12. Sponsoring Agency Name and Address
Oregon Department of Transportation
Research Section
200 Hawthorne Ave. SE, Suite B-240
Salem, OR 97301-5192
and
Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This research offers a novel formulation for including emissions into fleet assignment and vehicle routing, and for the trade-offs faced by fleet operators between cost, emissions, and service quality. This approach enables evaluation of the impact of a variety of internal changes (e.g. time window schemes) and external policies (e.g. spatial restrictions), and enables comparisons of the relative impacts on fleet emissions. In an effort to apply the above approach to real fleets, three different case studies were developed. Each of these cases has significant differences in their fleet composition, customers' requirements and operational features that provide this research with the opportunity to explore different scenarios.

The research includes estimations of the impact on cost, CO_2 and NO_X emissions from fleet upgrades, the impact on cost, emissions, and customer wait time when demand density or location changes, and the impact on cost, emissions, and customer wait time from congestion and time window flexibility. Additionally it shows that any infrastructure use restriction increases cost, and emissions. A discussion of the implications for policy makers and fleet operators in a variety of physical and transportation environments is also presented.

17. Key Words
Greenhouse Gas Emissions, Routing and Scheduling Model, Minimize Emissions, Cost trade-offs, Regional Trucking, Pick-up and Delivery System

18. Distribution Statement
Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 81	22. Price

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of our industrial case-study partners, Amazon Fresh, Cascade Express, and the University of Washington Mailing Service. In addition, thanks go to graduate students at the University of Washington, Kelly Pitera and Erica Wygonik, for their work on the project.

DISCLAIMER

COST, EMISSIONS, AND CUSTOMER SERVICE TRADE-OFF ANALYSIS IN PICKUP AND DELIVERY SYSTEMS

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1.0 INTRODUCTION

1.1 BACKGROUND

As commercial vehicle activity grows, the environmental impacts of these movements have increasing negative effects, particularly in urban areas. The transportation sector is the United States' largest producer of CO_2 emissions, by end-use sector, accounting for 32% of CO_2 emissions from fossil fuel combustion in 2008. Medium and heavy-duty trucks account for close to 22% of CO_2 emissions within the transportation sector, making urban pickup and delivery systems a key contributor to urban air quality problems *(U.S. EPA 2010a)*.

Vehicle routing minimizes travel cost or travel time for a fleet of vehicles picking-up and/or delivering goods. Most current vehicle routing strategies focus on optimizing operations for a single operator by minimizing financial cost and do not consider the impact of the operations to society and the environment. This research offers a novel formulation for including emissions into fleet assignment and vehicle routing, and for analysis of the contribution of pickup and delivery systems to emissions and the trade-offs between fleet cost, emissions, and service quality.

While emissions from transportation activities are understood at a broad level and between modes, this research looks carefully at relationships between cost, emissions, and service quality for an individual fleet. This new approach enables evaluation of the impact of a variety of internal changes and external policies based on different time window schemes, spatial restrictions, or carbon prices, so that it is possible to obtain particular and valuable insights from the changes in the relationship between cost, emissions, and service quality for different fleet characteristics.

In an effort to apply the above approach to real fleets, three different case studies were developed for this research. Each of these cases has significant differences in their fleet composition, customers' requirements, and operational features that provide this research with the opportunity to explore different scenarios.

Evaluation in each case study addresses the questions this research attempts to answer by developing proper scenarios that take advantage of each case study's distinctive features. This research does not seek to provide a conclusive answer for impacts on fleets similar to those in each case study, but does shed light on the general conclusions for each of the different features.

In summary, this research provides a better understanding of the relationships between emissions reductions and fleet operating costs, and is useful for agencies developing emissions reductions policies as well as and companies trying to better understand the business cost of emissions reductions strategies and develop effective emission-reduction policies.

1.2 RESEARCH QUESTIONS

This research is based on the following three guiding questions.

- What are the impacts on cost, CO_2 and NO_X emissions from fleet upgrades?
- What are the impacts on cost, emissions, and customer waiting time when demand density or location changes?
- What are the impacts on cost, emissions, and customer waiting time from congestion and time window flexibility

Each of these questions relates changes in operational cost (gas plus driver's salary), emissions, or customer waiting time with an internal change in the case study companies or an external input, such as changes in demand or traffic conditions.

The research questions are answered individually in each of the three case studies. Different answers are obtained because of the diverse features present in each company.

Section 8.0 summarizes the conclusions of this report, including the common points of each of the individual answers and general insights.

1.2.1 Q1: Impacts on cost, CO_2 and NO_X emissions from fleet upgrades

Vehicles have an associated emissions footprint which depends on the truck model, model year, and engine technology. Emissions are expected to decrease when fleet vehicles are replaced by newer model years. However, the emissions footprint of a company is also changed when vehicles are upgraded for ones with different capacity. The newer trucks can have a reduced or increased capacity which impacts the final routing and vehicle miles travelled (VMT).

If all features in a fleet remain constant, it is expected that newer model year trucks should have lower emissions per mile. However, the relationship is not that clear when considering capacity. A larger truck is expected to have a higher emission per mile rate but it can serve more customers and reduce VMT which may offset the increase in the emissions rate.

The impact of model year and capacity on cost, $CO_{2,}$ and NO_X emissions is carefully presented for each case study in this report.

1.2.2 Q2: Impacts on cost, emissions, and customer waiting time when demand density or location changes

Routes are designed based on customer locations. Any change in customer location affects the routing options, VMT, and scheduling, and therefore, cost, emissions and certainty in arrival times. Customer location density is also an important variable for routing and scheduling. The amount of time vehicles spend on freeways/highways and on local streets depends on how much customers are clustered. Each of these types of roads has different associated speeds and congestion exposure, parameters that affect cost, emissions and travel time certainty. The impact of different customer locations and customer densities on routing, and consequently on cost, emissions and customer waiting time is examined.

1.2.3 Q3: Impacts on cost, emissions, and customer waiting time from congestion and time window flexibility

Congestion increases cost because of additional driving hours and fuel consumption. Total emissions also increase when vehicles travel at lower speeds. These negative impacts can be counterbalanced by allowing more flexibility with customer time windows.

Time windows set a starting and ending time to serve a customer. The width of the time window impacts routing and scheduling. Narrower time windows reduce companies' ability to visit customers given that a vehicle has to visit a customer in a given location and time. This increase in restrictions increases VMT and the size of the fleet. When congestion is present, more flexible time windows (wider or different time windows) help to reduce the impact of slower traffic.

1.3 CASE STUDIES OVERVIEW

Three case studies serve as opportunities to examine the relationships between cost, emissions, and service quality. Each case study varies based on the location and distribution of their customers, type of service offered, vehicles in their fleet, and what type of road they use more frequently.

The first case study is the University of Washington Mailing Service (UWMS). The UWMS provides pickup and delivery service to customers located on the University of Washington's campus, as well as other Seattle neighborhoods and the cities of Bothell and Tacoma. The UWMS has a heterogeneous fleet with respect to capacity, mileage costs and emissions and they operate with a fixed schedule. Vehicles travel on freeways, arterials, and residential streets.

The second case study is Cascade Express (C.Exp.). C.Exp. provides pickup and delivery service along the west coast in California, Oregon, and Washington. Cascade Express' fleet includes trucks and trailers. Truck model years range from 1994 to 2008 and trailers have capacities of 62,000 lbs. and 42,000 lbs, all of them 52 feet long. Trucks have similar mileage costs and CO_2 emissions do not depend on the model year while NO_X does. Customers are mostly located near freeways so trucks primarily drive on them and do not spend significant time on local roads. Customers are promised a day for the pickup/delivery service and time windows are mostly flexible and constrained to working hours.

The third case study is Amazon Fresh (AF) which provides grocery delivery service in the Seattle area. Amazon Fresh has a homogeneous fleet with respect to capacity, mileage costs and emissions. Vehicles mainly travel on local streets. Customers place their orders online and choose the day and time for the delivery. The time for deliveries can take place in a one or three-hour time window.

The differences presented above make it possible to explore how cost, emissions, and customer service change in different pickup and delivery systems when operational changes or external policies are applied to them. The final results allow for new insights on the sensitivity of these features to changes in operations while also improving our understanding of the common reactions of this type of transportation system.

2.0 EXECUTIVE SUMMARY

In this section, project results are summarized, and an answer to each of the three study questions presented in Section 1.2 is provided.

2.1 Q1: IMPACTS ON COST, CO2, AND NO_X EMISSIONS FROM FLEET UPGRADES

2.1.1 UWMS

The introduction of hybrid vehicles to the fleet reduces both fuel cost and emissions. Overall costs are reduced by less than 0.5% because the cost of fuel is low compared to the cost of drivers. The fleet upgrade to hybrids always results in improved emissions. Emissions reductions of up to 33.88% can be identified, with a corresponding cost reduction of 0.32%.

2.1.2 Cascade Express

There are no CO_2 benefits from fleet upgrade when comparing model years from 1994 to 2010 and traffic conditions and travel speed that are kept constant. This happens because the ratio kg CO_2/mi has not changed in the last 16 years for the type of trucks used in this case (long haul tractor-trailers). Nonetheless, CO_2 emissions per mile for heavy-duty trucks are expected to reduce in the coming years due to CAFÉ standards which will be announced in 2011 by the E.P.A. This is different for the NO_X case where reductions are obtained if fleets are upgraded, although reductions do not take place in every new model year. NOx reductions are observed when vehicles are replaced for 1999, 2003, 2008, and 2010 models. Model years in between these years have the same emissions. The reductions at 60 mph are 26%, 54%, 50%, and 76% respectively. Future improvements in engine technology, converters, and fuel quality can continue helping to decrease these emissions.

2.1.3 Amazon Fresh

Emissions and monetary cost reduction can be made by about 7% if the existing fleet is upgraded to hybrid vehicles.

When the fleet is upgraded to larger vehicles, the more efficient routing decreases VMT, reduces fuel consumption, and cost. In terms of emissions, the lower emissions associated with fewer miles travelled can be offset by the higher emissions per mile of a larger truck, possibly resulting in a net higher emissions than the base case.

The smaller vehicles can improve emissions over the base case as their lower emissions per mile can offset increased VMT. Also, more vehicles may be needed to serve the same demand. Wide time windows and trucks not at capacity would be a good scenario to change a fleet to smaller vehicles.

2.1.4 Summary

Hybrid vehicles represent a good alternative to traditional vehicles. They reduce fuel consumption and operational cost as well as CO_2 emissions. It is also observed that there is not necessarily a reduction of cost or emissions when traditional vehicles are upgraded to a newer model year. There is not CO_2 reduction from such an upgrade. On the other hand, NO_X decreases with newer truck year although this change is not linear with model year. The benefits of upgrading to larger or smaller trucks depend on the time window structures and demand level since benefits will come from how total VMT can offset higher emissions per mile rate.

2.2 Q2: IMPACTS ON COST, EMISSIONS, AND CUSTOMER WAITING TIME WHEN DEMAND DENSITY OR LOCATION CHANGES

2.2.1 UWMS

Customers were consolidated for the morning and afternoon deliveries to study the impact of no time windows within these periods. These two consolidations help to understand the impact of customer location on cost, emissions and customer waiting time because the changes in the demand inputs impact routing design.

After consolidating the morning routes, emissions reductions of 7.35% can be obtained. This solution uses six vehicles to serve the customers and results in a cost increase of 3.47%. In the afternoon consolidation, emissions reductions of 35.15% can be identified, using four vehicles with a cost reduction of 4.81%. Depending on the initial ordering of vehicles, emissions can be slightly higher (when ordered on capacity and cost) or lower (when ordered on emissions) when compared to the sum of the base cases.

The new consolidated routes mean new visiting times to the customers. If these new times are provided to customers, no waiting time should be expected. However, such a change can mean modification in the internal logistic of each customer which can cause additional lost time and extra cost.

2.2.2 Cascade Express

In this case study, customers are mostly located near freeways and highways. Thus, there are not several routing options besides going from customer A to customer B through these freeways. Congestion reduces travel speed and a same trip requires more time. Longer trips increase cost because of the extra drivers' hours and additional gas needed for the increased driving. Also, lower speeds have higher emissions associated per mile since engines work further from the emission optimal speed (approximately 60 mph according to this research).

Waiting time would be affected if more miles are travelled in congested traffic due to its impact on travel time variability.

2.2.3 Amazon Fresh

We have estimated equations to identify the influence of customer density and time window on cost and emissions. The marginal change in cost and CO_2 emissions is obtained.

For the purpose of this questions, for example, the addition of 80 customers would save approximately \$3.50 (Equation 2-1) and 1 kilogram of CO_2 (Equation 2-2) per order.

Dollars per order

$$: \delta = -0.035*(\tau) - 0.045*(\eta) + 21.48 \tag{2-1}$$

Emissions per order:

$$\xi = -0.010*(\tau) - 0.015*(\eta) + 7.11 \tag{2-2}$$

With:

δ = dollars per order,

ξ = kg of CO_2per order,

τ = time window in minutes,

η = number of orders

2.2.4 Summary

Customer location determines routing options. If customers are located near freeways or highways, there will not be many routing options connecting customers. Thus, the addition of new customers following the same location pattern will have a reduced impact on current operations. On the other hand, customers located in urban areas can be sequenced in more ways because of the more dense transportation network. In this environment, if customers are located closer to each other, it is more likely to reduce emissions and costs due to less VMT.

Based on outcomes from the case studies, it is possible to estimate the increase in emissions for an extra dollar in operational cost. These numbers are presented in Table 2.1. Under the assumption used for these calculations, the resulting numbers are very similar across the case studies. Note that all of these values are positive, demonstrating that more costly routes are associated with more emissions. Similarly, less costly routes would result in fewer emissions. In all cases, there is not a trade-off between cost and emissions, but rather, these trend together.

Table 2.1: CO_2 emissions increase associated with cost increases

	Delta Emissions [kg CO_2 / US\$]
UWMS	0.34
AF	0.29
C.Exp.	0.27

2.3 Q3: IMPACTS ON COST, EMISSIONS, AND CUSTOMER WAITING TIME FROM CONGESTION AND TIME WINDOW FLEXIBILITY

2.3.1 UWMS

Both cost and emissions are reduced if no time windows are considered and every customer is only visited once. When all customers only receive mail delivery service once a day costs are decreased by an average of 34.74%, and CO_2 emissions by an average of 3.03% (compared to the morning and afternoon improved routes). There are also benefits from efforts to reduce NO_X emissions. A 10% reduction can be obtained, on average, if the UWMS assigns the truck with the least emissions to the routes with the largest delivery requirement, followed by successively more polluting vehicles.

2.3.2 Cascade Express

Cascade Express' customers are clustered into three groups: customers in California (cluster 1), near the depot which are not further than 2 hours north and 2 hours south of it (cluster 2), and customers in both western and eastern Washington (cluster 3).

Time windows have a higher impact on those customers in cluster 2, closer to the depot, because of the frequent trips back and forth. A more constrained operation reduces flexibility and increases cost due to the time that drivers do not drive. While in longer trips with few customers, tighter time windows can be off-set with flexibility on the departure times

Congestion has a higher impact on cluster 2. The high volume of trips in this area makes operation sensitive to slower speeds which impact cost and emissions but also the need for more trucks and drivers. On average, congestion causes an increase of 3% in cost and emissions for every two hours of additional congestion. Thus, time flexibility can help trucking companies to reduce the need for extra trucks and drivers to serve the same demand by avoiding periods with slower speeds.

2.3.3 Amazon Fresh

The equations presented on Section 4.1 provide the answer to this third question. The component for the time window variables in both equations is negative, meaning that wider time windows will decrease both the cost and emissions per order. This happens because wider time windows represent a gain in flexibility to solve the problem. Any optimization problem with more flexibility, or bigger solution space, will lead to better solutions, in this case, cheaper and cleaner ones.

For example, using the above equations, extending the time window 100 minutes would save approximately $3.50 and 1 kilogram of CO_2 per order.

2.3.4 Summary

Cost and emissions both increase with tighter time windows. The specific impact varies depending on the frequency with which a customer is visited and the relative distances between customers. Wider time windows increase consolidation of customers in a route and reduce the need of additional trucks (and the cost of drivers).

3.0 LITERATURE REVIEW

3.1 ROUTING MODELS (VRP MODELS, CONGESTION, EMISSIONS)

The Vehicle Routing Problem (VRP) was first formulated by Dantzig, Fulkerson, and Johnson *(1954)* and identifies a set of routes to serve customers at minimum cost. These routes are traveled by homogeneous vehicles which leave from a unique central depot. This model has been extended for a variety of different circumstances including the VRP with a fleet of varying vehicle capacities by Golden et al. *(1984).*

Nonetheless, limited research has been conducted which integrates vehicle routing with emissions reduction. Many of the existing extensions either compare emissions computed on a per mileage basis, without making routing decisions based on emissions characteristics, or indirectly minimize emissions by reducing miles travelled or avoiding congestion. Work by Quak and de Koster *(2007; 2009),* and Allen et al. *(2003)* measure the impact of certain policy measures on emissions on a broad scale, rather than the fleet level. Previous work has looked at the homogeneous time-dependent VRP (TDVRP), where vehicles can travel in periods with different speeds, emissions can be reduced indirectly by avoiding congestion, thus encouraging travel at optimal speeds, which reduces emissions *(Sbihi and Eglese, 2007).*

Previous research addressing emissions focuses on several different aspects of transportation. Considering passenger vehicles, Benedek and Rilett *(1998)* optimize on environmental objectives (CO, in particular) within traditional traffic assignment methodology on a simulated network, finding minimal change in time (0.5%) or emissions (0.15%) between scenarios optimized on one or the other. Their model did not consider routes with multiple stops, time windows, or vehicle capacity, and did not include the resulting costs for various routes. Also in the passenger vehicle side, Recker *(1999)* develops a model to minimize CO by chaining trips in such a way stopping times follow a sequence that reduces the times vehicles' engines transition from a hot to cold start. Engines working at a hot state have lower emissions than engines at a cold start, as when vehicles are turned on after 1 hour of not working. This research showed a reduction of 30% in CO by considering engines temperature in trip chaining. Looking at transit, Dessouky, Rahimi and Weidner *(2003)* optimize on cost, service, and environmental performance through simulation of a demand-responsive transit operation, where environmental performance is measured in terms life-cycle assessment costs. They found significant environmental improvements are possible with minimal additional costs for heterogeneous fleets optimized for emissions. These same benefits were not observed for homogenous fleets. This research looks at a number of measures of environmental performance and considers the life-cycle environmental impacts of each solution; it does not focus on or minimize the CO_2 emissions associated with routing.

Finally, focusing on vehicle routing, Palmer *(2007)* develops a vehicle routing method to minimize CO_2 emissions. Unlike the research presented in this paper, Palmer's methodology doesn't allow integration of multiple performance measures, and does not consider the policy implications or tradeoffs between these different optimizations. Figliozzi *(2010)* develops a VRP for a homogenous fleet that minimizes emissions and fuel consumption, where speed is included in the objective function. Figliozzi *(forthcoming).* develops a case study in Portland, OR to analyze CO_2 emissions for different levels of congestion and speed. He concludes minimum emissions can be achieved when vehicles can operate in an emissions efficient speed range, and considers the impact of fleet size and distance travelled. While few researchers have developed routing tools that optimize emissions, a number of researchers have considered emissions within routing problems and their work can provide insight into the expected relationships between cost, service quality, and emissions. A few of those relevant relationships are mentioned here.

Influence of Time Windows

Siikavirta et al. (*2002),* Quak and de Koster (*2007; 2009),* and Allen et al. *(2003)* adjusted output vehicle miles (or kilometers) traveled from delivery routing evaluations by emissions factors, finding more restrictive time windows have higher emissions than scenarios without time windows or with wider time windows.

Influence of Customer Density

Sally Cairns published a number of papers in the late 1990s illustrating significant VMT reductions associated with grocery delivery. Her work was based in the UK and focused on the density of customers and their distribution, finding that increasing VMT savings were possible with increasing customer density *(1998).*

Influence of Vehicle Fleet

Quak and de Koster *(2007; 2009)* and Allen et al. *(2003)* also found restrictions on vehicle types negatively impacted environmental performance. The influence of vehicle type was dependent on the characteristics of the deliveries in question – delivery providers with a single large quantity of goods had the most negative environmental impacts under policies that limit vehicle size.

Most of this work has applied flat emissions factors to VRP distance outputs, treating emissions as a post-processing output, not as an input or influencing factor. Other work has aimed to explicitly reduce emissions but achieves this goal by reducing overall miles travelled or changing route start times to avoid congested times. In sum, while the literature discussing the relationships between time windows, customer density, vehicle fleet, and emissions do not solve the problem presented in this paper, they do indicate emissions can be reduced by providing wide time windows, serving high customer density, and carefully matching vehicles to necessary capacity.

3.2 GROCERY DELIVERY STUDIES

Palmer's model has the capability of minimizing on emissions or calculating emissions for optimizations on time or distance. He found reductions in emissions of 4.8% when optimizing for emissions instead of time, and reductions in emissions of 1.2% when optimizing for emissions instead of distance. His model focuses on estimating emissions based on speed and vehicle performance, and he estimates speed based on congestion. Palmer's *(2007)* model is the closest to date at providing a useful model to consider the trade-offs between emissions and service. Because his model requires the cost of CO_2 as an input, it does not allow for insight into the appropriate cost of CO_2 to modify behavior.

The impact of the substitution of personal grocery store travel by delivery vehicles 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 become more common. Researchers have examined the vehicle mile reduction potential and the CO_2 emissions reduction potential associated with grocery delivery services compared to passenger travel. In addition, researchers have looked to identify under what circumstances the benefits associated with these services are greatest by evaluating various parameters and characteristics that contribute to reductions in vehicle miles or CO_2 emissions. 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 *(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 (*Siikavirta, et al. 2002; Punakivi and Saranen 2002; Punakivi, et al. 2001; Punakivi and Tanskanen 2001)*. This group has focused on how the interaction with the customer and the expected service parameters influence impacts, considering attended and unattended deliveries, service time windows, and the mechanism for unattended deliveries. This work considers the financial implications of various methods as well as the transportation impacts, and assumes groceries must be left in a secure location. The scenarios include attended delivery, centralized drop-off locations (near transit stations for example), and two types of secure bins for unattended delivery. Their early work observed reduction in VMT between 50 and 93 percent over personal travel for specific case studies, depending on time window size. Siikavirta et al. *(2002)* took the evaluation a step further, adjusting VMT by the LIISA emissions factors to illustrate an 18 to 87 percent CO_2 emissions reduction potential when traditional grocery shopping is replaced by different delivery service designs for a service in Finland. They estimated CO_2 equivalent reductions of 76 percent with 8-hour time window services serving randomly selected customers and were able to increase these savings to 87 percent when the customers were organized by postal code. Siikavirta et al.'s *(2002)* work 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 comparison between European case studies and the American case study presented here.

The above models and methodologies show an increasing interest in studying emissions within the context of routing problems. However, previous research has not considered the trade-offs between emissions, monetary costs, and service quality in heterogeneous pick-up and delivery systems as was completed in this project.

4.0 METHODOLOGY

In the present research, an optimization model is developed for the vehicle routing problem (VRP) for pickup and deliveries (PD) with hard time windows (TW), time dependent travel times (TD), and heterogeneous fleets in terms of capacity and emissions. The model in this research is an extension of the VRP. Given that the classic VRP is a NP-hard problem, this extension is also. This represents computational challenges because the computational time grows exponentially when instances increase in size (more customers, more vehicles more links in the network, etc.).

The analysis developed in this research includes instances of such a size that the present model can only be solved in many cases in days. Therefore, our methodology includes the development of a unique metaheuristic that solves a VRP with the properties presented above for the optimization model and approximates the solution of these problems in a manageable period of time. We also use state-of-the-art optimization routing package when an intense use of geo-data is required.

The optimization model is presented first. The objective function, constraints, and parameters are presented and explained. Secondly, the metaheuristic developed during this research is presented and includes details of each of its components. Finally, the software ArcGIS is introduced. This software was used to solve routing problems when geo-data was required.

4.1 OPTIMIZATION MODEL

A formulation for the VRP-PD-TW-TD with a heterogeneous fleet is provided below. This formulation minimizes the sum of a weighted monetary cost based on distance, time, and CO_2.

$$\text{Min} \sum_{p \in P} \sum_{v \in V} \sum_{j \in N} \sum_{i \in N} \left[CO^{v} \times D_{ij} + CT^{v} \times T_{ij}^{p} + TAX \times EF^{pv} \times D_{ij} \right] \times x_{ij}^{pv}$$

Subject to

Network

(0) $\sum_{v \in V} \sum_{j \in N^{+-} \cup N_{0-}} x_{ij}^{p_i v} = 0$, $i \in N_{D+}$

(1) $\sum_{p \in P} \sum_{v \in V} \sum_{j \in N^{+-}} x_{ij}^{pv} = 1$, $\forall i \in N^{+}, i \neq j$

(2) $\sum_{p \in P} \sum_{k \in N^{+-}} x_{ik}^{pv} - \sum_{p \in P} \sum_{k \in N^{+-}} x_{kj}^{pv} = 0$, $\forall i \in N^{+}$, $\forall j \in N^{-}$, $\forall v \in V$ / $DEM_{ij} > 0$

(3) $\sum_{p \in P} \left[\sum_{j \in N^{+} \cup N_{0-}} x_{ij}^{pv} \right] = 1$, $\forall i \in N_{0+} \wedge v \in V$

(4) $\sum_{p\in P}\left[\sum_{i\in N^{-}\cup N_{0+}} x_{ij}^{pv}\right] = 1$, $\forall j \in N_{0-} \wedge v \in V$

Sequence

(5) $\sum_{p\in P}\left[\sum_{k\in N^{+-}\cup N_{0+}} x_{ki}^{pv} - \sum_{k\in N^{+-}\cup N_{0-}} x_{ik}^{pv}\right] = 0$, $\forall i \in N^{+-}, \forall v \in \frac{V}{k} \neq i$ /

(6) $\sum_{p\in P}\sum_{v\in V}\left[\sum_{i\in N^{-}\cup N_{0+}} x_{ij}^{pv}\right] = CARD(V)$, $\forall j \in N_{0-}$

(7.1) $t_i^v \le \sum_{p\in P}\sum_{j\in N^{+}}\left[t_j - C_j - T_{ij}^p\right]\times x_{ij}^{pv}$, $\forall i \in N_{0+}$, $\forall v \in V$

(7.2) $t_i^v + \sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^p\right] \le t_j^v - C_j$, $\forall i \in N_{0+}$, $\forall j \in N_{0-}$, $\forall v \in V$

(7.3) $t_i + \sum_{v\in V}\sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^p\right] \le t_j - C_j$, $\forall i \in N^{+}$, $\forall j \in N^{-}$ / $DEM_{ij} > 0$

(7.4) $\sum_{v\in V}\sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^p - t_i - C_i\right] \le t_j^v - C_j$, $\forall i \in N^{-}, \forall j \in N_{0-}$

Schedule / Time Constraint

(8.1) $T_{ij}^p + C_j \le t_j - t_i^v + \left(1 - x_{ij}^{pv}\right)\times B_1$, $\forall i \in N_{0+}, \forall j \in N^{+-}$, $\forall v \in V, p \in P$

(8.2) $T_{ij}^p + C_j \le t_j^v - t_i^v + \left(1 - x_{ij}^{pv}\right)\times B_1$, $\forall i \in N_{0+}, \forall j \in N_{0-}$, $\forall v \in V, p \in P$

(8.3) $T_{ij}^p + C_j \le t_j - t_i + \left(1 - x_{ij}^{pv}\right)\times B_1$, $\forall i \in N^{+-}, \forall j \in N^{+-}$, $\forall v \in V, p \in P$

(8.4) $T_{ij}^p + C_j \le t_j^v - t_i + \left(1 \quad x_{ij}^{pv}\right)\times B_1$, $\forall i \in N^{+-}, \forall j \in N_{0-}$, $\forall v \in V, p \in P$

(9.1) $L_i^v \le t_i^v - C_i \le U_i^v$, $\forall i \in N_{0+} \wedge v \in V$

(9.2) $L_i \le t_i - C_i \le U_i$, $i \in N^{+-}$

(9.3) $L_i^v \le t_i^v - C_i \le U_i^v$, $i \in N_{0-}$

(10) $t_j^v - t_i^v \le DRIV$, $\forall i^{+} \in N^{+}, i^{-} \in N^{-}, v \in V$

(11.1) $t_i^v \le Z_{ij}^p + \left(1 - x_{ij}^{pv}\right)\times B_2$, $\forall i \in N_{0+}, \forall j \in N^{+-}\cup N_{0-}$,
$\forall v \in V, \forall p \in F$

(11.2) $t_i \le Z_{ij}^p + \left(1 - x_{ij}^{pv}\right)\times B_2$, $\forall i \in N^{+-}, \forall j \in N^{+-}\cup \frac{N_{0-}}{i} \neq j, \forall p \in P$

(11.3) $0 \le t_i^v + Z_{ij}^{p-1}\times x_{ij}^{pv}$, $\forall i \in N_{0+}, \forall j \in N^{+-}\cup N_{0-}$,
$\forall v \in V, \forall p \in F$

(11.4) $0 \le t_i + Z_{ij}^{p-1}\times x_{ij}^{pv}$, $\forall i \in N^{+-}, \forall j \in N^{+-}\cup N_{0-}\frac{0}{i} \neq j, \forall p \in P$

Capacity and Engine Temperature Constraint

(12) $b_i^v + \sum_{k\in N^{+-}} DEM_{kj} \le b_j^v + \left(1 - \sum_{p\in P} x_{ij}^{pv}\right)\times B$, $\forall i \in N_{0+}\cup N^{+-}\cup N_{0-}$,
$\forall j \in N^{+-}\cup \frac{N_{0-}}{i} \neq j; v \in V$

(13) $b_i^v = 0$, $\forall i \in N_p \cup A \quad v \in V$

(14) $b_i^v \le B_v$, $\forall i \in N_p - A \quad v \in V$

Variables

$x_{ij}^{pv} \in \{0,1\}$, $\forall i \in N; \forall j \in N; \forall v \in V; \forall p \in P$

$t_i^v \ge 0$, $\forall i \in N_{o^-} \cup N_{d^+}, \forall v \in V$

$t_i \ge 0$, $\forall i \in N^{+-}$

$b_i^v \ge 0$, $\forall i \in N, \forall v \in V$

Parameters

c_i	: service time for node *i*
L_0^v and U_0^v	: lower and upper time windows for the depot and each vehicle v
L_i and U_i	: time windows for customers (pickup and deliveries)
DEM_i	: demand between node *i* and *j* and it takes positive values when goods are picked up at *i* and delivered to *j*
CU^v and CT^v	: operational cost per mile and per minute for vehicle *v* respectively
TAX	: monetary value charged for each kg of CO_2
D_{ij}	: distance between node *i* and *j*
S_{ij}^p and T_{ij}^p	: speed and travel time from node i to j in period p which does not depend on the vehicle. They relate through the distance between nodes i and j
EF^{pv}	: emission factor for vehicle v in traffic period p and it is measured in kg CO_2 per mile
Q_v	: capacity of vehicle v
DRIV	: maximum allowed driving time
Z_{ij}^p	: the upper-bound time for each traffic period p
B	: maximum capacity in the fleet
B_1	: maximum route time possible
B_2	: latest possible return time to the depot

Constraint 0 ensures that variables x_{ij}^{0v} related to traffic period zero are equal to zero (traffic period zero is used to simplify the formulation). Constraint 1 ensures that only one vehicle visits each pickup client. Constraint 2 ensures each pickup-delivery pair is served by the same vehicle. Constraint 3 ensures a vehicle leaves the depot to perform a pickup or is not used. Constraint 4 ensures every vehicle is required to return to the depot from a delivery (not pick-up).

Constraint 5 requires that the vehicle that arrives at a node is the same vehicle that leaves the node. Constraint 6 ensures all vehicles return to the depot. Constraint 7 ensures the correct time sequencing in the schedules.

Constraint 8 ensures the arrival time is correct considering time dependent travel time. Constraint 9 ensures time window requirements are met and constraint 10 restricts a driver to the maximum time (eight hours in our case). Constraint 11 ensures that each of the traffic periods are included in the right order.

Constraint 12 updates the capacity variable, constraint13 initializes the capacity variables, and constraint 14 ensures that there is enough space available in the vehicle. Constraint 15 calculates the travel time for traffic period *p* between nodes *i* and *j*.

Variables of the problem are also shown: x_{ij}^{vp} is a binary variable equal to one when a vehicle v travels from node *i* to *j* in traffic period *p*, t_i^v is the departure and return time from/to the depot for each vehicle *v*, t_i is the departure time from each of the customers *i*, and b_i^v shows the good transported for vehicle *v* when leaving node *i*.

4.2 METAHEURISTIC

The optimization problem presented above is NP-hard, and the solution time grows exponentially. We therefore develop a local search metaheuristic to solve this vehicle routing problem (VRP) with hard time windows, time dependent travel times, and a heterogeneous fleet with regards to capacity, emissions and cost. The objective function (OF) in our metaheuristic is the same than the one presented above and is composed of three factors; distance, time and CO_2 emissions. They are combined by converting each metric to financial cost ($). Estimates of cost per mile and cost per minute for each truck were provided by the case study partner. Estimation of cost of CO_2 emissions is derived from the social cost of CO_2 *(Klein 2007).* However, the OF can also be used to minimize only one or two of the metrics by using a zero for the coefficient on the undesired metric. All constraints are met in the metaheuristic.

A local search metaheuristic and a tabu search metaheuristic were applied to the UWMS and to the Cascade Express case study respectively. The process flows for each of these metaheuristics are shown in Figure 4.1 and Figure 4.2 respectively. The details of the input data and creation algorithm have been omitted in Figure 4.2 to show details of the tabu search lists themselves. Nonetheless, these algorithms are the same in both metaheuristics.

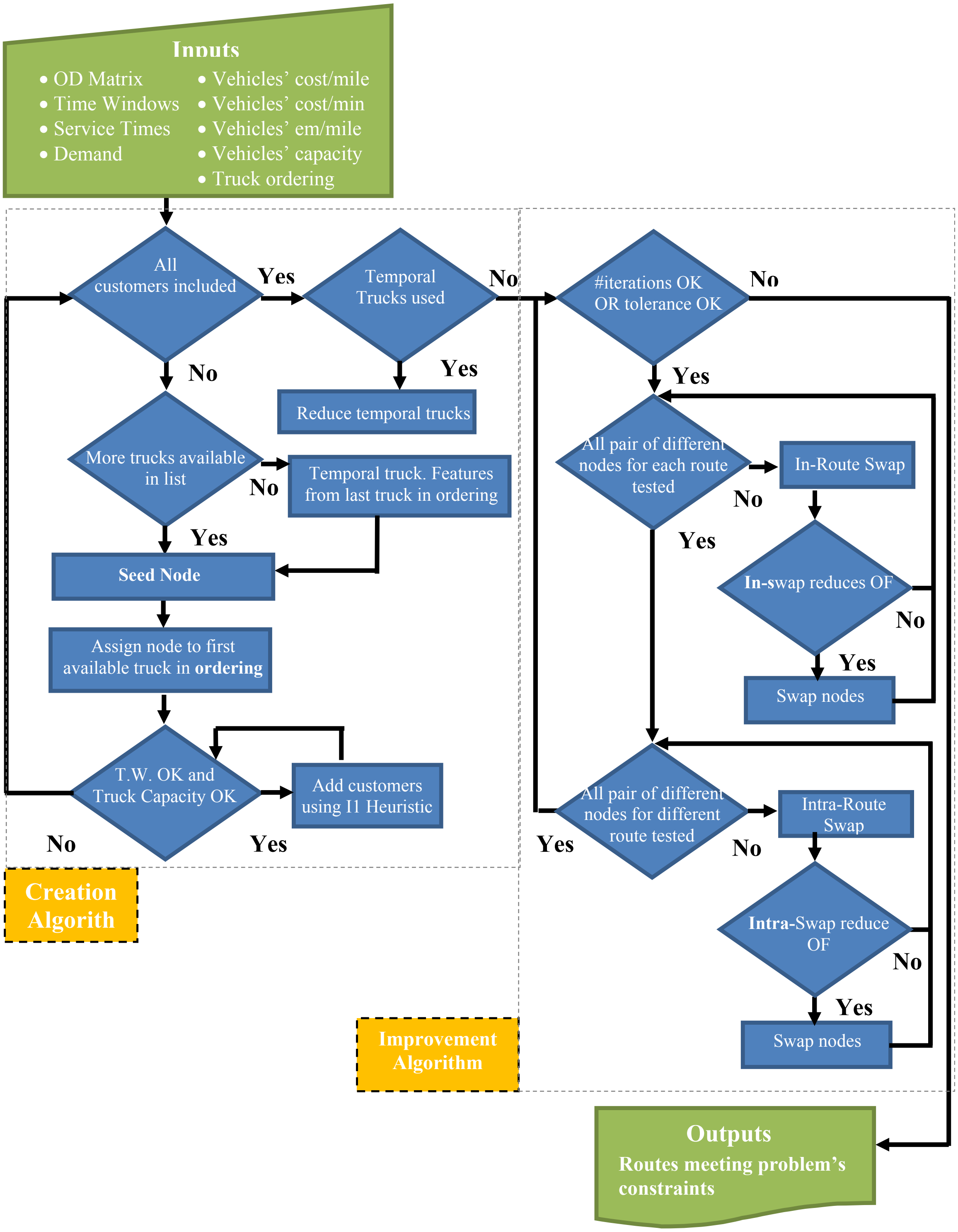


Figure 4.1: Local search metaheuristic process flow.

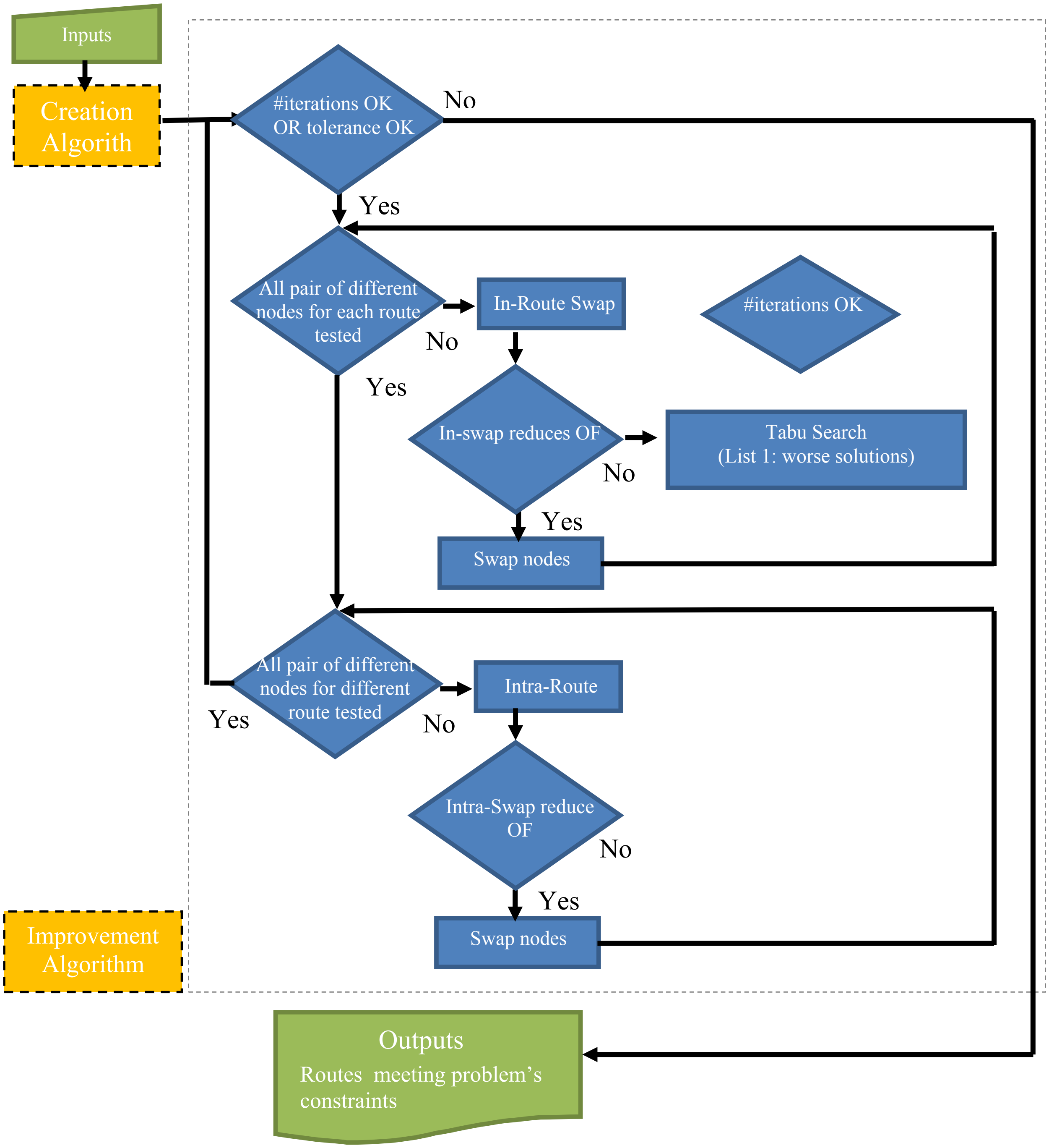


Figure 4.2: Tabu search metaheuristic process flow

Metaheuristics have both a creation and improvement algorithm and each of these algorithms are based on different heuristics *(Bräysy 2005a; Bräysy 2005b).* A heuristic is an algorithm that finds good solutions in a reasonable time but there is uncertainty as to the quality of the solution and if the solution time will be always reasonable (*The Free Dictionary 2010*). Each metaheuristic can include one or a combination of more heuristics for the creation and improvement algorithm.

Our creation algorithm is based on the I1 heuristic *(Bräysy 2005a),* and the improvement algorithm is based on applying the 2-opt heuristic to individual and pairs of routes *(Bräysy 2005b).* Both the creation and improvement algorithm are described below. The use of tabu lists are explained in the improvement sub-section.

4.2.1 Creation Algorithm

Inputs to the creation algorithm are shown in the top left. For the truck/vehicle ordering, this ordering dictates the sequence by which vehicles will be assigned customers in the creation algorithm, and as such influences the final solution obtained. Vehicles are ordered by capacity (largest to smallest), by emissions (cleanest to least clean), and by cost (lowest cost per mile to highest cost per mile).

Customers are included in the routes following the I1 heuristic. The starting customer for each route, or seed, is that with the earliest delivery time window. This customer is assigned to the first available truck in the input ordering. Subsequent customers in a route are included based on two steps. First, a list of candidate nodes to be inserted (along with their insertion position) into the existing route is calculated using a weighted sum of distance plus travel time and service time. This weighted sum is an extension of the heuristic developed by Clarke and Wright *(1964)* and has three parameters to control the impact of changes in distance travelled and time added to the route. Each of these parameters took values equal to 0.5 in this research. In the second step, the best candidate node from the list is chosen, using a weighted sum of distance to the depot plus the additional cost (calculated in the first step) to the route. A parameter controls the relative importance of the distance to the depot and was chosen to be 0.5.

Time windows and vehicle capacity constraints are met at every time and a new route is created when any of these constraints is violated. The I1 heuristic adds customers at any point of the route depending on where the greatest objective function savings take place. Links' speeds are time dependent to include congested conditions so the time a vehicle leaves a customer or depot can impact travel times.

As indicated in Figure 4.1, if customer requirements cannot be met with the existing fleet, the creation heuristic requires additional trucks. An extra truck with the same characteristics of the last truck in each ordering is temporarily added to the fleet. After assigning all customers to a route, the extra truck is then removed and the customers in this removed truck are consecutively assigned to the route with the earliest return time to the depot. If the capacity constraint or schedule horizon is met, customers are assigned to the next route with the earliest return time.

4.2.2 Improvement Algorithm

Once an initial feasible solution is found, the improvement algorithm uses the 2-opt exchange heuristic to improve upon the initial solution. The 2-opt heuristic is applied to exchange customers between pair of routes (inter-route swap) and within individual routes (in-route swap). The inter-route heuristic takes a customer from a route and exchanges it with a customer from another route. The in-route heuristic simply swaps two customers in an individual route. When an inter-route exchange take place, the in-route swap helps to relocate the new customer in the new route. The objective function is then recalculated to determine whether the change improves the objective function. Clearly, if travel times or emissions are changed due to the change in time for the activity, this is captured in the objective function value. Only exchanges that decrease the objective function value are accepted. The combined application of these heuristics allows exploring a larger area of the search space for improved routes. The inter-route and in-route swaps are run consecutively until a maximum number of iterations have been performed or the objective function reduction is lower than 0.1% over the previous iteration.

Tabu Lists

For the tabu search metaheuristic, two lists are created. These lists allow for exploration of the solution space. In particular, temporarily accepting solutions that do not improve the objective function a priori, but that may, at a later step, improve on the solution. "List 1" is used for the first case and keeps track of all the permutations performed while exploring solutions that do not improve the objective function. If no better solution is reached after an arbitrary number of iterations, this list is used to return to the original solution and continue with the original flow. This list can store an arbitrary number of solutions, so that, the same solutions are not analyzed in future calls of "List 1". A very long list will avoid visiting the same solution (that do not improve the objective function) more than once but storing this lists consume resources from the PC. The second list, "List 2" allows for visiting infeasible solutions. This list records the permutations that lead to those solutions. Analogously, the length of this list allows for some efficiency in not duplicating permutations that do not lead to feasible and/or better solutions. In order to explore the greatest number of permutations, it is better if this list can store many permutations but there is a trade off with PC resources.

4.3 USE OF ARCGIS

ArcGIS is a software program with geo-databases where information has associated locations. ArcGIS software includes a series of useful tools for wide range of spatial analysis including routing and scheduling. One of these is network analyst which has the ability to solve routing and scheduling problems. However, there is not the ability to minimize emissions from vehicle activity with this tool. Thus, we have extended the ArcGIS VRP tool to account for emissions enabling least-cost, least-time, and least-emissions routing for an urban pickup and delivery system with time windows.

ArcGIS can solve the VRP for urban pickup and delivery systems with capacity-constraints, multiple vehicles, and time windows. This tool can consider hard or soft time windows and is extended in this research to account for emissions when the problem involves shorter than one hour stops. Based on Environmental Protection Agency (EPA) standards, an engine with a catalytic convertor in hot state will pass to a cold-state after this amount of time and will require accounting for hot and cold start emissions, which is beyond the limits of this tool. However, stops in this case study do not exceed this one-hour threshold.

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 *(1959)* and order sequencing is completed with a tabu search heuristic *(Glover 1986).* These solutions are well-regarded for quickly producing reasonable results.

The model used in this evaluation is a modified version of the standard ArcGIS vehicle routing problem tool, extended to incorporate CO_2 emissions. Preliminary NO_x evaluation indicates for the fleet in the case study presented here NO_x emissions will follow a similar pattern to CO_2 emissions. Thus, the focus of this study is CO_2 emissions, serving as a marker for both CO_2 and NO_x. Two key extensions are necessary to allow the ArcGIS tool to include emissions.

First, the ArcGIS VRP tool is designed to minimize one of two variables: time or distance. It also allows for a weighted combination of these two variables. While other tools in ArcGIS's Network Analyst package allow the user to minimize on any available data element, the VRP tool is restricted to one time and one distance variable. Additional variables are not possible, thus limiting the ability of modeling all four variables of interest (time, distance, cost, and emissions) within one system. In addition, due to the necessity of adhering to time windows, the time variable cannot be altered. The distance variable, however, can represent any numerical field labeled as such. By adding emissions information to the network before it was built, emissions could take the role of a distance in the optimization. Financial cost is minimized by using the distance and time based cost parameters to combine distance and time into one cost objective. To minimize on only one variable, the coefficient on the second variable is set to zero.

Second, because only two variables can be modeled at once, additional processing was required to track the third variable. To gather this data, the VRP output allowed simplification of the problem into a TSP and the output ordered and route-assigned stops could be run through the traditional Network Analyst Routing tool, recording the remaining variable.

This modified tool enables analysis of different policies regarding changes in road network conditions, time window constraints, and fleet composition to consider the changes in cost and emissions for different scenarios.

5.0 UNIVERSITY OF WASHINGTON MAILING SERVICE

The University of Washington Mailing Service (UWMS) provides pickup and delivery of internal campus, as well as U.S. Postal Service mail. It serves the three University of Washington campuses in Bothell, Seattle, and Tacoma, as well as several other university buildings in downtown Seattle and other Seattle neighborhoods. This requires the fleet to travel on controlled access freeways, arterials, and residential streets. The UWMS has a heterogeneous fleet with respect to capacity, mileage costs and emissions. The UWMS operates as fixed and scheduled routing and as a repetitive distribution scheme. The service characteristics are similar to other fixed mailing services, transit services, community supported agriculture (CSA) deliveries, and waste removal services.

Mail to be delivered is organized at the main (and unique) central depot. Mail going to different university departments (or P.O. Box numbers) is placed in different bins. Then, these bins are loaded into different trucks based on route and destination. Finally, each of these bins is delivered to its final destination where a bin with outgoing mail is collected to be further processed at the central depot.

Currently, the UWMS has fixed routes and known schedules so each department knows at what time their mail will be picked up and delivered. Each morning, seven routes serve customers on and nearby campus. Most departments receive mail during the morning runs which occur between 8am and 12pm. Those departments who do not receive morning mail service are instead serviced in the afternoon, along with several departments who receive a second delivery due to high volumes of mail. In the current service, there are a total of five afternoon routes. An additional route serves the two University satellite campuses, as well as other university buildings which are not in close proximity to the main campus. This route services customers over the course of the entire day.

The UWMS has provided data regarding current operations. Information on existing routes includes customers (departments), delivery location, and delivery times. The time provided is a "time check," meaning that the driver will wait, if early, to deliver mail to each location until the time indicated. Additionally, the UWMS has provided the vehicle number, make, model and year, fuel type, and average cost of fuel per mile for each vehicle in their fleet.

The costs associated with distance and time were provided by the UWMS ($/mile and $/minute which are expanded on below), while the cost associated with emissions is obtained from Klein et al. *(2007)* (12 [US$/ton CO_2] for 2005 which is inflated by a 4% annually for a present value of 15 [US$/ton CO_2]). This cost is not directly borne by the fleet operator, and is only used to combine terms in the OF. Scenario four improves the solutions based on reductions of distance and time (setting emissions to zero). This scenario best captures the existing fleet's objective.

The above local search was developed to include time dependent and road-class dependent travel times by having congested periods and links with different speeds. Link speed is identified by time of departure, and therefore this approach may not respect the FIFO principle when trips depart near the beginning or end of the congested period *(Ichoua et al. 2003).*

5.1 DATA

5.1.1 Fleet Information

The existing mailing services fleet used within this analysis consists of seven vehicles. As previously mentioned, all vehicle attributes, with the exception of capacity, were provided by the UWMS. The capacity was estimated after a visual inspection of the vehicles. Table 5.1 provides a summary of fleet input specifics for capacity and cost. Table 5.2 provides the specifics for CO_2 and NO_X emission factors for each of the vehicles.

Table 5.1: UWMS Fleet Attributes. Capacity and Costs

Vehicle Description	Year	Capacity (bins)	Fuel Cost [$/mile]
Cargo Van	2005	22	0.16
Step Van	2001	30	0.36
Step Van	1995	30	0.44
Step Van	1995	30	0.44
Step Van	1994	30	0.42
Step Van	1994	30	0.42
Box Truck	1994	40	0.37

Table 5.2: UWMS Fleet Attributes – CO_2 and NO_X Emissions Factors (average conditions)

Vehicle Description	Year	CO_2 Emission Factors [kg CO_2/mile]			NO_X Emission Factors [kgNO_X/mile]		
		55mph, freeway	15mph, freeway	15mph, local road	55mph, freeway	15mph, freeway	15mph, local road
Cargo Van	2005	0.4289	0.6872	0.7030	0.0036	0.0080	0.0082
Step Van	2001	0.4717	0.7667	0.7838	0.0029	0.0069	0.0069
Step Van	1995	0.4355	0.7240	0.7413	0.0041	0.0099	0.0098
Step Van	1995	0.4355	0.7240	0.7413	0.0041	0.0099	0.0098
Step Van	1994	0.4120	0.6890	0.7045	0.0043	0.0103	0.0102
Step Van	1994	0.4120	0.6890	0.7045	0.0043	0.0103	0.0102
Box Truck	1994	0.8059	1.3972	1.3972	0.0088	0.0260	0.0263

5.1.2 Cost Data

Drivers' wages were calculated on a per unit time basis. Using a compilation of University of Washington employee salaries *(Ibloom.net, 2009 Trego and Murray 2010),* it was determined that UWMS drivers earn approximately $18 per hour. Distance-based operational costs for each vehicle were approximated using the fuel costs provided by UWMS (see Table 5.1). While operational costs typically also include tires, maintenance, and repair, these costs are difficult to quantify and fuel costs often make up a large portion of the overall operational costs.

Additionally, because the routes for this case study are very short in distance, the operational costs are much smaller than hourly costs incurred for drivers.

5.1.3 Emissions Factors

Emissions factors were obtained from the Environmental Protection Agency (EPA) Motor Vehicle Emissions Simulator (MOVES) model. CO_2 emissions are reported in kilogram of CO_2 per mile. And the NO_X emissions in kilograms of NO_X per mile (see Table 5.2 for values which are an average of the 9 AM and 2 PM values for average weather conditions). Within MOVES, the following settings were used to obtain emissions factors used within the model:

- Calculation Type: Emission Rate
- Vehicles/Equipment: Passenger Truck (Cargo Vans), Light Commercial Truck (Step Vans), Single Unit Short Haul Truck (Box Truck)
- Fuel: Gasoline
- Age: 1994-2005
- Time of Day: 9AM and 2PM.
- Road Type: Urban Restricted Access (for freeway traffic), Urban Unrestricted Access (for local roads)
- Pollutants and Processes: CO_2 Equivalent, NO_X
- Speed: 15 mph and 55 mph

Within the model, emissions factors for 9 AM and 2 PM are used for morning and afternoon delivery runs, respectively. Emissions factors reported in Table 5.2, above, are an average of the 9 AM and 2 PM values.

The speed of the vehicles is used to distinguish between congested and uncongested periods of time. During uncongested periods, vehicles on local (campus) roads are assumed to travel at 15mph, while vehicles on the freeway are assumed to travel at 55mph. During congested periods, speeds on the freeway are assumed to drop to 15 mph. Speeds on local roads remain the same. When congested periods are specified within the model, applicable emissions factors (depending on speed) are used to develop a solution.

5.1.4 Customers and Travel Distance

The individual customers of the mailing service are composed of departments within the University system. A total of 56 stops, or customers, were identified. These locations, along with a depot from which vehicles are dispatched from and return to, were used to develop an origin-destination matrix, based on miles travelled. Locations were identified in ArcGIS and the “OD Cost Matrix” tool was utilized to develop this matrix. This tool calculates the distance of the shortest routes among all origin-destination pairs. Using the origin-destination matrix, travel times between customers were estimated assuming that vehicles travelled at 15 mph on, and nearby, campus and at 55 mph on freeway connections for free flow conditions or 15 mph for congested traffic conditions on them.

5.1.5 Service Time

Service time is defined as the time required to deliver and pickup mail, including the time required to walk between departments which are served by one truck stopping location. The service time is reported in minutes. Time checks along existing routes were used to determine the service times required at each customer by subtracting the travel time between destinations from the difference in arrival times at successive destinations.

5.1.6 Demand

Customer demand is defined as the amount of mail needing to be delivered to each customer and is based on historical demand for bins. Service times are estimated based on driver knowledge, and represent typical delivery times used for planning and scheduling. Customer demand is reported in units of bins, referring to the bins used to store and transport mail.

5.1.7 Time Windows

As mentioned earlier, the UWMS operates on a fixed schedule, and time checks serve as time windows, indicating the earliest time mail will be picked up at a given location. While certain times, such as the morning, are more preferable for mail pickup/delivery, it is assumed that mail could in theory be delivered anytime between 8 am and 4:30 pm, and that customers do not have control over determining the time when they are served.

5.2 ANALYSIS AND SOLUTION METHODOLOGY

Several scenarios were examined within the case study. For each set of scenarios, the local search metaheuristic presented in the above section was used to provide outputs. This information included: distance traveled in each route, time required, cost and emissions.

The scenarios developed in this case study were as follows:

5.2.1 Base

First, the existing routing, or base case, was replicated using the vehicle routing tool. Thirteen existing routes are examined. Many of the morning base routes include a break for truck drivers to return to the depot

5.2.2 Improved routing

The individual routes are improved using the optimization heuristics to identify cost and emissions reductions that can be made by simply reordering the deliveries within the existing routes. These improved routings do not include the break mentioned above.

5.2.3 Morning and Afternoon Consolidation

The time constraints due to existing routings are removed to allow for improvements of all morning and all afternoon deliveries.

5.2.4 Fleet Upgrade

Existing step-vans are replaced with hybrid versions. Hybrid versions of small delivery vehicles can reduce emissions, while improving fuel economy. Using the results from a 2009 report by the National Renewable Energy Laboratory (laboratory tests showed that hybrid delivery vans had a fuel economy that was an average of 34% greater than standard diesel vans, and reduced CO_2 emissions by an average of 27%), emissions and fuel economy values are adjusted to model the impact of this vehicle replacement on fleet operations (*Lammert 2009*).

5.2.5 Consolidation of Service

Customers who currently receive mail deliveries twice a day experience a reduction in service to once a day. This change increases time windows flexibility allowing a better solution both in cost and emissions. This analysis considers serving all customers and at any time during working hours.

5.2.6 The Effects of Congestion

The impact on cost and emissions is studied when the effect on congestion is included on those routes traveling on freeways.

5.2.7 Practical Applications for Fleet Managers

The methodology developed in this research starts by creating an order of trucks under a criteria. The three criteria used were by capacity (the truck with more capacity goes first), by cost (the truck with the lowest cost is assigned first), and by emissions (cleanest truck first). Different routing with different cost and emissions were obtained depending on the chosen truck order. In summary, the finding suggests that it is appropriate to propose simple rule of thumb that operators can follow to reduce cost and emissions.

5.3 RESULTS AND TRADE-OFF ANALYSIS

Applying the metaheuristic to the input scenarios listed above, several conclusions can be made from the results. Given that the model uses heuristics to find solutions, the model does not guarantee a global optimal solution, but results show the heuristics are consistently able to find significant improvements when compared to current operations.

5.3.1 Improved routing

On runs where a driver break occurred in the base case, but was removed as routes were improved, the improved scenarios reduce cost by an average of 32.01%, and reduce emissions by an average of 21.61%. On runs where a driver break did not occur within the base case, the improved solutions reduce cost by an average of 9.37% and reduce emissions by an average of 8.92%, illustrating that within this case study, there are routing efficiencies to be gained that can improve both costs and emissions. For further comparisons, the cost and emissions of the base cases were adjusted to discount the cost and emissions associated with the break. The existing policy of drivers returning to the depot for break midway through existing routes increases both cost and emissions of the routes and is clearly inefficient. It seemed unfair to take credit for these improvements when considering the trade-offs. Discounting the cost and emissions associated with the break, the improved solutions reduce cost by an average of 8.98%, and reduce emissions by an average of 5.53%.

While the improved routing does not include the existing driver break time, the longest improved route is 2 hours and 25 minutes. If breaks are required mid-morning, and morning runs started at 8:00am, all drivers would be able to return to the depot by 10:25am at the latest for breaks. If breaks needed to be taken earlier than the end of the tour, allowing breaks to occur along the route would eliminate the need to return to the depot mid-tour, and still reduce distance traveled and emissions.

5.3.2 Morning and Afternoon Consolidation of Customers

When the constraints due to existing routings were eliminated, consolidated routing for both morning and afternoon customers could be developed. For the morning consolidation, emissions reductions of 7.35% can be obtained by consolidating customers. This solution uses six vehicles to serve the customers and results in cost increase of 3.47%. In the afternoon consolidation, emissions reductions of 35.15% can be identified, using four vehicles with a cost reduction of 4.81%. Depending on the initial ordering of vehicles, emissions can be slightly higher (when ordered on capacity and cost) or lower (when ordered on emissions) when compared to the sum of the base cases.

5.3.3 Fleet Upgrade

The introduction of hybrid vehicles to the fleet reduces both fuel cost and emissions. Overall costs are reduced by less than 0.5% because the cost of fuel is low compared to the cost of drivers. The fleet upgrade always results in improved emissions. Emissions reductions of up to 33.88% can be identified, with a corresponding cost reduction of 0.32%.

Due to the limited distances travelled along near-campus routes, the introduction of electric commercial trucks into the UWMS fleet would be operationally feasible. These zero tailpipe emissions vehicles would not only significantly reduce emissions, but would also reduce costs associated with fuel. Using an electricity rate from the US Department of Energy of $0.0648 per kilowatt hour (in Washington State) and an estimate of 2 kilowatt hours of energy units per mile for electric trucks (The Port of Los Angeles), the electricity to operate a truck costs approximately $0.13/mile. If an electric vehicle in the UWMS fleet travels an average of 10 miles per day and saves $0.29 of fuel costs per mile of travel, it would take just under 7 years (assuming 250 days of deliveries per year) to recoup every $5,000 of vehicle upgrade costs.

5.3.4 Consolidation of Service

Currently, six vehicles go out each morning for deliveries on near or on campus routes which take an average of approximately two hours to complete. In the afternoon, four vehicles make shorter near or on campus delivery runs which take approximately 90 minutes to complete. The

UWMS fleet is underutilized. If deliveries were spaced out the total number of trucks within the fleet could be reduced. Using the optimized routings as an example, if vehicles made deliveries up to eight hours per day, only three vehicles would be required to do the same work. If vehicles made deliveries up to six hours per day, only four vehicles would be required. Table 5.3 illustrates this reduction in fleet size.

Table 5.3: Suggested Reductions in Fleet Size

	Current Assignments				
Vehicle	**Length of routes assigned (nearest minute)**				**Total**
Step Van	111	-	-	-	111
Step Van	128	69	-	-	197
Step Van	146	80	-	-	226
Step Van	118	74	-	-	192
Step Van	128	-	-	-	128
Box Truck	238	238	-	-	476
	Suggested Assignment (8 hours of delivery)				
Vehicle	**Length of routes assigned (nearest minute)**				**Total**
Step Van	111	128	69	146	454
Step Van	80	118	74	128	400
Box Truck	238	238	-	-	476
	Suggested Assignment (6 hours of delivery)				
Vehicle	**Length of routes assigned (nearest minute)**				**Total**
Step Van	111	128	69	-	308
Step Van	146	80	128	-	354
Step Van	74	238	-	-	316
Box Truck	118	238	-	-	356

By reducing the number of trucks needed to meet demand, fewer drivers are required. If drivers are paid more than those explicitly tasked with sorting mail, replacing drivers with additional sorters can reduce cost.

When all customers only receive mail delivery service once a day (compared to the morning and afternoon improved routes), cost decreases by an average of 34.74%. Currently, 23 aggregated customers receive mail twice a day. These customers represent 155 departments, or approximately 20% of all departments served.

Also, emissions are decreased. After the service consolidation, CO_2 emissions are reduced by an average of 3.03% and NO_X by an average of 10%.

5.3.5 The Effects of Congestion

Most delivery routes used by the UWMS do not have to contend with the problem of congestion, given that they travel on or near campus, with the exception being the route which serves the satellite campuses and other off-campus destinations. The majority of these routes travel along an interstate, which is often congested during peak hours. The existing routing consolidates these off campus customers into one route which is served by the vehicle with the least emissions. Our analysis is able to capture the effect of congestion by reducing the speed during peak periods (to

15 mph), during the off-peak period, a speed of 55 mph is used. Considering no congestion, and congestion in one hour increments up to a total of a 5-hour period (7am to 12pm), the impact of increasing congestion on cost and emissions can be seen in Figure 5.1. The cost evaluated here only includes the direct costs of congestion, such as increased time and increased mileage due to the optimized routing through congestion, and does not include the costs of emissions.

Cost and emissions both increase with longer periods of congestion, however, the trend appears step-like. For example, there is a large jump between the emissions impacts of 2 and 3 hours of congestion. This is due to the fact that we use a constant speed on the link (either all or none of the trip is exposed), and the specifics of customer location and demand.

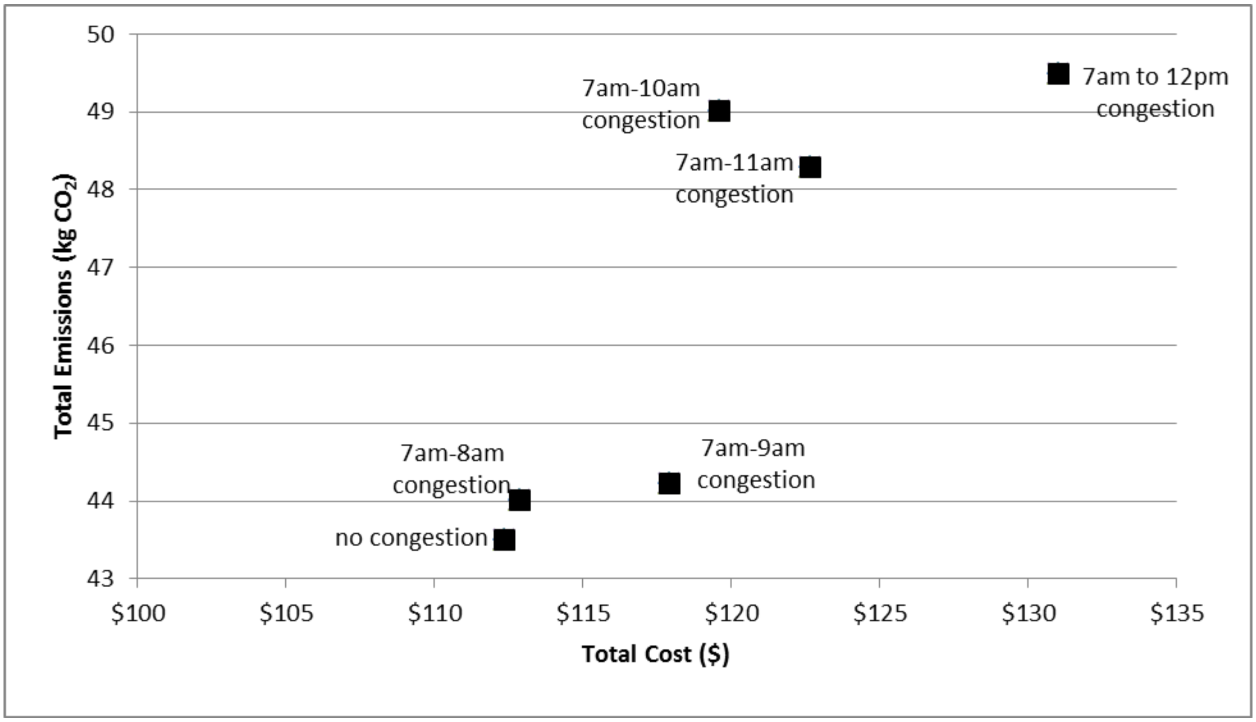


Figure 5.1: A comparison of cost to emissions over increasing periods of congestion

5.3.6 Practical Applications for Fleet Managers

As explained previously, the creation heuristic takes vehicle ordering as input. An ordering based on capacity will first assign customers to the largest vehicles, assigning customers to the smallest vehicles last. An ordering based on emissions will first assign customers to the cleanest vehicles first, while an ordering based on cost will assign customers to the cheapest vehicles first. The initial ordering affects the quality of the final result, and can also be used to model the impact of assignment strategies that may be used by fleet managers in the absence of a more complex optimization tool.

In our case study, most of the vehicles have a very similar cost basis. As a result, cost varies little as a function of vehicle ordering, but the impact of vehicle order is more apparent when considering emissions. Within the UWMS fleet, the vehicles with larger capacities have poor emissions and therefore when the vehicles are ordered by capacity, the largest vehicles is assigned the most customers and travels a considerable distance. For the morning consolidation, ordering vehicles by CO_2 emissions and costs result in average emissions reductions of 16.91% and 8.62%, respectively, when compared to ordering vehicles by capacity. The difference between different vehicle orderings is greater within the afternoon consolidation due to the smaller number customers served. Fewer vehicles are used, specifically when vehicles are ordered by CO_2 emissions or cost, the largest capacity truck (which also has the highest emissions) is not used. In the afternoon consolidation, ordering vehicles by emissions and costs result in average emissions reductions of 45.07% and 41.15%, respectively, when compared to ordering vehicles by capacity. Similar results are obtained for the NO_X case. When results from different truck assignment are compared in the single delivery case, an ordering based on NO_X emissions and cost result in a decrease of 10% on emissions and 15% on cost when compared to the capacity assignment. These results show the multiple benefits of simple tools when, by following a simple rule to assign trucks, not only cost is reduced but also CO_2 and NO_X.

It is important to notice that capacity did not have a relationship to model year in this case study and a different combination of these two parameters may produce different outcomes.

Managers of small fleets of vehicles are less likely to use optimization tools to determine the routing of their vehicles, and instead will rely on simple rules of thumb. When focusing on reducing emissions, those vehicles with low emissions should be utilized to the fullest before vehicles with higher emissions are introduced into the routing. This is contrary to most fleet managers current approach, which, when minimizing cost, is to utilize the largest vehicles.

5.4 POLICY ANALYSIS

5.4.1 Rescheduling activities and different vehicle assignments

As indicated above, policies involving the removal of existing schedule restrictions, including the policy of driver breaks, and reassignment of vehicles, result in reductions of both cost and emissions. While time windows cannot completely be eliminated, the model is able to identify both emissions and cost improvements by reassigning route and time windows.

The UWMS should consider this reassignment. Additionally, removal of driver breaks is suggested as this increases both cost and emissions of the routes and is clearly inefficient to have the vehicles return to the depot mid-route. The lengths of improved routes (all less than 2 hours and 30 minutes) do not seem to warrant such a break, but if one is needed, the break should occur along the route to eliminate the need to return to the depot mid-tour, and still reduce distance traveled and emissions.

As reported above on runs where a driver break occurred in the base case, but was removed as routes were improved, the improved scenarios reduce cost by an average of 32.01%, and reduce emissions by an average of 21.61%. Discounting the cost and emissions associated with the break, the improved solutions resulting from rerouting reduce cost by an average of 9%, and reduce emissions by an average of close to 6%.

5.4.2 Reassignment of vehicles to routes and customers

A reassignment of vehicles policy is also recommended for the UWMS. Typically smaller vehicles have better emissions, thus when focusing on reducing emissions, vehicles with low emissions should be utilized to the fullest before vehicles with higher emissions are introduced into the routing. Ordering of vehicles by CO_2 emissions results in emissions reductions of between 17% and 45% for the UWMS. In the same way, when trucks are sorted by NO_X emissions, it is possible to observe reductions of 10% (only one scenario was analyzed for NO_X). When assignments were based on emissions instead of capacity (bigger-truck first rule), it was observed that not only emissions were lower but also cost.

Thus, there is a close relationship between marginal cost and marginal emissions that makes possible to have both to cheaper and cleaner routing at the same time.

6.0 CASCADE EXPRESS

Cascade Express provides long-haul pickup and delivery services along the west coast, serving customers in California, Oregon, and Washington. The majority of travel by the fleet occurs on freeways, and customers are often located near freeways, resulting in trucks spending minimal time on local roads. Goods are loaded and unloaded at the customers' location. Sometimes trailers are left with the customer and the trucks returns to the depot without a trailer, or picks up another trailer either at the same or a different location along the route.

The Cascade Express fleet includes with model years, ranging from 1994 to 2008, and 53-foot trailers with either 62,000 lbs. or 42,000 lbs. capacity. Customers are promised a day for pickup or delivery service, and the time window is flexible with constraints due to customer working hours. Drivers visit customers during the day and some trips may require an overnight stay.

Within the case study, the routing is relatively uncomplicated because most of the customers are located near a freeway or highway. To reduce the number of customer locations in the model, customers were clustered into 33 zones, representing distinct cities, where customers are not further than 15 minutes traveling at 55mph from the city. Customer cluster locations are shown in Figure 6.1. This figure illustrates 19 of the 33 customer clusters are located in the vicinity of I-5, making this corridor important.

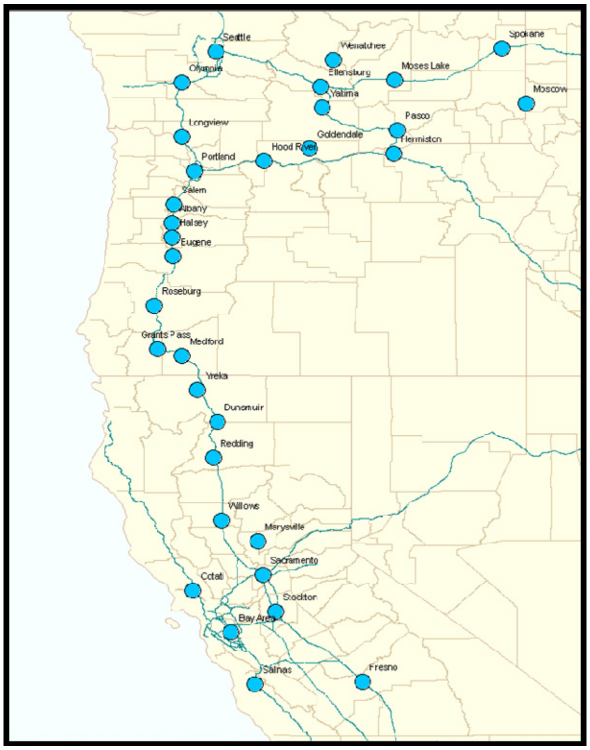


Figure 6.1: Customer clusters' locations are near freeways and highways

Cascade Express provided one month of operational data (October 2009) to use in the case study. This information includes customers visited by each truck each day, weight picked up and delivered, arrival and departure time from each customer (travel time are obtained by subtracting to consecutive departure and arrival times) and hours when drivers rest. Additionally, the vehicle make, model, year, and fuel type was provided along with the trailers capacity information. Cost data was not provided and estimations from ATRI were used. CO_2 and NO_X emissions per mile were obtained from the model MOVES by the EPA. Both cost and emissions data was confirmed to be consistent with the internal estimations by Cascade Express.

The tabu search metaheuristic, presented in the previous chapter, was used for routing analysis. Link speed is identified by time of departure, and therefore this approach may not follow the FIFO principle when trips depart near the beginning or end of the congested period *(Ichoua et al. 2003).*

6.1.1 Data

6.1.2 Fleet Information

Cascade Express has a fleet of 80 trucks. Table 6.1 provides a summary of fleet input specifics, including emissions factors, which are discussed below. Table 6.1 provides a summary of fleet input specifics for capacity and cost for each model year. Table 6.2 provides the specifics for CO_2 and NO_X emission factors for each of the model year.

Table 6.1: Cascade Express Fleet Attributes

Year	# of Vehicles	Capacity (bins)	Fuel Cost ($/mile)	Drivers' Cost ($/hr)
1994	1	62,000	0.9942	25.02
1995	2			
1997	5			
1998	4			
1999	17			
2000	10			
2001	2			
2002	2			
2003	5			
2006	20			
2007	6			
2008	6			
Total	**80**			

Table 6.2: Cascade Express Fleet. CO_2 and NO_X Emission Factors

Model Year	CO_2 Emissions [kg CO_2/mi]		NO_XEmissions [kg NO_X/mi]	
	55 mph ,	30 mph ,	55 mph ,	30 mph ,
	freeway	freeway	freeway	freeway
1994	0.69	1.63	0.029	0.037
1995			0.029	0.037
1996			0.029	0.037
1997			0.029	0.037
1998			0.027	0.031
1999			0.020	0.024
2000			0.020	0.024
2001			0.020	0.024
2002			0.020	0.023
2003			0.009	0.013
2004			0.009	0.013
2005			0.009	0.013
2006			0.009	0.013
2007			0.005	0.006
2008			0.005	0.006

Cascade Express has 53 foot trailers and trucks pull only one trailer at a time. 213 trailers have a capacity of 62,000 lbs and 85 of them of 42,000 lbs. Despite the fact there are two types of trailers, we assume a homogenous capacity of 62,000 lbs because we were provided complete information of weighted transported in each trip but less complete information on the type of trailer used. This assumption should not affect the quality of the final results because the transported weight is usually greater than 31,000 lbs (90.36 %) which does not allow combining two trips using larger trailers.

6.1.3 Cost Data

Cost information was not provided by the case study partner and estimations from ATRI were used. Cost was divided in two components: cost per mile and cost per hour. The calculations developed by ATRI assumes a traveled speed equal to 48.4 mph but most of the time vehicles travel at 55 mph in our case. Thus, we applied a cost correction factor to include this difference. Finally, we haven't included the tolling component in the ATRI's cost estimation because most of the freeways and highways used by Cascade Express are not tolled.

The cost per mile used was equal to \$0.9942 per mi. The cost per hour used was \$25.02 per hr.

6.1.4 Emissions Factors

Emissions factors were obtained from the Environmental Protection Agency (EPA) Motor Vehicle Emissions Simulator (MOVES) model. Emissions values are reported in kilograms of

CO_2 per mile and in kilograms of NO_X per mile. The emissions values account for a diesel powered vehicle, an average of a daily temperature, on freeways, free glow speed (55mph) and congestion level (15mph). Within MOVES, the following settings were used to obtain emissions factors used within the model:

- Calculation Type: Emission Rate
- Vehicles/Equipment: Single Unit Long Haul Truck
- Fuel: Diesel
- Age: 1994-2008
- Road Type: Urban Unrestricted Access (used for traffic on freeways and highways)
- Pollutants and Processes: CO_2 Equivalent and NO_X
- Speed: 30 mph and 55 mph

Emissions factors are reported in Table 6.2. The emissions values for CO_2 equivalent do not depend on vehicle age because of regulations on gas consumption per mile by the EPA, which is directly correlated to CO_2 production.

The speed of the vehicles is used to distinguish between congested and uncongested periods of time. Vehicles are assumed to always travel at the most common free flow speed limit on freeways, 55 mph. During congested periods, speeds on the freeway are assumed to drop to 30 mph.

6.1.5 Customers and Travel Distance

Customers are located in California, Oregon and Washington, primarily near freeways and highways. They have been grouped in 33 representative locations or clusters based on a radial travel time no longer than 15 minutes on free flow conditions. These locations along with the unique depot in Albany, OR, were used to develop an origin-destination matrix based on miles travelled. Locations were identified in ArcGIS using the "OD Cost Matrix" tool to develop this matrix. This tool calculates the distance of the shortest routes among all origin-destination pairs. Using this matrix, travel times between customers were estimated assuming 55 mph for free flow conditions and 15 mpg for congested ones.

6.1.6 Service Time

Service time is defined as the time required to deliver and/or pickup goods at customers' location. The service time to serve a customer is estimated from the drivers' logs which include the arrival and departure time for all stops. All individual service times are averaged for a given customer and then a representative cluster service time is obtained from the averages of the customers contained in the cluster. Service times are reported in minutes.

6.1.7 Demand

Customer demand is defined as the weight of goods delivered to or picked up from a customer. It is based on the records provided by the case study. Customer demand is reported in pounds.

6.1.8 Time Windows

Time windows to visit customers occur within the period from 8 AM to 6 PM. Further restrictions to these time windows only occur when specific scenarios and policies are studied. There are no time windows at the depot because Cascade Express allows for total flexibility to avoid typical congestion periods in both morning and afternoon. Occasionally this may induce some waiting time at the destination but that is not captured in our analysis. We arbitrarily induce the possibility of waiting times for the purpose of analysis by having a time window structure and congested period hours that open this possibility.

6.2 ANALYSIS AND SOLUTION METHODOLOGY

Several scenarios were examined within the case study and the tabu search metaheuristic was used to solve the instances.

An analysis of the travel patterns in the current operations of this case study showed the existence of primarily three types of trips:

- long-haul trips between the depot and California and short haul trips in the Bay Area and Sacramento area
- local trips between Portland, OR, and Eugene, OR
- long-haul trips between the depot and Western Washington and between the depot and Eastern Washington (there are no trips between Eastern Washington Western Washington trips).

These patterns shaped the scenarios and analyses performed. More details about these patterns are included in the next section. Sometimes the word cluster is also used to describe the trip patterns although it was used to explain the idea of representing several customers under a common city. The scenarios developed in this case study were as follows:

6.2.1 Base

First, the existing routing, or base case, was replicated using the vehicle routing tool. Base costs, distances, and emissions values are determined. These analyses were developed within each of the clusters and included one, two, and three days of operation.

6.2.2 Reduction of Empty Trips

An analysis of empty trips is developed, and potential cost and emissions reductions are studied for each of the clusters. Improvements occur with the introduction of better trip chaining to reduce empty trips. Cost reductions are obtained from less VMT and emissions reductions are calculated using the emission factors times the miles travelled in each case. 2-hour congested periods have been assumed for the morning between 7 AM and 9 AM and for afternoon between 4 PM and 6 PM. Calculations are developed in Excel using the data provided by the case study.

6.2.3 Impact of Congestion and Time Windows Flexibility

The impact of congestion on cost, CO_2 and NO_X emissions is studied for the Albany to Portland pair. Two scenarios are considered: minimize cost and minimize emissions under different levels of congestion (different number of hours). The Albany-to-Portland pair s considered because it represents 44% of the total number of trips.

Congestion s a significant factor in this corridor, and so this example serves to highlight the impact of congestion on operations.

6.2.4 Fleet Upgrade

The CO_2 and NO_X emissions benefit from upgrading vehicles is studied. The analysis combines the effect of newer model year and their environmental impacts at different speed values.

6.2.5 Different speed limit

The impact on cost and emissions are analyzed when the speed limit is 55 mph, 60 mph, and 65 mph.

6.3 RESULTS AND TRADE-OFF ANALYSIS

For the month of operational data, the cost and emission for the base case were estimated using the cost estimation from Trego and Murray *(2010)* and emission factors from MOVES.

The total cost was estimated by multiplying the total driving hours by the driver’s salary per hour and the total distance by the cost per mile. The CO_2 emissions came from assuming two congested periods between 7-9 AM and 4–6 PM and multiplying the total driving time under congested and uncongested traffic by the 15mph and 55mph emission factors respectively. This resulted in a total cost of $1M and CO_2 emissions on 490,000 kg of CO_2.

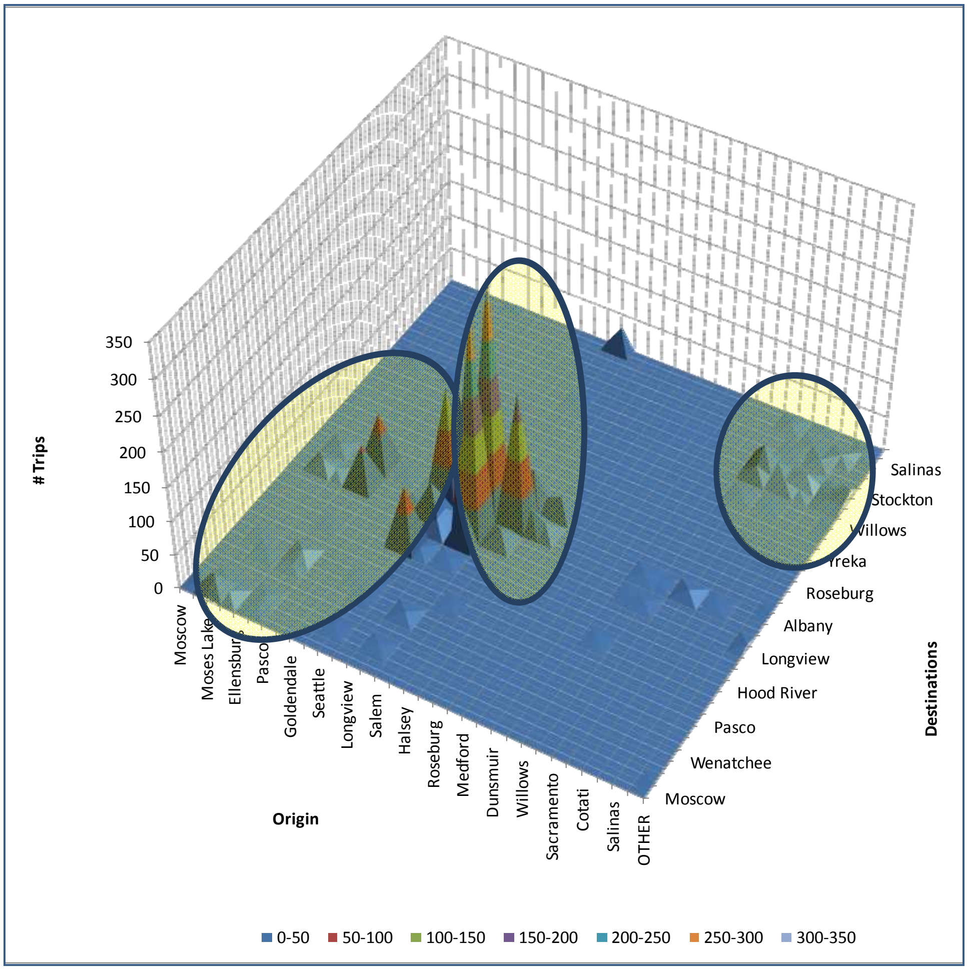
6.3.1 Reducing empty trips

In Figure 6.2, a graph with the total empty trips distribution for the month of data is shown. The pyramids represent the number of trips for each OD pair. The variation of colors helps to illustrate the varying increments of trips.

It is possible to see that empty trips are concentrated in three distinct areas. The circle on the right shows a concentration of empty trips starting and finishing in California. A second circle in the center shows a clear concentration of empty trips with origins and destinations in Oregon. Finally, the third circle on the left of the figure mainly shows empty trips starting mostly in Yakima and Seattle and going to Portland or Albany. Overall, there are no other considerable numbers of empty trips outside of these three areas.

One important conclusion from this figure is that there is no evidence of empty trip concentration of from Oregon to California, and vice versa. This shows that companies understand the high cost of moving trucks empty for such a long distance. In fact, Cascade Express confirmed their special efforts in traveling with goods between these states. Sometimes, they visit more than one customer to increase the utilization rate. They also wait to have a load to pick up when returning from California or coordinate with other carriers to serve a customer and share the incomes while reducing the empty miles. When it is not possible to avoid an empty trip, a customer is just charged more for that trip. However, this is not always possible given market concerns.

Coming back to the figure, the concentration of empty trips within Oregon is substantial. Forty-four percent of the total trips are empty and half of them (or 22% of the total trips) are concentrated around the depot (second circle), mainly in trips with the following origins and destinations: Albany-Albany, Portland-Portland, Albany-Portland, and Portland-Albany.



*Origins on the horizontal axis and destinations on the vertical one

Figure 6.2: Empty trip distribution.

Also, 66% of trips from Washington to Oregon returned empty. They mainly started in Yakima and Seattle, and went to Portland or Albany.

Empty trips starting and finishing in California performed better with 28% of them empty.

Based on the above analysis, there was a concentration of empty trips in specific OD pairs. The concentration of these trips helps to develop strategies to increase efficiencies. We present three proposals to quantify the potential cost and emission reduction by reducing or eliminating the empty trips in each of the clusters.

Cluster 1: California

Within the concentration of empty trips starting or ending in California, there are two lines of action. First, there is a large benefit that can be realized by reducing the 28% of empty trips in California which mostly take place between: Sacramento and Stockton (both ways) and the Bay Area to Stockton (one way). Secondly, a few trips from California to Oregon are empty. However, the distance between these states is in the order of hundreds of miles and every marginal reduction can have a significant impact on cost and emissions. If the above trips are reduced there is a potential cost reduction of 1.6% and emissions reduction of 1.8%. This benefit comes from fewer miles traveled in both congested and uncongested traffic.

Intra California trips can be reduced by finding new customers who wish to move goods in the direction of the empty legs. Empty trips to California can be reduced by allowing drivers to wait for a new load or coordinating with other providers.

Cluster 2: Oregon

Most of the empty trips happened in this area (44%). Moreover, most of the total trips during the month being analyzed took place here (52%). The distance traveled in this area was usually less than 2 hours (trips were concentrated in Albany and Portland) which means the empty trips did not cost as much as longer trips. However, there were many of these empty trips and if these can be reduced, this will result in the most significant potential reduction of the three clusters. If deadheading is totally avoided within this cluster, a reduction of 6.4% in cost and 7.0% in emissions could be possible.

The potential reductions would only take place in an ideal scenario but the analysis sheds light on where to focus partial improvements. If part of these potential savings is achieved, Cascade Express can considerably reduce its costs and emissions.

Cluster 3: Washington

Most of the empty trips started in Seattle and Yakima and went to Portland and Albany. There were limited customers between these pairs, especially within Eastern Washington. An opportunity to reduce VMT appears when trucks in Eastern Washington go to Western Washington and pickup loads before continuing to Oregon. The proposed routing scheme reduces the number of empty trucks travelling up from southern Washington or northern Oregon to eastern Washington. This improvement in the routing reduces cost by 3.9% and emissions by 4.4%.

The success of these recommendations depends on the existence of demand in desired locations. However, the proposed improvements seek to show ideal reductions and guide future efforts for partial reductions. As a summary of the above recommendation, Table 6.3 shows a summary of the potential cost and emissions reduction in each cluster.

Table 6.3: Summary of potential cost and emissions reductions from empty trips reduction strategies in the three customer clusters

	Potential Cost & Emissions Reduction		
	Cluster 1	**Cluster 2**	**Cluster 3**
Cost	-1.6%	-6.4%	- 3.9%
CO_2 eq	-1.8%	-7.0%	- 4.4%

6.3.2 Impact of Congestion and Time windows Flexibility

Working with a representative day of operations, we solve the routing and scheduling problem using the tabu search metaheuristic. To study the impact of congestion on cost, emissions and customer service, periods of congestion of two, four, six, and eight hour long are included. As we are interested in also studying the impact of time windows flexibilities, we have done the calculations twice. In the first case, a 10 minute window before the start of the congestion period was included. In the second case, this window was extended to 90 minutes.

In Table 6.4, the results of minimizing the routing on cost are shown. The relative increase in cost, emissions and number of vehicles needed is shown in each row. Each column shows the relative change when the congested period increases by two hours. Thus, the first column and first row shows the change in cost when congestion increases from zero to two hours while the least column shows this relative change when congestion increases from six to eight hours.

Table 6.4: Impact of congestion in cost, CO_2 emissions and number of required vehicles

	Increase in hours of congestion						
	0-2	2-4	4-6	6-8	Average		
Change in cost	2%	4%	0%	4%	3%	10min	Min before congestion
Change in em.	-2%	7%	0%	7%	3%		
Change in # veh	25%	0%	0%	0%	6%		
Change in cost	3%	0%	3%	0%	2%	90min	Min before congestion
Change in em.	9%	0%	11%	0%	5%		
Change in # veh	0%	0%	25%	0%	6%		

The top half of the table, labeled as "10 min" represent the outcomes when vehicles could depart only 10 minutes before the beginning of the congested period. The second bottom half shows the outcomes when this window was equal to 90 minutes.

Overall, cost, emissions, and fleet size increase with congestion. One exception to this is when congestion increases from zero to two hours. The CO_2 emissions decrease in 2 %. This is a particular result caused by customers' distribution and the addition of new trucks. The resulting routing has lower VMT which decreases emissions. However, there is an increase in driving time because of the congestion and the cost per hour (drivers' salary) is relatively much higher than the cost per mile. Notice the stronger impact on fleet size than on cost or emissions. Our model does not capture the fixed cost of vehicles, only the operational cost.

Both cases have similar increase but it is important to notice *when* the required fleet increases. When more flexibility is allowed (bottom half of the table), it is possible to delay the need of an extra vehicle (to serve the same demand fulfilling the problems constraints). This suggests that flexibility does not only impact cost and emissions directly but also capital investment.

Table 6.5 and Table 6.6 are similar to Table 6.4 and show the results for NO_X as the pollutant in the optimization. The difference between Table 6.5 and Table 6.6 is the order trucks were assigned. Table 6.5 shows the outcomes when the truck with the highest NO_X per mile ratio is assigned first, while Table 6.6 is the one with the lowest.

Both tables show an increasing average value suggesting that longer periods of congestion increase cost, NO_X emissions and number of vehicles required. The need for a new vehicle is again delayed thanks to the time windows flexibility.

Table 6.5: Impact of congestion in cost, NO_X emissions and number of required vehicles. Trucks with higher NO_X per mile ratio assigned first

	Increase in hours of congestion						
	0-2	2-4	4-6	6-8	Average		
Change in cost	2%	4%	0%	4%	3%	10min	Min before congestion
Change in em.	-2%	6%	0%	5%	2%		
Change in # veh	25%	0%	0%	0%	6%		
Change in cost	3%	0%	3%	3%	2%	90min	Min before congestion
Change in em.	4%	0%	4%	5%	3%		
Change in # veh	0%	0%	25%	0%	6%		

Table 6.6: Impact of congestion in cost, NO_X emissions and number of required vehicles. Trucks with lower NO_X per mile ratio assigned first

	Increase in hours of congestion						
	0-2	2-4	4-6	6-8	Average		
Change in cost	2%	4%	0%	4%	3%	10min	Min before congestion
Change in em.	-2%	7%	0%	7%	3%		
Change in # veh	25%	0%	0%	0%	6%		
Change in cost	3%	0%	3%	3%	2%	90min	Min before congestion
Change in em.	6%	0%	6%	6%	5%		
Change in # veh	0%	0%	25%	0%	6%		

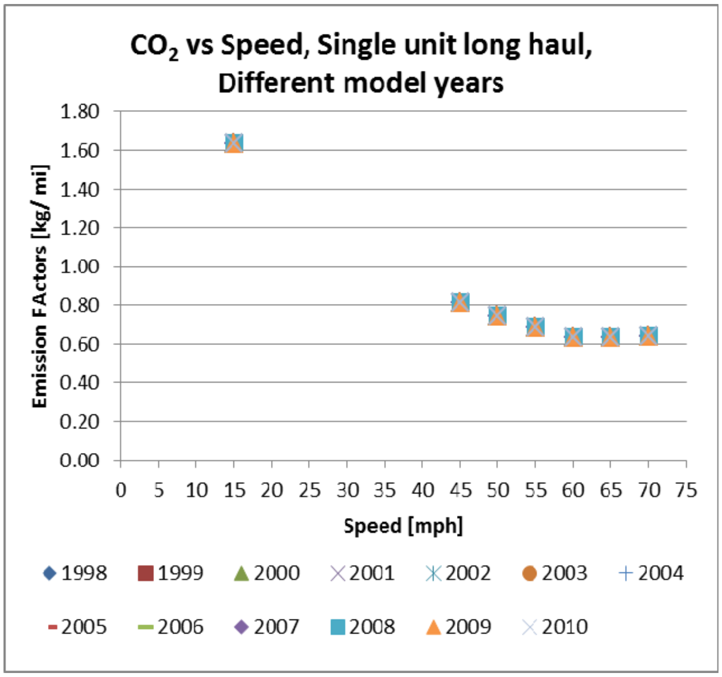
However, one of the main results of this analysis comes from the absolute NO_X emissions. For Table 6.5, the absolute emissions of NO_X increase from 41.5 to 47.6 kg while in the second Table 6.6 there is an increase from 6.7 to 8.1 kg of NO_X. Although, the average increase is around 2%-3% the difference for each period of congestion is over an 80% reduction by having different assignment rules.

These results suggest that for homogenous fleet with different model year, it is better to assign the newest vehicles because they have much lower NO_X emissions per mile.

6.3.3 Fleet replacement

The distribution of CO_2 emission factors for different model year is presented in the Figure 6.3 and for NO_X in Figure 6.4.

As seen in Figure 6.3, regardless of model year, all trucks have the same value of CO_2 per mile when speed is controlled. A vertical separation between the lines in the graph would mean a change in the emissions per mile for different model year in the given speed but this is not the case for CO_2. The reason for this is the lack of fuel efficiency improvements in the last 12 years. These emissions are closely correlated to fuel consumption.



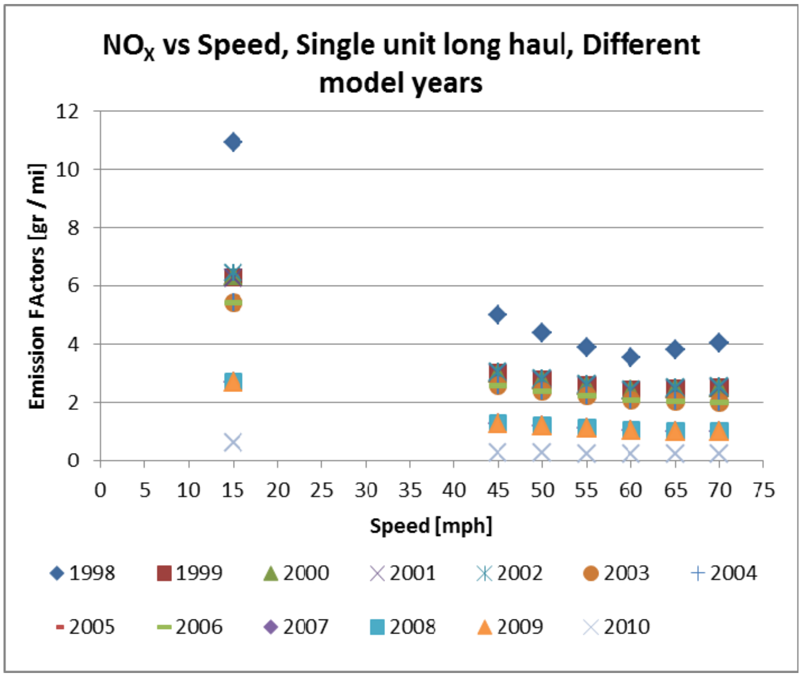
Source: MOVES by EPA

Figure 6.3: Scatter plot of emissions factors for long haul trucks, model year from 1998 to 2010. CO_2 [kg/mi] versus speed [mi]

However, Figure 6.4 shows a different behavior when considering NOx. This figure shows the emissions of NO_X per mile for different speeds and model years. The vertical separation at a given speed represents a change in emissions per mile for different model years. Reductions do not take place in every new model but in certain years: 1999, 2003, 2008, and 2010. This means, for example, a 2005 truck should be replaced with a model year after 2008 in order to have lower NOx emissions. Also, trucks of newer model years have a smaller difference in emissions at speeds of 60 mph and lower. This smaller difference reduces the negative impacts on emissions when a vehicles travels in congested conditions instead of free flow.

The use of newer trucks does not result in CO_2 emissions reductions, but NO_X emissions are reduced. Also, on newer trucks, there is a smaller difference in NO_X emissions at higher speeds which reduces the negative impact of congested traffic on NO_X levels.

Both CO_2 and NO_X emissions increase for speeds above 60 mph. Therefore we call 60 mph the emissions optimal speed.



Source: MOVES by EPA

Figure 6.4: Scatter plot of emissions factors for long haul trucks, model year from 1998 to 2010. NO$_X$ [gr/mi] versus speed [mi]

The maximum NO$_X$ reduction, achieved from a complete fleet replacement with 2008 vehicles is 70%. We estimate this value by calculating the NO$_x$ emissions at 55 mph at the actual model year distribution (see Table 6.1) and compare it with a fleet of only 2008 vehicles (their newest vehicle). If the vehicles were upgraded to the new 2010 standards, reductions can be as large as 93%.

Although newer trucks do not represent reduction in CO$_2$ emissions, these are important reductions in NOx. It is important to notice that the CO2 emissions are based on physical properties of engines and do not consider aerodynamic improvements.

6.3.4 Different speed limits

Driver salary is a larger component of overall cost than operational costs (which includes fuel).Operating at higher speeds will reduce drivers' hours, however, above 60 mph there will be an increase in emissions (particularly CO$_2$).

In Figure 6.5, CO$_2$ emissions per mile and cost per mile over various speeds are presented. CO$_2$ decreases when the speed changes from 15 mph to 60 mph but it increase for greater values of speed. Cost per mile continues to decreases as speed increases. Although fuel consumption increases above 60 mph, drivers' salary has a relative higher weight in the cost structure and its gain in efficiencies offsets the increase fuel cost.

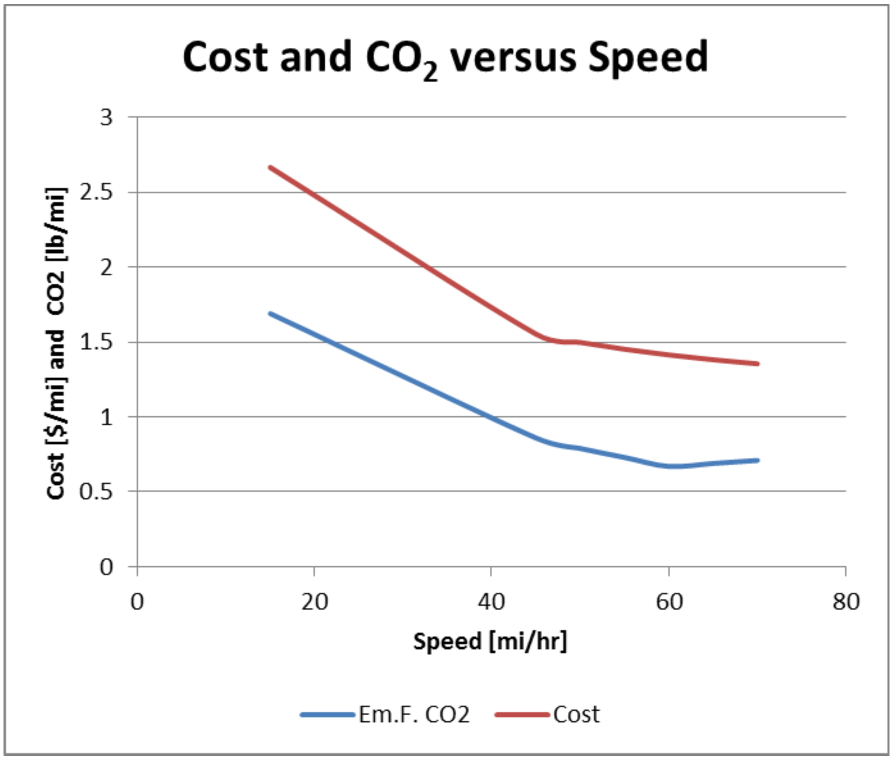


Figure 6.5: Cost per mile and CO_2 emissions per mile for different speeds

Source: Cost curve based on ATRI's cost estimation. Emission factors from MOVES

This graph provides information for speed limit analysis. It is possible to achieve both cost and emission reductions if the speed limit is increased to 60 mph. However, if a public agency seeks to reduce CO_2 and NO_X with speed limit laws, it should avoid any speed above 60 mph.

It is important to notice the pivot value of 60 mph was obtained for average weather conditions in a year in Washington State. Weather conditions can affect emissions and thus change the pivot value in other geographical locations. Therefore, specific analysis must be done for areas where speed limit changes are being considered.

The potential impact on CO_2 emissions by having speed limits at 55, 60, and 65 mph is presented in the Table 6.7. For these calculations we have assumed that all trips were done at the speed limit for the month of data.

Table 6.7: Potential impact on CO2 emissions by increasing speed limit from 55 mph

	Speed Limit [mph]		
	55	**60**	**65**
Kg CO2	1,574,630	1,562,896	1,658,036
Change w/r to 55 mph		-1%	6%

The results suggest that there will be a reduction in emissions of about 1% if the speed limit is increased to 60 mph. However, emissions would increase if the speed limit is increased to 65 mph, 6% with respect to the level at 60 mph.

6.4 POLICY ANALYSIS

6.4.1 Reassignment of current fleet

As expected, an empty trip implies higher cost and emissions, especially when a truck needs to travel for a long distance. Cascade Express is aware of this and has developed their own pricing or coordination with other companies to reduce long-haul empty to and from California. However, there is no similar effort for short trips around the depot. Apparently, the additional cost of an empty trip in this case is offset by the income from serving a customer in the area. The result is similar for medium trips as those to Washington.

Cascade Express has a considerable proportion of trips concentrated around the depot, especially in between Albany and Portland which is roughly a 2 hour segment. By removing all of these empty trips, total cost could be reduced by 6.4% and CO_2 emissions by 7.0%. This is the highest reduction among the proposed empty trip reduction strategies. While Cascade Express is sensitive to the cost of empty travel for longer distances, they are not as sensitive to the cost of these shorter trips. However, with such a large number of short trips, the cost of these empty trips outweighs the cost of the same percentage of empties on longer trips. Access to routing tools or training on database software could improve fleet manager knowledge, and encourage empty reductions for these local trips.

6.4.2 Upgrade of current fleet to newer model year

For the CO_2 and cost case, the basic ratio of cost and emissions per mile is sufficient to understand the impact of newer model year on total operational cost or emissions. There is no vertical difference in the graph, which means different model years do not affect cost or emissions. This is not the case for NO_X, where a vertical difference exists for each speed. This difference happens on certain years meaning that the NO_X emission per mile ratio is not improved with every new model year launched to the market.

Policies intended to reduce CO_2 emissions by enforcing the purchase of newer trucks do not have an impact on these emissions and just mean an additional cost for companies. Literature on emissions reductions from aerodynamic improvements has not been covered in this research and this may be an optional way to reduce CO_2 emissions and fuel consumption. However, this policy does have an effect on NO_X emissions and the required model year has to be considered in such a policy since the marginal reduction on the emissions rate take place on certain years.

For the monthly data of operations, it is estimated a potential NO_X reduction of 70% if the current fleet is totally updated to 2008 model year vehicles. Even higher reductions are met if vehicles are upgraded to 2010 standards. In this case, the potential reductions can be 93%.

6.4.3 Freeway speed limit

Figure 6.3, Figure 6.4 and Figure 6.4 show the CO_2, NO_X and cost ratios for the Cascade Express fleet at different speed values. Both CO_2 and NO_X decrease at higher speed but the ratio increases when the speed takes values higher than 60 mph.

The results from this case study show a reduction in emissions of about 1% if the speed limit is increased to 60 mph. However, emissions would increase if the speed limit is further increased to 65 mph, 5% with respect to the 55 mph limit and 6% more when compared to a limit of 60 mph. However, cost will decrease when vehicles are allowed to travel at higher speeds due to the significance of drivers' salary versus the operational cost per mile. A reduction of 3% can be obtained of vehicles travel at 60 mph instead of 55 mph. The reduction is higher when vehicles travel at 65 mph, causing a reduction of 5% with respect to the cost at 55mph.

7.0 AMAZON FRESH

Amazon Fresh provides grocery delivery service in the Seattle area. Customers shop and place their orders online along a day for the delivery to take place. Customers can choose from attended or doorstep delivery where totes are given to somebody in the provided address or left by the entrance door respectively. Customers can choose a one-hour time window for attended deliveries and three-hour time windows or delivery before 6AM for a doorstep service.

Amazon Fresh has a homogeneous fleet with respect to capacity, mileage costs and emissions and vehicles travel mainly on arterial and local streets but also freeways when customers are far apart and when traveling from/to the depot located in Bellevue. Groceries are transported in totes, all of them of the same size.

Orders are received till midnight each day. Then, routes are designed and the sequence of customer decided. This information is sent to the central depot where totes are filled with the orders and loaded into the respective trucks. Trucks leave and return to the same depot. Empty totes are picked up when groceries are delivered to customers. This operational practice can induce the need of a higher number of totes. However, it reduces VMT and increases the certainty for deliveries because avoids visiting customers (and the subsequent detour) to just pick up empty totes, as it was done prior to this change.

Amazon Fresh has provided data of two days of operation. This data includes customers' location, the requested times windows, the sequence each customer is visited and to what truck were assigned, as well as the number of totes to be delivered to each of them. Information of actual travel and service time was not provided although time windows are respected. Additionally, Amazon Fresh has provided the vehicles' make, model, year, and fuel type used. Also, self-generated data has been created for the purpose of develop more extensive analysis.

The methodology using ArcGIS presented in the previous section is used for the analysis developed in this case study. The primary focus is to study the potential emission reductions from changing the length of time windows, and also the influence of customer density on emissions as well as having cleaner trucks and vehicles with different capacity.

Twelve scenarios were developed after changing the length of time windows offered; the capacity, cost, and emission profile of the fleet, and the density of customers in the area served. For each scenario, two different objective functions were optimized to minimize cost (dollars) and emissions (kilograms of CO_2).

7.1 DATA

ArcGIS is used to minimize emissions and consider the trade-offs between emissions, cost, and service quality, for a specific case study fleet. This case study is based on a real pickup and delivery system, its customers, order quantities, and delivery time windows. Some details of the operator, including its name, are omitted to protect confidentiality. In this section the specifics of the data provided are described.

7.1.1 Fleet Information

The delivery service provider has a homogenous fleet, in terms of capacity and engine technology, of 17 vehicles. All of their trucks are less than three years old, all are diesel, and all are approximately 16' single-unit vehicles. The vehicles can carry 90 bins, approximately 30 customer orders, and spend about 5 to 15 minutes servicing each customer. The customers are residences spread throughout the urban area and are served by one warehouse also located in the urban area.

7.1.2 Cost Data

Actual costs associated with this delivery system are proprietary, therefore costs were developed using industry data. Costs were developed for each link in the network assuming average hourly wages of $26.55 for van, light duty, and heavy duty truck drivers in the Seattle metropolitan area according to *Salary.com (2010)* and typical truck operating costs of $1.13 per mile (not including driver wages and benefits which are included above) provided by Trego and Murray *(2010).* These values were converted to costs per second and costs per foot for analysis.

7.1.3 Emissions Factors

Emissions factors were obtained from the 2010 MOVES model *(U.S. EPA 2010b).* This analysis assumed uncongested conditions, so speed limit data from the Street Map North America data set was used as the default flow speed for each road segment. Since the trucks work with hot engines due to their short stopping time, only running exhaust emissions are tracked.

The base assumption in the model reflects the provider fleet and uses emissions factors for single-unit short haul trucks with diesel fuel. Emissions factors were also developed for three scenarios: hybrid vehicles, larger trucks, and smaller trucks. To develop emissions factors for hybrid trucks, the base emissions factors were reduced by 40% as suggested by an EPA white paper *(U.S. EPA 2006).* Emissions factors for large trucks were represented with factors for combination short-haul trucks with diesel fuel, and emissions factors for smaller trucks were represented with factors from light commercial trucks with diesel fuel.

Emission factors were selected for an analysis year of 2010. Preliminary NO_x evaluation indicates for the fleet in the case study presented here NO_x emissions will follow a similar pattern to CO_2 emissions. Thus, the focus of this study is CO_2 emissions, serving as a marker for both CO_2 and NO_x. 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. Roadways with speeds of 5, 20, 25, and 35 miles per hour used urban unrestricted road type emissions factors, and roadways with speeds of 45 and 55 miles per hour used urban restricted road type emissions factors. Since the case study fleet is comprised of modern vehicles of varying age, emissions factors for 2007-2010 model years were averaged.

7.1.4 Network Data Set

The base network is pulled from the ESRI StreetMap North America data set *(ESRI, 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.

This data set was modified in a number of ways for this evaluation. First, the data set was trimmed to only include road segments in the study area to reduce processing time. Next, the length in feet of each road segment was calculated and 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.

7.1.5 Customer Sample

A one day customer sample was gathered from the case study delivery service. The data set reflects three service windows (PreDawn, Breakfast, and Lunch/Dinner) and includes 576 customers. The PreDawn sample includes 283 customers all served within one 3.5 hour time window between 2:30 AM and 6:00 AM. The Breakfast sample includes 140 customers and time windows from 7:00 AM until 1:00 PM, and the Lunch/Dinner sample includes 153 customers and time windows from 3:00 PM until 9:00 PM. The Breakfast service window includes one 3-hour time window, in which one third of its customers are served, and five 1-hour time windows. The Lunch/Dinner service window includes two 3-hour time windows, in which 60 percent of its customers are served; six 1-hour time windows; and one 2-hour time window.

Two types of deliveries occur, and service times vary according to this delivery type and the order size. Each customer's address, time window, order size in bins, and delivery type was recorded.

7.1.6 Assumptions

A number of assumptions were required within the modeling system. First, because this delivery service provider places a premium on service quality, all optimizations used hard time windows, guaranteeing that promised delivery times would be met.

Next, service times were developed based on the delivery type, delivery time (PreDawn or other), and the order size. The service time length directly affects how many customers can be served by one truck within the allowable window. Service times have fixed and variable components. The fixed component is lower during the PreDawn service window, and the variable component, which is associated with the number of bins in an order, is lower for one delivery type. The values used in this analysis are used by the case study service in their planning and are based on observed delivery times.

Customer orders are delivered in nestable, stackable plastic bins. These bins are picked up on subsequent orders. Because they nest, they take up little space, and are not considered in the capacity limits of the trucks. In addition, because the bins are returned by customers during their next order, no additional stops occur to pickup bins. This problem is therefore 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.

7.2 ANALYSIS AND SOLUTION METHODOLOGY

The model used in this evaluation is a modified version of the standard ArcGIS vehicle routing problem tool, extended to incorporate CO_2 emissions. Three analyses are developed for this case study to study the impact of different time windows structures, customer density and fleet changes. Twelve scenarios in addition to the baseline are developed for this purpose. These scenarios are presented in the Table 7.1. For each scenario, two different objective functions were optimized to minimize cost (dollars) and emissions (kilograms of CO_2).

Table 7.1: Description of Scenarios

		Description	Service windows	Time windows	density	Capacity (bins)	Cost	emissions factors
	Baseline	Baseline - Predawn Baseline - Breakfast Baseline - Lunch /dinner	3	base	base	90	base	MOVES: single unit short-haul truck
	Scenario 1	New baseline	1	base	base	90	base	base
time windows	Scenario 2	1.5 hr time windows	3	90 minutes	base	90	base	base
	Scenario 3	1 hr time windows	3	60 minutes	base	90	base	base
	Scenario 4	30 min time windows	3	30 minutes	base	90	base	base
	Scenario 5	15 min time windows	3	15 minutes	base	90	base	base
customer density	Scenario 6	50% customer density	3	base	50%	90	base	base
	Scenario 7	33% customer density	3	base	33%	90	base	base
	Scenario 8	25% customer density	3	base	25%	90	base	base
	Scenario 9	12.5% customer density	3	base	12.50%	90	base	base
fleet modification	Scenario 10	hybrid vehicle	3	base	base	90	80% of base	60% of base
	Scenario 11	larger vehicle	3	base	base	150	base	MOVES: combo short-haul truck
	Scenario 12	smaller vehicle	3	base	base	45	base	MOVES: light commercial truck

The hourly costs were kept consistent for all scenarios, since they reflect driver wages and benefits. The mileage costs were kept consistent for all scenarios except the one that considers implementation of a hybrid fleet. For this scenario, the ATRI fuel/oil costs and fuel tax costs were reduced to reflect the 70% improvement in fuel economy reported by the EPA (2006) and leasing and maintenance costs were increased by 25% to reflect additional costs of owning and repairing hybrid vehicles. In the end, the hybrid scenario assumed each mile of travel cost $0.91, a reduction of approximately 20% over standard vehicles.

The scenarios included constraints to ensure work hour regulations were not violated (8 hour limits on each truck), and the truck capacities were not violated (90 totes using current vehicles). The provider currently operates 17 trucks, and this limit was considered the upper bound of the number of allowable vehicles.

Table 7.2 illustrates the number of orders and given or weighted average (denoted with an [a]) time windows for all scenarios. The weighted average time window is given for all Breakfast and Lunch/Dinner scenarios that use the base time window distribution and thus have a mixed set of time windows.

Table 7.2: Number of Orders and Weighted Average of Given Time Windows Size

		PreDawn		Breakfast		Lunch/Dinner	
		Number of Orders	Time Window (minutes)	Number of Orders	Time Window (minutes)	Number of Orders	Time Window (minutes)
Base	Baseline	283	210	140	101a	153	137a
Scenario 1	new baseline	283	210	140	101a	153	137a
Scenario 2	1.5-hour time windows	283	90	140	90	153	90
Scenario 3	1-hour time windows	283	60	140	60	153	60
Scenario 4	30-minute time windows	283	30	140	30	153	30
Scenario 5	15-minute time windows	283	15	140	15	153	15
Scenario 6	50% customer density	142	210	70	103a	76	197a
Scenario 7	33% customer density	94	210	47	111a	51	198a
Scenario 8	25% customer density	70	210	35	98a	39	213a
Scenario 9	12.5% customer density	35	210	17	109a	20	215a
Scenario 10	hybrid vehicles	283	210	140	101a	153	137a
Scenario 11	larger vehicle --> comb. short-haul truck	283	210	140	101a	153	137a
Scenario 12	smaller vehicle --> light commercial truck	283	210	140	101a	153	137a

7.2.1 Base line

Currently, this provider assigns delivery vehicles in three shifts: PreDawn, Breakfast, and Lunch/Dinner. To replicate that baseline, initial optimizations were run for each of the three delivery shifts.

An additional “new baseline” (Scenario 1) was developed with the three shifts merged into one main file, to determine potential gains from redistribution of the time windows within the service windows.

7.2.2 Impact of Time windows on cost and emissions

The extension of the time window affects both customers and the company. Shorter time windows are more convenient for customers, therefore represent higher service quality, but are associated with higher costs and potentially higher emissions for the service provider. If service windows are extended, businesses have greater flexibility on route choice and delivery ordering (which can reduce vehicle miles traveled).

Scenarios 2 to 5 show the impact of time windows. To do so, all orders were reassigned into 90-minute, 60-minute, 30-minute, and 15-minute time windows, respectively.

7.2.3 Impact of density on cost and emissions

Customers grouped in different densities impact cost and emissions because of the different VMT required to serve the same number of customers. Denser neighborhoods allow businesses to reduce cost and emissions level. Scenarios 6 to 9 consider the impact of density and include 50 percent, 33 percent, 25 percent, and 12.5 percent of the original number of orders, respectively.

7.2.4 Fleet changes

Finally, a third evaluation compares the benefits from these earlier analyses with gains achieved by modifying the fleet either to newer and cleaner trucks or by utilization of trucks with different capacity. Cleaner vehicles will likely be associated with reduced emissions, but at a higher cost. Larger vehicles may provide more efficient service, but require a capital investment and have higher externalities per vehicle.

Scenarios 10, 11, and 12 consider the impact of alternative vehicles by adjusting the capacity, cost, and emissions factors representing hybrid, larger, and smaller vehicles. The hybrid vehicles were assumed to have the same capacity as the current fleet, but with more efficient engine technology. The larger vehicles were assumed to be two-thirds larger and carry 150 bins, while the smaller vehicles were assumed to be half the size of the existing fleet and carry 45 bins.

7.3 RESULTS AND TRADE-OFF ANALYSIS

The methodology based on ArcGIS has been applied to solve the scenarios mentioned above. Conclusions regarding the impact of time windows, customer density and fleet upgrade are presented. The outcomes from this case study allow getting insights into the behavior of urban delivery systems and trade-offs between cost, emissions and customer service level.

The heuristics used by ArcGIS to calculate routing and scheduling do not guarantee a global optimal solution but the results in this research are consistent and the heuristics are able to find significant improvements when compared to current operations.

7.3.1 Cost of Lower Emissions

The method described above allows an analysis of the cost of reducing emissions. Figure 7.1 illustrates the relationship between cost in dollars per order and kilograms of CO_2 per order, considering Scenario 2 through Scenario 9, along with the Baseline, grouped by scenario type (base, time window, density). As illustrated, the cost per order increases between \$3.15 and \$3.77 for each additional kilogram of CO_2 for each scenario type, with high r^2 values (0.85 to 0.91). This relationship is very consistent within all of these scenarios and illustrates the close relationship between monetary cost and CO_2 emissions.

This relationship is examined in comparison to the number of orders and the time window length for each case in Figure 7.2. Most of the cases have dollars per kilogram of CO_2 values between 0 and 5, with no discernable relationship to the number of orders or the time window size. Two outliers are observed, each with notably high values of dollars per kilogram of CO_2.

These two figures indicate a stable relationship between monetary cost and CO_2 emissions, with an average value of approximately \$3.50 per kilogram of CO_2.

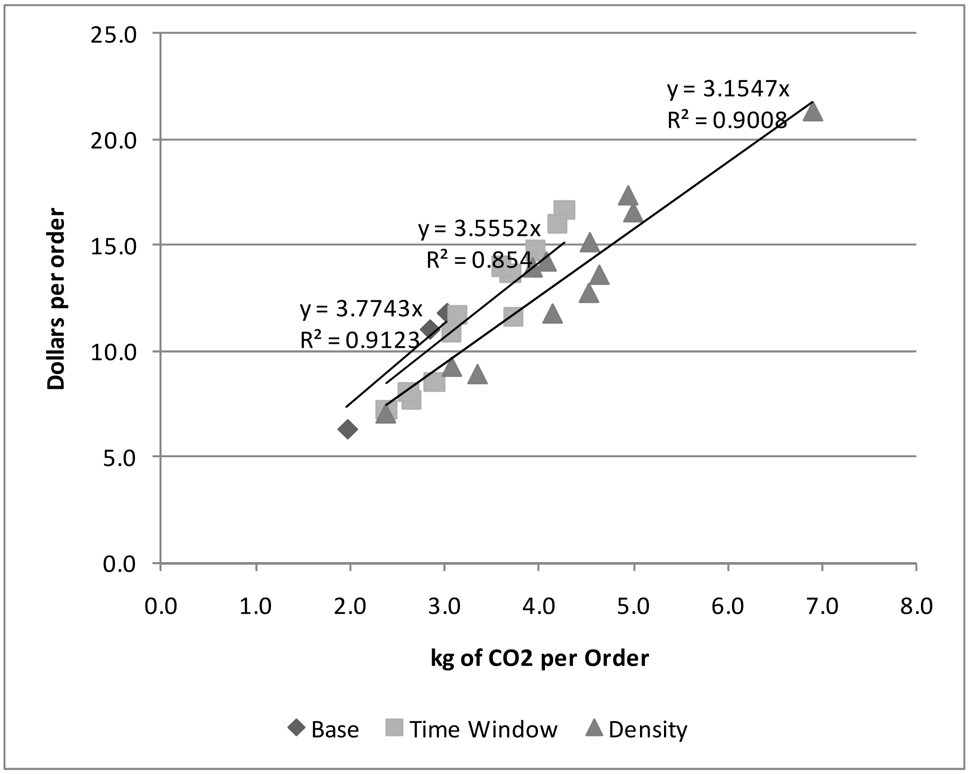


Figure 7.1: Relationship between dollars and kilograms of CO_2.

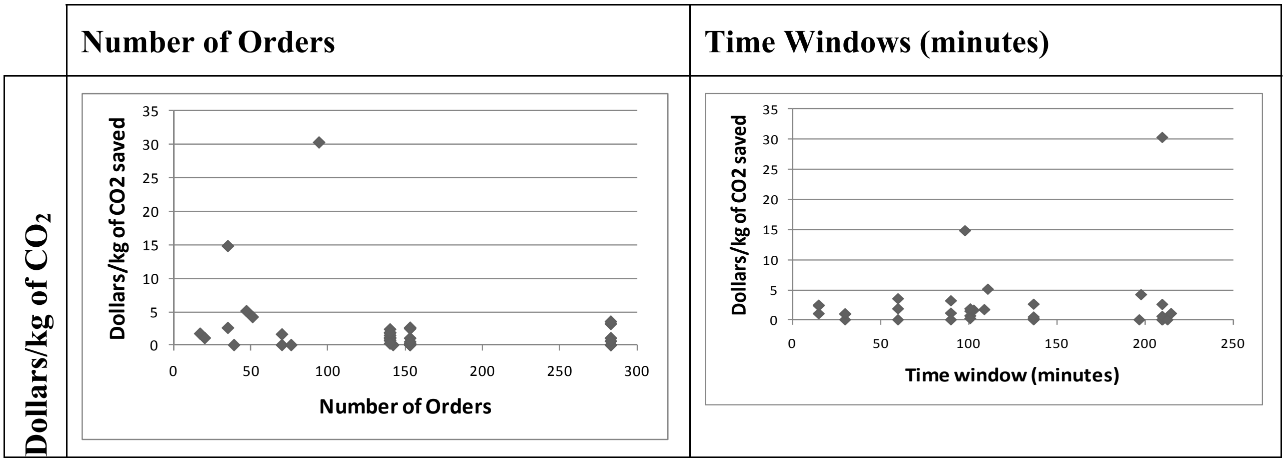


Figure 7.2: Relationship between cost of CO_2, order quantity, and time windows.

7.3.2 Monetary and Environmental Costs of Improved Service

To determine the relationship between service quality and monetary and environmental cost, regression equations were developed considering time window size, number of customers, and monetary cost or CO_2 emissions.

After optimizing on dollars, multiple linear regression indicates the coefficients for time window size and number of customers are significant at the 0.01 level with either dollars or emissions as the dependent variable, resulting in Equation 1 and Equation 3, respectively. After optimizing on emissions, multiple linear regression indicates both coefficients are significant at the 0.01 level with either dollars or emissions as the dependent variable, resulting in Equation 2 and Equation 4, respectively. These results indicate the number of orders is always more influential than the width of the time window, but they are of similar magnitudes. Each additional customer provides roughly the same benefit, in terms of dollars or environmental performance, as an additional minute of time window width.

Intuitively, optimizing on emissions has a baseline increase in monetary cost of \$23.33 - \$21.48 = \$1.85 compared to optimizing on dollars. The monetary cost of serving an order set is more sensitive to the time window length and the number of orders when optimizing on emissions. The coefficient for time window size when optimizing on emissions is -0.040, as opposed to the -0.035 coefficient for time window size when optimizing on dollars. Likewise, the coefficient for number of orders when optimizing on emissions is -0.050, as opposed to the -0.045 coefficient for number of orders when optimizing on dollars.

Also intuitively, the baseline kilograms of CO_2 generated when serving an order set is lower (by 0.88 kg [7.11-6.23kg]) when the routing and scheduling is optimized on emissions. The emissions resulting from serving an order set is more sensitive to the time window length and the number of orders when optimizing on dollars. The coefficient for time window size when optimizing on dollars is -0.010, as opposed to the -0.007 coefficient for time window size when optimizing on emissions. Likewise, the coefficient for number of orders when optimizing on dollars is -0.015, as opposed to the -0.013 coefficient for number of orders when optimizing on emissions.

Using these equations, the influence of customer density and time window length can be quantified. For example, the addition of 80 customers in this service area or extending the time window 100 minutes would save approximately \$3.50 and 1 kilogram of CO_2 per order.

Equation 1: Optimize Dollars, Calculate Dollars per order

$$\delta = -0.035*(\tau) -0.045*(\eta)+21.48$$

Equation 2: Optimize Emissions, Calculate Dollars per order

$$\delta = -0.040*(\tau) -0.050*(\eta)+23.33$$

Equation 3: Optimize Dollars, Calculate Emissions per order

$$\xi=-0.010*(\tau) -0.015*(\eta)+7.11$$

Equation 4: Optimize Emissions, Calculate Emissions per order

$$\xi =-0.007*(\tau)-0.013*(\eta)+6.23$$

With:
τ=time window in minutes,
η=number of orders,
δ=dollars per order,
ξ=kg of CO_2per order

Higher costs and higher emissions per order are associated with fewer orders and shorter time windows (see Figure 7.3 and Figure 7.4). These relationships between cost and emissions to order number and time window length parallel one another, resulting in the consistent cost per kilogram of CO_2 noted above.

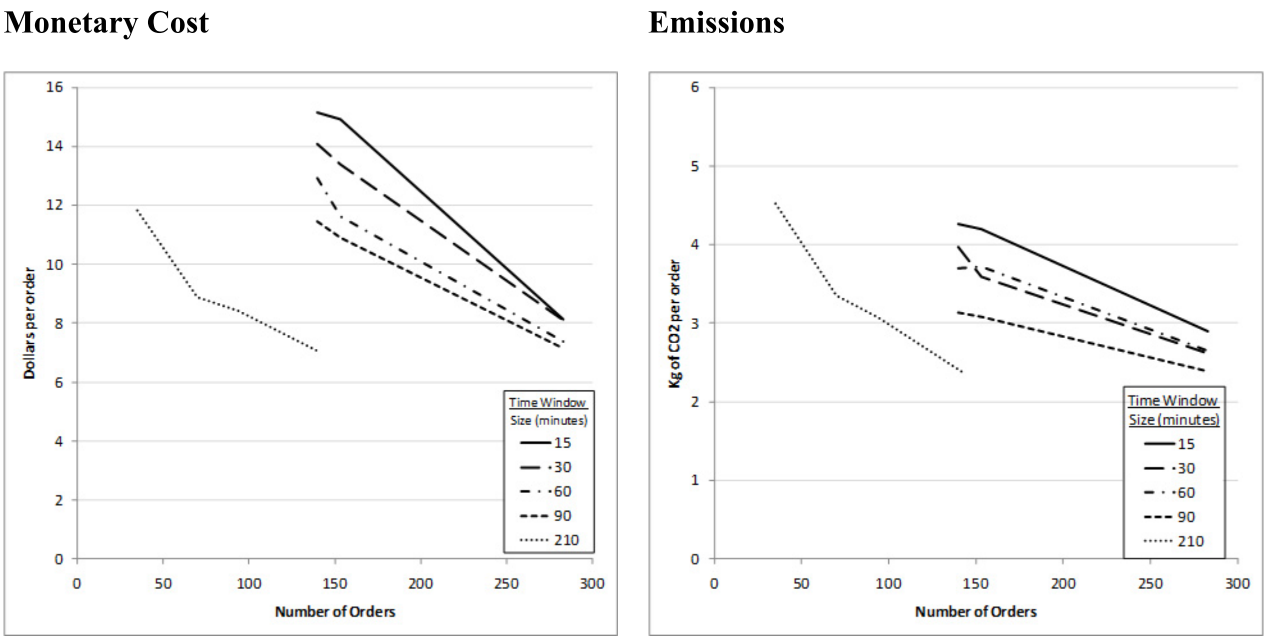


Figure 7.3: Relationship between number of orders and monetary cost or emissions.

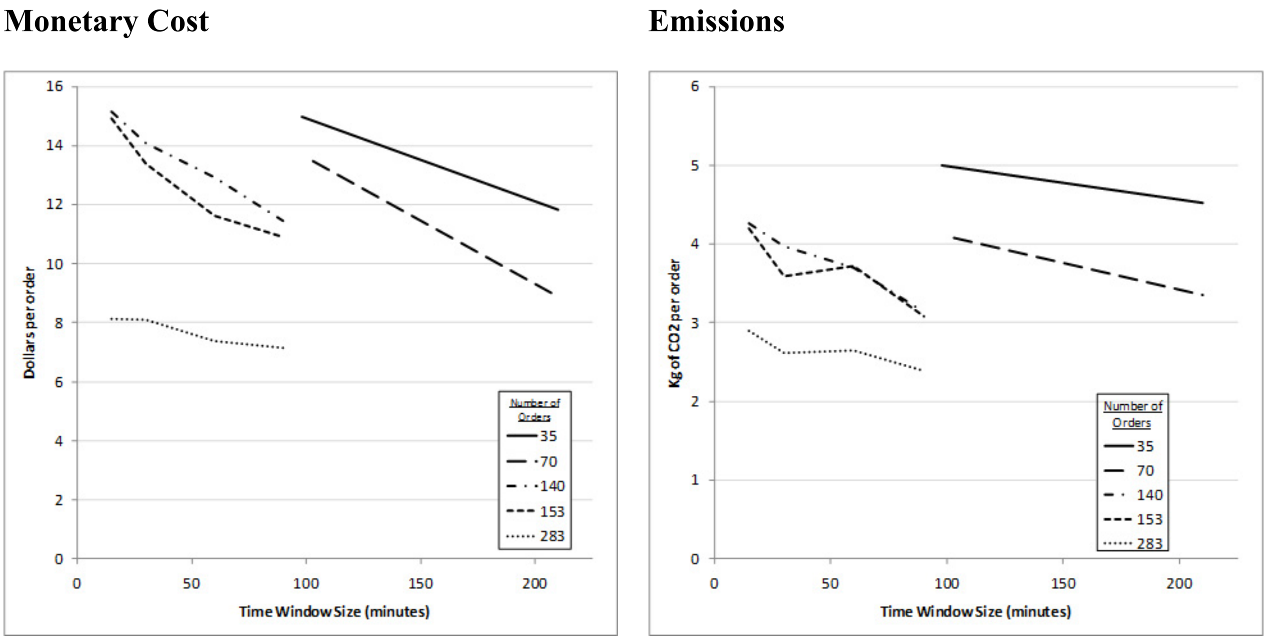


Figure 7.4: Relationship between time window size and monetary cost or emissions.

7.3.3 Influence of Vehicle Fleet

Finally, significant emissions and monetary cost reduction can be made by using hybrid vehicles. For all three service windows, the lowest emissions are observed in the cases with a hybrid fleet of the same capacity as the existing fleet. The routing for the fleet is the same in the base case and the hybrid case, but with the benefit of the reduction in emissions and monetary costs associated with the hybrid vehicles.

The more efficient routing enabled by larger trucks is more than offset by their higher emissions, resulting in net higher emissions than in the base case.

The smaller vehicles yield improved emissions over the base case in some instances, but a 17-vehicle fleet of smaller trucks is not always able to serve the customer base. For the service windows with lower customer demand, smaller vehicles are more efficient than the existing fleet, but less efficient than the hybrid vehicles. For the service window with the largest demand (PreDawn) the smaller vehicles are only able to serve about 70% of the existing demand.

A complete summary of the data is provided in Table 7.3.

Table 7.3: Summary of Output Data

			PreDawn		Breakfast		LunchDinner		Total	
		optimize on	dollars	emissions	dollars	emissions	dollars	emissions	dollars	emissions
	Base	Dollars	1776	555	1618	476	1573	478	4967	1509
		Emissions	1776	555	1653	422	1687	434	5116	1411
	Scen1	Dollars							5614	1710
		Emissions							6287	1376
90 min tw	Scen2	Dollars	2020	681	1605	472	1666	471	5291	1623
		Emissions	2041	674	1640	439	1666	471	5348	1584
60 min TW	Scen3	Dollars	2089	773	1807	577	1778	569	5675	1919
		Emissions	2171	750	1917	517	1778	569	5866	1836
30 min TW	Scen4	Dollars	2288	740	1972	655	2047	642	6307	2037
		Emissions	2288	740	2066	555	2141	550	6495	1845
15 min TW	Scen5	Dollars	2297	929	2120	689	2282	712	6699	2330
		Emissions	2410	818	2335	597	2453	642	7198	2057
50% customer density	Scen6	Dollars	995	337	943	318	893	315	2831	970
		Emissions	995	337	996	285	893	315	2884	937
33% customer density	Scen7	Dollars	791	291	653	225	630	220	2075	736
		Emissions	867	289	712	213	711	200	2290	702
25% customer density	Scen8	Dollars	622	234	524	179	530	181	1676	594
		Emissions	622	234	580	175	530	181	1731	590
12.5% customer	Scen9	Dollars	414	171	341	130	324	121	1079	422
		Emissions	446	158	363	117	347	99	1156	375
hybrid	Scen10	Dollars	1657	333	1514	285	1466	914	4637	1532
		Emissions	1657	333	1561	253	1596	260	4814	847
big truck	Scen11	Dollars	1569	902	1594	937	1490	851	4654	2690
		Emissions	1569	902	1691	884	1490	851	4751	2637
small truck	Scen12	Dollars	1472	344	1811	1086	1760	1053	5044	2483
		Emissions	1480	331	1973	328	2093	334	5546	993

7.4 POLICY ANALYSIS

7.4.1 Impacts on cost and emissions from spatial restrictions

The relationship between monetary cost and CO_2 emissions has been found to be consistent between scenarios at approximately \$3.50 per kilogram of CO_2. These results indicate a direct relationship between monetary cost and emissions, and delivery providers who focus on low cost routing will generally also have low emissions. Since costs and CO_2 emissions of these systems are directly related to distance traveled, the impact on spatial restrictions can be estimated using these results. Spatial restrictions will increase the cost and emissions if compared to current operations. A change in demand or time window requirements would be required to reduce distance travelled.

7.4.2 Time restrictions and spatial considerations

Both customer density and time window length are strongly correlated with the monetary cost and emissions per order. An extra 80 customers in this service area or extending the time window 100 minutes would save approximately \$3.50 and 1 kilogram of CO_2 per order. Given the potential gains and the ability for time window length to mitigate the impacts of customer density, these types of services may be useful for providing necessary resources to rural populations. Government agencies should have further interest in supporting these types of services since they can eliminate food deserts and provide services to home-bound residents.

Beyond providing insight into the trade-offs between costs, emissions, and service quality, these results can also inform delivery providers regarding the relative cost of various business decisions. The cost increases associated with a lower customer density can be offset through wider time windows. Delivery providers looking to expand their service area into less populated regions may be able to do so cost effectively by developing appropriately adjusted time windows. For example, a delivery provider with 90 minute time windows, typically serving 100 customers, can serve 50 customers at the same cost if the time windows are increased to 155 minutes.

7.4.3 Fleet upgrade

The results from the evaluation of four different fleets illustrates significant environmental and monetary gains can be achieved through the use of hybrid vehicles. In addition, the optimal vehicle size for a given customer density and service quality is neither too big nor too small and must be carefully selected to ensure adequate but not excessive capacity. Restricting vehicle size may increase CO_2 emissions by increasing the VMT of the system, and generally should be discouraged in light of CO_2 emissions reduction targets.

8.0 SUMMARY

A summary of the results are presented in this section and they are organized in three sub-sections: Methods, Trade-offs, and Policies. In the Methods sub-section, we explain the strengths and opportunities of the optimization model, metaheuristic, and optimization tools developed in this research. In the Trade-offs sub-section, we summarize the main results from the three case studies and conclude general insights. Finally, in the Policies sub-section, we summarize the policy analysis from each case study.

The three case studies in this research differ in terms of the location and distribution of their customers, type of service offered, type and model year of the vehicles in their fleet, and type of road frequently used. As a result, different methods were developed to take advantage of each case study's features. The Vehicle Routing Problem (VRP) formulated, and the metaheuristics developed to find solutions are designed to solve practical problems in a reasonable amount of time. The final outcomes provide us with insights for the fleets under study and to find common ground so we can make general conclusions regarding trade-offs and policies. By analyzing real operational data (rather than synthesized data), it is possible to realize the diversity in pickup and delivery services and quantify the trade-offs.

8.1 METHODS

The problem solved in this research is a vehicle routing problem for pickup and deliveries, with hard time windows, time dependent links, with a heterogeneous fleet in capacity, and emissions. An optimization model was developed to formulate this problem. However, any VRP problem, and an extension of it, is a NP-hard problem. The computational time to solve this problem grows exponentially when instances increase in size (more customers, more vehicles, more links in the network, etc.).

The objective function minimizes the cost associated with distance and time plus a monetary conversion of emissions. In this way, different objective functions can be implemented and compared. One case can be just minimizing total cost, or total emissions, etc.

Although computers are faster and can solve problems that years before would have taken a lot of time, new formulations, such as ours, for ever more complex extensions require alternative solution methods such as metaheuristics. The problem in this research is a very detailed extension. For this reason, metaheuristics were developed to solve it in reasonable times. These metaheuristics are developed by specifically considering the features of these case studies and have not been tested with other case studies or problem instances. Metaheuristics are typically tested with known benchmarks in order to test quality of the solutions and required solution time. Because the problem here is so novel, there are not benchmark problems yet to provide a comparison.

The first metaheuristic is based on a local search and is applied on the UWMS case study. We can use this approach to test the performance of simple truck assignment rules and compare how they impact cost and emissions. Three assignment rules were tried: by largest capacity, lowest cost per mile, and lowest emissions per mile. The results show the possible improvements in cost and/or emissions when simple concepts are provided to operators.

The second metaheuristic is based on a tabu search approach. This metaheuristic was used to study the Cascade Express case study due to it is complexity and size. A tabu search metaheuristic increases the searchable solution space and it is more likely to find newer and better solutions. In addition, Cascade Express offers both pickup and delivery services, which adds an additional complication to the problem (some customers have to be visited before others.

One challenge with solving problems with metaheuristics is determining how close the solutions are to the global optimal. Our metaheuristics were consistent when inputs were changed. That is a sign of being close to the optimal. Also, our main concern was finding improvements over current operations, which we have consistently been able to do, demonstrating the value of the approach.

Finally, an additional tool was developed to study the Amazon Fresh case study. A more complete routing heuristic was implemented in ArcGIS to account for emissions. This extension uses the existing Network Analyst tool which solves routing and scheduling problems. The extended tool allows enables least-cost, least-time, and least-emissions routing for an urban pickup and delivery system with time windows.

The main reason to use ArcGIS in this case study is the capability to see the location of customers and the flexibility to change the customers' density. Not all the case studies were studied using this tool because only homogenous fleet can be used and it is not possible to have time dependent links. However, the use of a GIS framework allows the millions of possible routes to be evaluated, which would not be feasible in the optimization framework.

Three methods to represent and study each case study were developed. The variety of methods represents the rich features of the companies under analysis. In the next sub-section, a summary of the trade-offs is presented.

8.2 TRADE-OFFS

Several trade-offs were explored. Each case study showed a specific response to a change, and the combination of the three case studies allows for an understanding of the fundamentals of this relationship. The trade-offs studied in this research were: cost/emissions and fleet upgrade, cost/emissions/service and customer density, cost/emissions/service and customer location, cost/emissions/service and congestion, and cost/emissions/service and time window flexibility.

- We found that hybrid vehicles represent a good alternative because they reduce both fuel cost and emissions. Upgrading to hybrid vehicles in the UWMS case overall decreases cost by less than 0.5% and CO_2 emissions up to 33.88%. In the AF case, the cost and emissions reduction are about 7%. The UWMS travels a much shorter total distance that the AF trucks.

- When trucks are upgraded to a newer model year (hybrid vehicles not considered), there is not necessary a reduction in operational cost. The drivers' salary is constant so savings will come from less maintenance cost and fuel consumption. Nonetheless, these upgrades reduce NO_X emissions. For long-haul trucks this reduction can be between 20% and 75% depending on the current fleet composition and what new model year is chosen.

- The benefits of upgrading to larger or smaller trucks depends on the time window structures and demand level. A different mix of trucks in terms of capacity will change the total VMT, either increasing or decreasing it (and therefore emissions).

- From the UWMS and AF case study, it is clear that serving customers more densely located reduces cost and emissions. Nonetheless, the type of network plays a role in the magnitude of the benefit. If customers are located near freeways or highways, as in the Cascade Express case, this reduces the number of routing options that connect customers. Thus, more customers primarily increase the number of stops along a relatively fixed route. If customers are located in an urban area, with a more dense transportation network, there are more routing and sequencing options.

- As it was shown in Table 2.1, there is an average tendency to increase CO_2 emissions when cost increases, approximately 0.3 kg of CO_2 for every additional dollar.

- Congestion and narrower time windows increase cost and emissions. More congestion reduces travel speed which increase fuel consumption, increase emissions, and requires more driving hours to serve the same demand.

- Time window flexibility reduces cost and emissions. In the UWMS analysis, when customers were freely assigned in a day, cost was reduced by an average of 34.8% and emissions by 3.03%. In the Cascade Express case study, the reductions had an average of 3% for both cost and emissions, and from the AF case, extending the time windows an additional 100 minutes saves \$3.5 and 1 Kg of CO_2.

- Wider time windows increase consolidation of customers in a route and reduce the need for additional trucks.

8.3 POLICIES

8.3.1 Internal operational changes are preferred to policy approaches

All internal changes (fleet directed operational changes), are preferred to external policy changes. Internal changes can provide both cost and emissions improvements. In all case studies, these could be found WITHOUT service quality reductions. These improvements can be found through the use of optimization techniques, and because current operations are not already optimized.

Fleet upgrades could be considered internal changes or could be required through policy implementations, but upgrades can provide emissions reductions at limited cost. Changing speed limits can also be considered both internal changes (if the limit is company policy), or external. Depending on the current limit, this can provide both cost and emissions improvements.

External policy changes such as time of day restrictions increase cost and emissions. Costs and emissions are directly related to distance traveled. Spatial restrictions, such as a road or district closure, will increase the total distance travel because they may disrupt the optimal routing. They do not provide benefit to the carrier or the region. These strategies are only effective if they are combined with another change, such as customer demand changes in time and space.

8.3.2 Encourage flexible time windows

More flexible time windows allow for better routing, as well as reducing cost and emissions. This is an example of a change that must be made internal to a fleet, but could be encouraged through better training and analysis tools for fleet operators.

8.3.3 Information exchange

When more information is available, companies can make better decisions, be this through better analysis of current operations, or the ability to find loads to reduce empty truck travel. There are opportunities to reduce cost, emissions, and increase service level if companies are provided with training or analysis tools, or if there is a common platform to create business relationship and cooperation.

8.3.4 Speed limit

Although cost decreases when trucks travel faster (less working hours), CO_2 and NO_X increase after a certain value. We call this value emissions optimal and it was determined to be 60 mph. Cost and emissions reduce by 3% and 1% when vehicles travel at 60mph instead of 55 mph. However, cost reduces by 5% but emissions increase by 6% when vehicles now travel at 65 mph.

8.3.5 Fleet upgrade considering emissions

Vehicles of different technology may provide CO_2 and NO_x benefits with cost reductions (e.g. hybrid). For internal combustion engines, newer trucks reduce NO_X emissions but not necessarily CO_2. Long-haul truck-trailers have the same CO_2 ratio for all the models in the last 16 years while light-duty and medium-duty trucks present reductions in CO_2 over this time period.

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