Evaluation of Emissions Reduction in Urban Pickup Systems

Heterogeneous Fleet Case Study

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A case study of the University of Washington Mailing Service, which operates a heterogeneous fleet of vehicles, provides insight into the impact of operational changes on cost, service quality, and emissions. An emissions minimization problem was formulated and solutions were identified with a creation and local search algorithm based on the I1 and 2-opts heuristics. The algorithm could be used to find many solutions that could improve existing routing on both cost and emissions metrics, reduce emissions by an average of almost 6%, and reduce costs by an average of 9%. More significant cost and emissions savings could be found with service quality reductions. For example, reducing delivery frequency to once a day could lead to emissions and cost savings of close to 35% and 3%, respectively. Rules of thumb for vehicle assignment within heterogeneous fleets were explored to gain an understanding of simple implementations, such as assigning cleaner vehicles to routes with more customers and longer travel distances. This case study identified significant emissions reductions that could be obtained with minimal effects on cost and service and that offered new, practical applications that could be used by fleet managers interested in reducing their carbon footprint.

As commercial vehicle activity grows, the environmental impact is increasingly negative, particularly in urban areas. The transportation sector is the United States' largest producer of carbon dioxide (CO_2) emissions by end use, 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 (*1*).

Vehicle routing minimizes travel cost or travel time for a fleet of vehicles picking up or delivering goods. Most vehicle routing strategies optimize operations for a single operator by minimizing financial cost and do not consider the impact of the operations on 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 urban pickup and delivery systems to urban emissions and the trade-offs between fleet cost, emissions, and service quality. A case study of a local, heterogeneous delivery fleet presents an interesting opportunity for trade-off analysis.

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 companies trying to better understand the business cost of emissions reductions strategies and wanting to develop effective policies for emissions reduction. Results are compared with cost and emissions from existing routing and scheduling techniques used by the case study partner.

CASE STUDY DESCRIPTION

The University of Washington Mailing Service (UWMS) provides pickup and delivery of internal campus mail and U.S. Postal Service mail. It serves the three University of Washington campuses, in Bothell, Seattle, and Tacoma, as well as several 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 fleet is heterogeneous in capacity, mileage costs, and emissions. UWMS operates as fixed and scheduled routing and as a repetitive distribution scheme. The service characteristics are similar to those of other fixed mailing services, transit services, community-supported agriculture deliveries, and waste removal services.

Mail to be delivered is organized at the main (unique) central depot. Mail going to various university departments (or post office boxes) is sorted into respective bins, which are then loaded into trucks depending on route and destination. Each of these bins is delivered to its destination, where a bin of outgoing mail is collected to be processed at the central depot.

UWMS has fixed routes and schedules, so each department knows at what time its mail will be picked up and delivered. Each morning, seven routes serve customers on and near campus. Most departments receive mail during the morning runs, which occur between 8:00 a.m. and noon. Those departments that do not receive morning mail service are serviced in the afternoon, along with several departments that receive a second delivery because of their high volumes of mail. The current service has five afternoon routes. An additional route serves the two university satellite campuses, as well as other university buildings that are not near the main campus. This route services customers during the course of the day.

UWMS provided data for current operations. Information on existing routes includes customers (departments), delivery locations, 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 provided the vehicle number, make, model, year, fuel type, and average cost of fuel per mile for each vehicle in its fleet.

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LITERATURE REVIEW

The vehicle routing problem (VRP) was first formulated by Dantzig et al. and identifies a set of routes to serve customers at minimum cost (*2*). These routes are traveled by homogeneous vehicles that leave from a unique central depot. This model has been extended for a variety of circumstances, such as by Golden et al., who developed heuristics for the heterogeneous VRP for fleets of varying vehicle capacities (*3*).

Little research has been done that integrates vehicle routing with emissions reduction. Many of the existing extensions either compare emissions computed on a per mileage basis, without basing routing decisions on emissions characteristics, or indirectly minimize emissions by reducing miles traveled or avoiding congestion. Work by Quak and de Koster (*4, 5*) and Allen et al. (*6*) measured the impact on emissions of certain policy measures on a broad scale, rather than at the fleet level. Previous work looked at the homogeneous time-dependent VRP, in which vehicles can travel in periods with different speeds, and emissions can be reduced indirectly by avoiding congestion, which encourages travel at optimal speeds, which reduces emissions (*7*).

Previous research addressing emissions focused on several aspects of transportation. For passenger vehicles, Benedek and Rilett optimized on environmental objectives (CO_2, in particular) within traditional traffic assignment methodology on a simulated network (*8*). In transit, Dessouky et al. optimized on cost, service, and environmental performance through simulation of a demand-responsive transit operation, where environmental performance is measured in life-cycle assessment costs (*9*). Focusing on vehicle routing, Palmer developed a vehicle routing method to minimize CO_2 emissions (*10*). Unlike the research presented in this paper, Palmer's methodology does not allow integration of multiple performance measures and does not consider the policy implications or trade-offs between these optimizations. Figliozzi developed a VRP for a homogeneous fleet that minimizes emissions and fuel consumption, where speed is included in the objective function (*11*). Figliozzi developed a case study in Portland, Oregon, to analyze CO_2 emissions for different levels of congestion and speed (*12*). He concluded that minimum emissions can be achieved when vehicles can operate in an emissions-efficient speed range and considered the impact of fleet size and distance traveled.

These models and methodologies show an increasing interest in study of 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 pickup and delivery systems. This paper presents a formulation and a heuristic for this problem and analyzes the results in the context of a specific case study.

FORMULATION

Model

A formulation for the time-dependent VRP with a heterogeneous fleet is provided. This formulation minimizes the sum of a weighted monetary cost based on distance, time, and CO_2. 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 (*13*). Details regarding costs are explained later in the paper.

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

Network Constraints

$$\sum_{v\in V}\sum_{j\in N^{+-}\cup N_{D-}} x_{ij}^{P_0 v}=0 \qquad i\in N_{D^+} \tag{0}$$

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

$$\sum_{p\in P}\sum_{k\in N^{+-}} x_{ik}^{pv}-\sum_{p\in P}\sum_{k\in N^{+-}} x_{kj}^{pv}=0$$
$$\forall i\in N^{+}, \forall i\in N^{-}, \frac{\forall v\in V}{\mathrm{DEM}_{ij}}>0 \tag{2}$$

$$\sum_{p\in P}\left[\sum_{j\in N^{+}\cup N_{D-}} x_{ij}^{pv}\right]=1 \qquad \forall i\in N_{D^+}\ \ \Lambda v\in V \tag{3}$$

$$\sum_{p\in P}\left[\sum_{i\in N^{-}\cup N_{D+}} x_{ij}^{pv}\right]=1 \qquad \forall j\in N_{D^-}\ \ \Lambda v\in V \tag{4}$$

Sequence Constraints

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

$$\sum_{p\in P}\sum_{v\in V}\left[\sum_{k\in N^{-}\cup N_{D+}} x_{kj}^{pv}\right]=\mathrm{CARD}(V) \qquad \forall j\in N_{D-} \tag{6}$$

$$t_i^{v}\leq \sum_{p\in P}\sum_{j\in N^{+}}\left[t_j-C_j-T_{ij}^{p}\right]\times x_{ij}^{pv} \qquad \forall i\in N_{D+}, \forall v\in V \tag{7a}$$

$$t_i^{v}+\sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^{p}\right]\leq t_j^{v}-C_j \qquad \forall i\in N_{D+}, \forall j\in N_{D-}, \forall v\in V \tag{7b}$$

$$t_i+\sum_{v\in V}\sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^{p}\right]\leq t_j-C_j \qquad \forall i\in N^{+}, \frac{\forall j\in N^{-}}{\mathrm{DEM}_{ij}}>0 \tag{7c}$$

$$\sum_{v\in V}\sum_{p\in P}\left[x_{ij}^{pv}\times T_{ij}^{p}-t_i-C_i\right]\leq t_j^{v}-C_j \qquad \forall i\in N^{-}, \forall j\in N_{D-} \tag{7d}$$

Schedule and Time Constraints

$$T_{ij}^{p}+C_j\leq t_j-t_i^{v}+\left(1-x_{ij}^{pv}\right)\times B_1$$
$$\forall i\in N_{D^+}, \forall j\in N^{+-}, \forall v\in V, p\in P \tag{8a}$$

$$T_{ij}^{p}+C_j\leq t_j^{v}-t_i^{v}+\left(1-x_{ij}^{pv}\right)\times B_1$$
$$\forall i\in N_{D^+}, \forall j\in N_{D^-}, \forall v\in V, p\in P \tag{8b}$$

$$T_{ij}^{p}+C_j\leq t_j-t_i+\left(1-x_{ij}^{pv}\right)\times B_1$$
$$\forall i\in N^{+-}, \forall j\in N^{+-}, \forall v\in V, p\in P \tag{8c}$$

$$T_{ij}^{p}+C_j\leq t_j^{v}-t_i+\left(1-x_{ij}^{pv}\right)\times B_1$$
$$\forall i\in N^{+-}, \forall j\in N_{D^-}, \forall v\in V, p\in P \tag{8d}$$

$$L_i^v \leq t_i^v - C_i \leq U_i^v \qquad \forall i \in N_{D^+} \Lambda v \in V \tag{9a}$$

$$L_i \leq t_i - C_i \leq U_i \qquad i \in N^{+-} \tag{9b}$$

$$L_i^v \leq t_i^v - C_i \leq U_i^v \qquad i \in N_{D^-} \tag{9c}$$

$$t_j^v - t_i^v \leq \text{DRIV} \qquad \forall i^+ \in N^+, i^- \in N^-, v \in V \tag{10}$$

$$t_i^v + B_2 \times x_{ij}^{pv} \leq Z_{ij}^p + B_2$$
$$\forall i \in N_{D^+}, \forall j \in N^{+-} \cup N_{D^-}, \forall v \in V, \forall p \in P \tag{11a}$$

$$t_i + B_2 \times x_{ij}^{pv} \leq Z_{ij}^p + B_2$$
$$\forall i \in N^{+-}, \forall j \in N^{+-} \cup N_{D^-}, i \neq j, \forall p \in P \tag{11b}$$

$$t_i^v + Z_{ij}^{p-1} \times x_{ij}^{pv} \geq 0 \qquad \forall i \in N_{D^+}, \forall j \in N^{+-} \cup N_{D^-}, \forall v \in V, \forall p \in P \tag{11c}$$

$$t_i + Z_{ij}^{p-1} \times x_{ij}^{pv} \geq 0$$
$$\forall i \in N^{+-}, \forall j \in N^{+-} \cup N_{D^-}, i \neq j, \forall p \in P \tag{11d}$$

Capacity and Travel Time Constraints

$$b_i^v + \sum_{k \in N^{+-}} \text{DEM}_{kj} - B \leq b_j^v - B \times \sum_{p \in P} x_{ij}^{pv}$$
$$\forall i \in N_{D^+} \cup N^{+-} \cup N_{D^-}, \forall j \in N^{+-} \cup N_{D^-}, i \neq j, v \in V \tag{12}$$

$$b_i^v = 0 \qquad \forall i \in N_{D^+} \Lambda v \in V \tag{13}$$

$$b_i^v \leq B_v \qquad \forall i \in N_{D^-} \Lambda v \in V \tag{14}$$

$$T_{ij}^p = D_{ij} \times S_{ij}^p \qquad \forall i \in N, \forall j \in N, i \neq j, \forall p \in P \tag{15}$$

Variables

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

$$t_i^v \geq 0 \qquad \forall i \in N_{D^+} \cup N_{D^-}, \Lambda v \in V$$

$$t_i \geq 0 \qquad \forall i \in N^{+-}$$

$$b_i^v \geq 0 \qquad \forall i \in N \Lambda v \in V$$

Parameters

C_i = service time for node *i*;
L_i^v and U_i^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_{ij} = demand between nodes *i* and *j*; takes positive values when goods are picked up at *i* and delivered to *j*;
CO^v, CT^v = operational cost per mile and per minute for vehicle *v*, respectively;
TAX = monetary value charged for each kilogram of CO_2;
D_{ij} = distance between nodes *i* and *j*;
S_{ij}^p, T_{ij}^p = speed and travel time from node *i* to node *j* in period *p*; does not depend on vehicle;
EF^{pv} = emission factor for vehicle *v* in traffic period *p*; measured in kilograms of CO_2 per mile;
B_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; and
B_2 = latest possible return time to the depot.

Constraint 0 ensures that variables $x_{ij}^{p_o v}$ related to traffic period 0 are equal to 0 (traffic period 0 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 pickup).

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. Constraints 7*a* to 7*d* ensure the correct time sequencing in the schedules. Constraints 8*a* to 8*d* ensure the arrival time is correct considering time-dependent travel time. Constraints 9*a* to 9*c* ensure time window requirements are met, and Constraint 10 restricts a driver to the maximum time (8 h in this case). Constraints 11*a* to 11*d* ensure that each of the traffic periods is included in the right order. Constraint 12 updates the capacity variable and avoids subtours, Constraint 13 initializes the capacity variables, and Constraint 14 ensures enough space is 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}^{pv} is a binary variable equal to 1 when a vehicle *v* travels from node *i* to *j* in traffic period *p*, t_i^v is the departure and return time from and to the depot for each vehicle *v*, t_i is the departure time from each of the customers *i*, and b_i^v relates to the goods transported by vehicle *v* when leaving node *i*.

Metaheuristic

The presented problem is NP-hard, and the solution time grows exponentially. Thus, a local search metaheuristic is developed to solve this VRP with hard time windows, time-dependent travel times, and a heterogeneous fleet for capacity, emissions, and cost. The objective function is the same as presented earlier and is composed of three factors: distance, time, and CO_2 emissions. These are combined by converting each metric to financial cost in dollars. However, the objective function can also minimize only one or two of the metrics by using 0 for the coefficient on the undesired metric. All constraints are met in the metaheuristic.

Solution Approach

The local search metaheuristic created for this application has both a creation and an improvement algorithm (Figure 1). The creation algorithm is based on the I1 heuristic (*14*), and the improvement

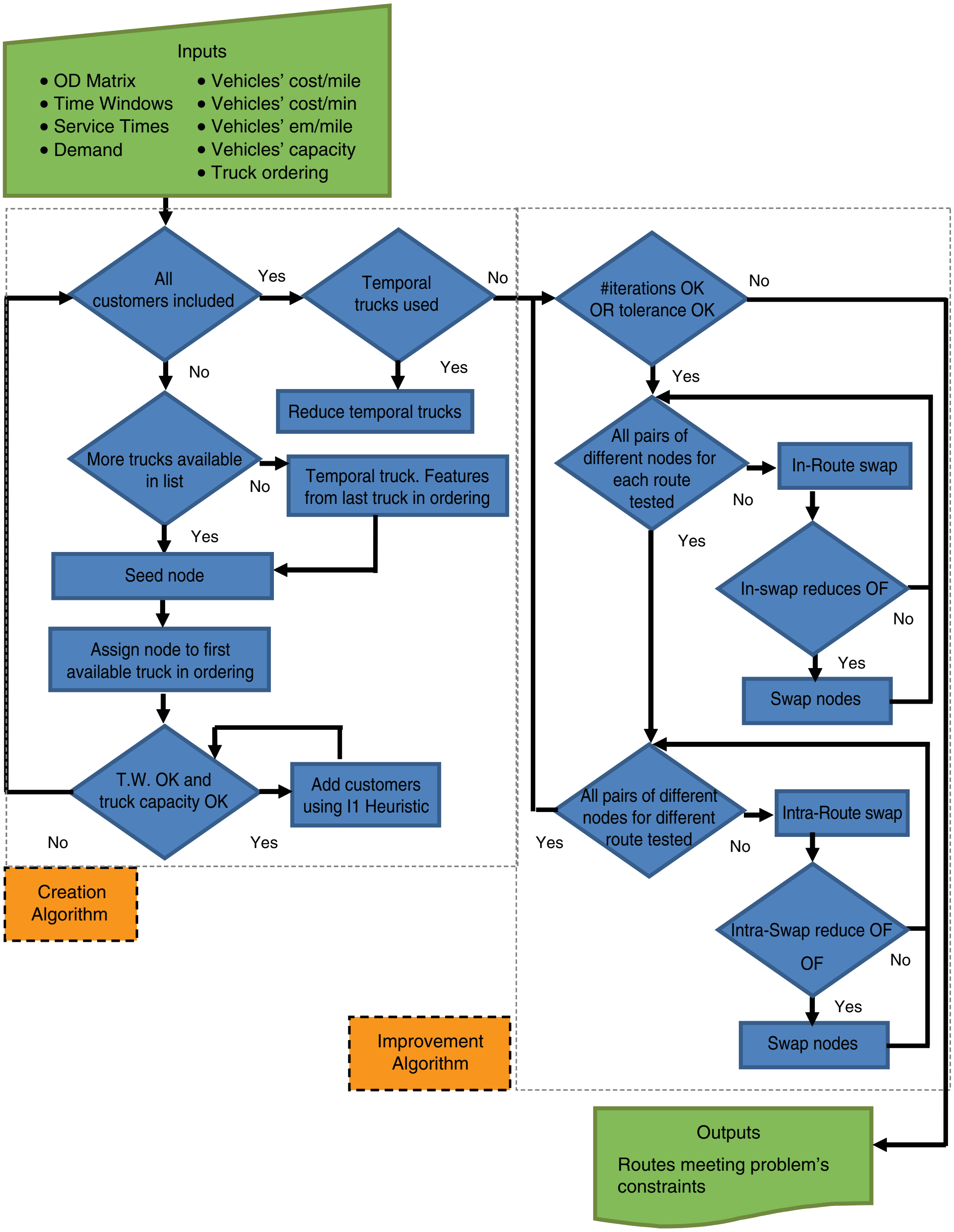

FIGURE 1 Local search metaheuristic process flow: T.W. = time window, OF = objective function.

algorithm is based on applying the 2-opt heuristic to individual and pairs of routes (*15*).

Creation Algorithm

Inputs to the creation algorithm are shown in the top left of Figure 1. For truck 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 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. Two steps are followed to include subsequent customers in a route. First, a weighted sum of distance plus travel time and service time is used to calculate a list of candidate nodes to be inserted (along with their insertion position) into the existing route. This weighted sum is an extension of the heuristic developed by Clarke and Wright (*16*) and has three parameters to control the impact of changes in distance traveled and time added to the route. Each of these parameters took values equal to 0.5 in this research. In the second step, a weighted sum of distance to the depot plus the additional cost (calculated in the first step) to the route is used to choose the best candidate node from the list. 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 affect travel times.

As indicated in Figure 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.

Improvement Algorithm

Once an initial feasible solution is found, the improvement algorithm uses the 2-opt exchange heuristic to improve on the initial solution. The 2-opt heuristic is applied to exchange customers between pair of routes (interroute swap) and within individual routes (in-route swap). The interroute 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 interroute 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. If travel times or emissions are changed because of 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 interroute 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.

CASE STUDY APPLICATION

The described methodology was applied to the UWMS case study. Four scenarios were modeled by varying costs of distance, time, and emissions parameters in the objective function. Scenarios 1, 2, and 3 improve the solutions based on reduced distance (setting the cost of time and emissions to 0), time (setting the cost of distance and emissions to 0), and emissions (setting the cost of distance and time to 0). The costs associated with distance and time were provided by the UWMS ($/mile and $/minute), and the cost associated with emissions was obtained from Klein et al. [12 ($/ton CO_2) for 2005, which is inflated by a 4% annually for a present value of 15 ($/ton CO_2)] (*13*). This cost is not borne directly by the fleet operator and is used only to combine terms in the objective function. Scenario 4 improves the solutions through reductions of distance and time (setting emissions to 0). This scenario best captures the existing fleet's objective.

The preceding 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 first-in–first-out principle when trips depart near the beginning or the end of the congested period (*17*).

Model Inputs

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 and to which they return, were used to develop an origin–destination (O-D) matrix based on miles traveled. Locations were identified in ArcGIS, and the OD Cost Matrix tool was used to develop this matrix.

Service Time

Service time is defined as the time required to deliver and pick up mail, including the time required to walk between departments that are served by one truck stopping location. The service time is reported in minutes. The O-D matrix was used to estimate travel times between customers, assuming that vehicles traveled at 15 mph on and near campus and at 55 mph on freeway connections. 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.

Demand

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

Vehicle Fleet

The existing mailing services fleet used in the analysis consists of seven vehicles. All vehicle attributes, except capacity, were provided by UWMS. The capacity was estimated after a visual inspection of the vehicles. Table 1 provides a summary of fleet input specifics, including emissions factors.

TABLE 1 UWMS Fleet Attributes

Vehicle Description	Year	Capacity (bins)	Fuel Cost ($/mile)	Emissions: 55 mph, freeway (kg CO_2)	Emissions: 15 mph, freeway (kg CO_2)	Emissions: 15 mph, local road (kg CO_2)
Cargo van	2005	22	0.16	0.4289	0.6872	0.7030
Step van	2001	30	0.36	0.4717	0.7667	0.7838
Step van	1995	30	0.44	0.4355	0.7240	0.7413
Step van	1995	30	0.44	0.4355	0.7240	0.7413
Step van	1994	30	0.42	0.4120	0.6890	0.7045
Step van	1994	30	0.42	0.4120	0.6890	0.7045
Box truck	1994	40	0.37	0.8059	1.3972	1.3972

Emissions Factors

Emissions factors were obtained from the U.S. Environmental Protection Agency motor vehicle emissions simulator (MOVES) model. Emissions values are reported in kilograms of CO_2 per mile. The emissions values account for differences in fuel type (unleaded or diesel), routing time of day (morning or afternoon), type of road (freeways or local roads), speed (associated with type of road), and congestion level (associated with speed). Within MOVES, the following settings were used to obtain emissions factors used within the model:

- Calculation type: emission rate;
- Vehicles and equipment: passenger truck (cargo vans), light commercial truck (step vans), single-unit short-haul truck (box truck);
- Fuel: gasoline;
- Age: 1994 to 2005 models;
- Road type: urban restricted access and urban unrestricted access;
- Pollutants and processes: CO_2 equivalent; and
- Speed: 15 and 55 mph.

Within the model, emissions factors for 9:00 a.m. and 2:00 p.m. are used for morning and afternoon delivery runs, respectively. Emissions factors reported in Table 1 are an average of morning and afternoon values, which are within 1% of each other.

Vehicle speed is used to distinguish between congested and uncongested periods. During uncongested periods, vehicles on local (campus) roads are assumed to travel at 15 mph, and vehicles on the freeway are assumed to travel at 55 mph. 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.

Costs

Drivers' wages were calculated on a per-unit time basis. It was determined from a compilation of University of Washington employee salaries that UWMS drivers earn approximately $18 per hour (*18*). Fuel costs provided by UWMS were used to approximate distance-based operational costs for each vehicle (Table 1). Although operational costs typically 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 the hourly costs incurred for drivers.

Time Windows

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. Although certain times, such as the morning, are preferable for mail pickup and delivery, it is assumed that mail could be delivered anytime between 8:00 a.m. and 4:30 p.m. and that customers do not have control over the time at which they are served.

Scenarios

Several scenarios were examined within the case study. For each set of scenarios, the model provides output information, including distance traveled, time required, cost, and emissions.

Base

The existing routing, or base case, was replicated with the vehicle routing tool. Thirteen existing routes are examined. Many of the morning base routes include a break so truck drivers may return to the depot.

Improved

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

Morning and Afternoon Consolidation

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

Single Deliveries

In the single-deliveries scenario, customers who currently receive mail deliveries twice a day experience a reduction in service to once a day.

Fleet Upgrade

In a fleet upgrade, existing step vans are replaced with hybrid versions. Hybrid versions of small delivery vehicles can reduce emissions while improving fuel economy. The results from a 2009 report by the National Renewable Energy Laboratory (where 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%) were used to adjust emissions and fuel economy values to model the effect of this vehicle replacement on fleet operations (*19*).

ANALYSIS AND DISCUSSION

Several conclusions may be drawn from the results of applying the model to the input scenarios. Because the model uses heuristics to find solutions, it does not guarantee a global optimal solution, but results show the heuristics are consistently able to find significant improvements to current operations.

Simple Rerouting

On runs in which 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 in which 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, routing efficiencies can be gained that can improve both costs and emissions. For further comparisons in this paper, the cost and emissions of the base cases were adjusted to discount the cost and emissions associated with the break. The existing policy by which drivers return to the depot for break midway through existing routes increases both cost and emissions of the routes and is clearly inefficient. It would be 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%.

Although the improved routing does not include the existing driver break time, the longest improved route is 2 h 25 min. If breaks are required midmorning and morning runs start at 8:00 a.m., all drivers would be able to return to the depot by 10:25 a.m. for breaks. If breaks were needed earlier than the end of the tour, allowing breaks to occur along the route would eliminate the need to return to the depot midtour, and the distance traveled and emissions would still be reduced.

Consolidation of Morning and Afternoon Customers

When the constraints of 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 increases of 3.47%. In the afternoon consolidation, emissions reductions of 35.15% can be identified though four vehicles with a cost reduction of 4.81%. Depending on the initial ordering of vehicles, emissions can be slightly higher (ordered on capacity and cost) or lower (ordered on emissions) compared with the sum of the base cases.

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%.

Because of the short distances traveled along near-campus routes, the introduction of electric commercial trucks into the UWMS fleet would be operationally feasible. These zero-tailpipe-emissions vehicles not only would significantly reduce emissions but would also reduce costs associated with fuel. Using an electricity rate from the U.S. Department of Energy of $0.0648 per kilowatt hour in Washington State (*20*) and an estimate of 2 kilowatt hours of energy units per mile for electric trucks (*21*), the electricity to operate a truck costs approximately $0.13/mi. If an electric vehicle in the UWMS fleet travels an average of 10 mi 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 the upgrade cost of $5,000 per vehicle.

Fleet Size Reduction

Six vehicles go out each morning for deliveries on near- and on-campus routes, which take an average of approximately 2 h to complete. In the afternoon, four vehicles make shorter near- or on-campus delivery runs, which take approximately 90 min to complete. The UWMS fleet is underutilized. If deliveries were spaced throughout the day and trucks were used more often, the total number of trucks within the fleet could be reduced. With the optimized routings as an example, if vehicles made deliveries up to 8 h per day, only three vehicles would be required to do the same work as the six vehicles do currently. If vehicles made deliveries up to 6 h per day, only four vehicles would be required. Table 2 illustrates this reduction

TABLE 2 Suggested Reductions in Fleet Size

Vehicle	Length of Route Assigned (nearest minute)				Total
Current Assignment					
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 h of delivery)					
Step van	111	128	69	146	454
Step van	80	118	74	128	400
Box truck	238	238	—	—	476
Suggested Assignment (6 h of delivery)					
Step van	111	128	69	—	308
Step van	146	80	128	—	354
Step van	74	238	—	—	316
Box truck	118	238	—	—	356

in fleet size. 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.

Customer Service

UWMS offers a higher quality of service by providing more than one delivery per day. When all customers receive mail delivery service only once a day, costs are decreased by an average of 34.74% (compared with morning and afternoon improved routes), and emissions are reduced by an average of 3.03%. Currently, 23 aggregated customers receive mail twice a day. These customers represent 155 departments, or approximately 20% of all departments served.

Effects of Congestion

Most delivery routes used by UWMS do not have to contend with congestion because they travel on or near campus. The exception is the route that serves the satellite campuses and other off-campus destinations. Most of this route travels along an Interstate, which is often congested during peak hours. The existing routing consolidates these off-campus customers into one route that is served by the vehicle with the lowest emissions. The presented analysis can 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. The impact on cost and emissions of increasing congestion from none through congestion in 1-h increments up to a 5-h period (7:00 a.m. to noon) is shown in Figure 2. The cost evaluated includes only the direct costs of congestion, such as increased time and increased mileage due to 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 steplike. For example, there is a large jump between the emissions impact of 2 and 3 h of congestion, because a constant speed on the link is used (either all or none of the trip is exposed) and because of the specifics of customer location and demand.

Practical Applications for Fleet Managers

The creation heuristic takes vehicle ordering as input. An ordering based on capacity will first assign customers to the largest vehicles, and then assign customers to the smallest vehicles last. An ordering based on emissions will first assign customers to the cleanest vehicles first, and 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 this case study, most vehicles have a similar cost basis, so cost varies little as a function of vehicle ordering. The impact of vehicle order is more apparent when emissions are considered. Within the UWMS fleet, the vehicles with larger capacities have poor emissions, and therefore when the vehicles are ordered by capacity, the largest vehicle is assigned to the most customers and travels a considerable distance. For the morning consolidation, ordering vehicles by emissions and costs results in average emissions reductions of 16.91% and 8.62%, respectively, when compared with ordering vehicles by capacity. The differences among vehicle orderings is greater within the afternoon consolidation because of the smaller number of customers served. Fewer vehicles are used; specifically, when vehicles are ordered by 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 results in average emissions reductions of 45.07% and 41.15%, respectively, compared with ordering vehicles by capacity.

Managers of small fleets of vehicles are less likely to use optimization tools to determine the routing of their vehicles, relying instead on simple rules of thumb. When focusing on reducing emissions, those vehicles with low emissions should be used to the fullest before vehicles with higher emissions are introduced into the routing. This

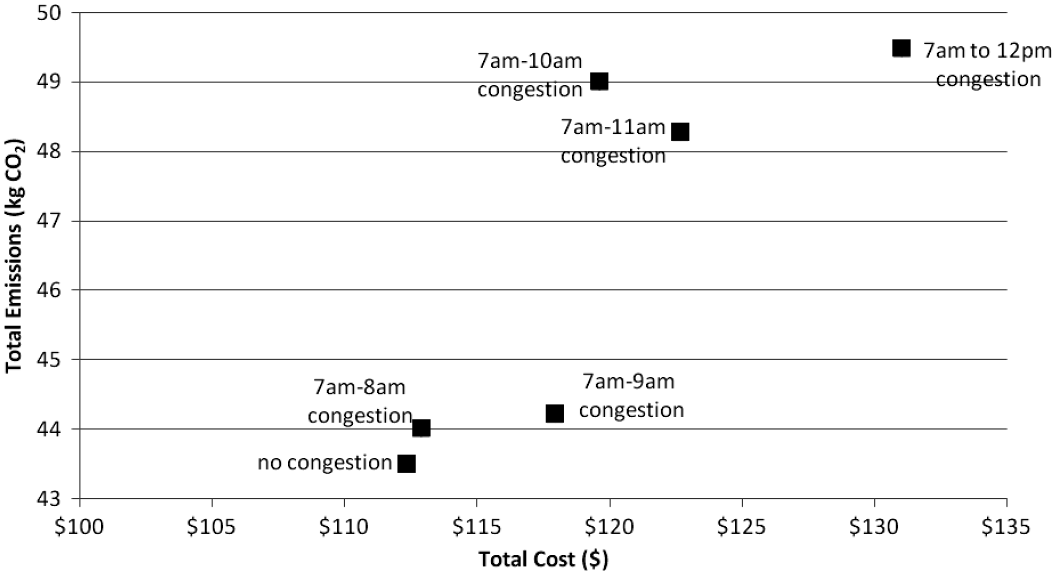

FIGURE 2 Comparison of cost to emissions for increasing periods of congestion.

is contrary to most fleet managers' current approach, which, when minimizing cost, is to use the largest vehicles.

CONCLUSIONS

Although decreasing emissions can increase cost, this case study indicates that numerous operational changes can be made that would reduce both costs and emissions. With the formulation and metaheuristic developed for the UWMS routing, emissions can be reduced by an average of almost 6% while also reducing costs by an average of 9%. Although these are substantial and mutually beneficial improvements identified by the detailed improvements of the routing algorithm, greater improvements are identified through compromises on service frequency, driver break scheduling, and vehicle technology. When delivery frequency is reduced, emissions can be reduced by approximately 3%, but many customers will receive a reduced level of service. Eliminating midroute driver breaks results in emissions reductions of close to 22%, coupled with cost reductions of more than 30%. The introduction of hybrid vehicles into the UWMS fleet can result in emissions reductions of nearly 34%. The results demonstrate the importance of avoiding congestion, which should prompt fleets to consider substantial schedule changes, such as changes to delivery times or frequencies to congested areas.

Because the use of a routing optimization tool is unlikely for many fleet managers, the results of this research highlight several general concepts that can be more easily implemented. As a rule of thumb, in an attempt to reduce emissions, vehicles within a heterogeneous fleet should be assigned to customers in increasing emissions order, with those vehicles with the lower emissions traveling the furthest distances.

As the urgency to reduce emissions increases, both governing agencies and companies are taking more interest in reducing fleet emissions. Understanding the opportunities for emissions reductions, and the implications of these for cost and service quality, is important to supporting development of appropriate policies, penalties, and incentives.

REFERENCES

1. U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1998–2008.* EPA 430-R-10-006. April 15, 2010. http://epa.gov/climatechange/emissions/usinventoryreport.html. Accessed July 14, 2010.
2. Dantzig, G., D. Fulkerson, and S. Johnson. Solution of a Large Scale Traveling Salesman Problem. *Journal of the Operations Research Society of America,* Vol. 2, No. 4, Nov. 1954, pp. 393–410.
3. Golden, B., A. Assad, L. Levy, and F. Gheysens. The Fleet Size and Mix Vehicle Routing Problem. *Computers and Operations Research,* Vol. 11, No. 1, 1984, pp. 49–66.
4. Quak, H. J., and M. B. M. de Koster. Exploring Retailers' Sensitivity to Local Sustainability Policies. *Journal of Operations Management,* Vol. 25, No. 6, 2007, pp. 1103–1122.
5. Quak, H. J., and M. B. M. de Koster. Delivering Goods in Urban Areas: How to Deal with Urban Policy Restrictions and the Environment. *Transportation Science,* Vol. 43, No. 2, May 2009, pp. 211–227.
6. Allen, J., G. Tanner, M. Browne, S. Anderson, G. Christodoulou, and P. Jones. *Modelling Policy Measures and Company Initiatives for Sustainable Urban Distribution: Final Technical Report.* Transport Studies Group, University of Westminster, London, 2003. http://home.wmin.ac.uk/transport/download/sus_u-d_final.pdf. Accessed July 14, 2010.
7. Sbihi, A., and R. W. Eglese. Combinatorial Optimization and Green Logistics. *4OR: A Quarterly Journal of Operations Research,* Vol. 5, No. 2, 2007, pp. 299–116.
8. Benedek, C., and L. Rilett. Equitable Traffic Assignment with Environmental Cost Functions. *ASCE Journal of Transportation Engineering,* Vol. 124, Issue 1, 1998, pp. 16–22.
9. Dessouky, M., M. Rahimi, and M. Weidner. Jointly Optimizing Cost, Service, and Environmental Performance in Demand-Responsive Transit Scheduling. *Transportation Research Part D,* Vol. 8, No. 6, 2003, pp. 433–465.
10. Palmer, A. *The Development of an Integrated Routing and Carbon Dioxide Emissions Model for Goods Vehicles.* PhD dissertation. Cranfield University, Bedfordshire, United Kingdom, 2007. https://dspace.lib.cranfield.ac.uk/bitstream/1826/2547/1/Palmer%2c%20A%20PhD.pdf. Accessed July 14, 2010.
11. Figliozzi, M. Emissions Minimization Vehicle Routing Problem. Presented at 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.
12. Figliozzi, M. The Impacts of Congestion on Time-Definitive Urban Freight Distribution Networks CO_2 Emission Levels: Results from a Case Study in Portland, Oregon. *Transportation Research Part C,* Vol. 19, No. 5, 2011, pp. 766–778.
13. Klein, R. J. T., et al. Inter-relationships Between Adaptation and Mitigation. Climate Change 2007: Impacts, Adaptation and Vulnerability. In *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, eds.), Cambridge University Press, Cambridge, United Kingdom, 2007, pp. 745–777.
14. Solomon, M. Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints. *Operations Research,* Vol. 35, No. 2, 1987, pp. 254–265.
15. Bräysy, O., and M. Gendreau. Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms. *Transportation Science,* Vol. 39, No. 1, 2005, pp. 104–118.
16. Clark, G., and J. W. Wright. Scheduling of Vehicles from a Central Depot to a Number of Delivery Points. *Operations Research,* Vol. 12, No. 4, 1964, pp. 568–581.
17. Ichoua, S., M. Gendreau, and J. Potvin. Vehicle Dispatching with Time-Dependent Travel Times. *European Journal of Operational Research,* Vol. 144, No. 2, 2003, pp. 379–396.
18. *2009 University of Washington List of Employees, Job Title and Salary.* Seattle, Wash. http://lbloom.net/uw09.html. Accessed May 13, 2010.
19. Lammert, M. *Twelve-Month Evaluation of UPS Diesel Hybrid Electric Delivery Vans.* Technical Report NREL/TP-540-44131. National Renewable Energy Laboratory, U.S. Department of Energy, Golden, Colo., 2009.
20. *Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State.* U.S. Energy Information Administration, Independent Statistics and Analysis, U.S. Department of Energy. http://www.eia.doe.gov/electricity/epm/table5_6_a.html. Accessed Nov. 13, 2010.
21. *Electric Truck Demonstration Project Fact Sheet.* Port of Los Angeles, Calif. http://www.portoflosangeles.org/DOC/Electric_Truck_Fact_Sheet.pdf. Accessed Nov. 13, 2010.

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