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Evaluating CO_2 emissions, cost, and service quality trade-offs in an urban delivery system case study

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ABSTRACT

Growing pressure to limit greenhouse gas emissions is changing the way businesses operate. This paper presents the trade-offs between cost, service quality (represented by time window guarantees), and emissions of an urban pickup and delivery system under these changing pressures. A model, developed by the authors in ArcGIS, is used to evaluate these trade-offs for a specific case study involving a real fleet with specific operational characteristics. The problem is modeled as an emissions minimization vehicle routing problem with time windows. Analyses of different external policies and internal operational changes provide insight into the impact of these changes on cost, service quality, and emissions. Specific consideration of the influence of time windows, customer density, and vehicle choice are included.

The results show a stable relationship between monetary cost and kilograms of CO_2, with each kilogram of CO_2 associated with a \$3.50 increase in cost, illustrating the influence of fuel use on both cost and emissions. In addition, customer density and time window length are strongly correlated with monetary cost and kilograms of CO_2 per order. The addition of 80 customers or extending the time window 100 minutes would save approximately \$3.50 and 1 kilogram of CO_2 per order. Lastly, the evaluation of four different fleets illustrates significant environmental and monetary gains can be achieved through the use of hybrid vehicles.

The results demonstrate there is not a trade-off between CO_2 emissions and cost, but that these two metrics trend together. This suggests the most effective way to encourage fleet operators to limit emissions is to increase the cost of fuel or CO_2 production, as this is consistent with current incentives that exist to reduce cost, and therefore emissions.

1. Introduction

The 2010 Inventory of U.S. Greenhouse Gas Emissions and Sinks (covering years 1990 through 2008) indicates the transportation sector produces the largest percentage of emissions from fossil fuel combustion by end-use sector, producing more than 1800 teragrams (Tg) of CO_2 equivalents in 2008 and representing nearly one-third of emissions from fossil fuel combustion [1].

As demand on the world's resources continues to increase, cities, regions, and states find themselves needing to foster economic growth and development while minimizing impacts to the environment. More than one thousand mayors in the United States have signed the Kyoto Protocol, committing to reduce greenhouse gas emissions by 7 percent over 1990 levels by 2012 [2]. Often viewed as a competing interest, those very mayors are struggling to protect their residents' economic and social well-being without compromising the environmental goals they have established. Unfortunately, current business practices and land use patterns often create situations in which these goals do conflict – economic well-being requires extensive use of energy and travel.

This research offers one approach for including emissions into fleet assignment and vehicle routing to consider the trade-offs between monetary costs, emissions impacts, and service quality in residential urban pickup and delivery systems. While emissions from transportation activities are understood at a broad level and between modes, this research looks carefully at emissions for an individual fleet. This approach enables evaluation of the impact of a variety of internal changes and external policies on fleet performance metrics such as time window size, spatial restrictions to target or avoid dense areas, and vehicle size or type restrictions.

2. Theory

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.

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Siikavirta et al., Quak and de Koster, Allen et al., and van Rooijen et al. [3–7] 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. Given the significant contribution of fuel use to both costs and CO_2 emissions, any parameter that restricts the VRP optimization, including constrictive time windows, will likely yield higher costs and emissions.

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 [8]. Quak and de Koster and Allen et al. [4–6] 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.

Overall, the literature supports the theory that in general the goals of the private market (to reduce costs) are frequently aligned with the goals of society (to reduce emissions) and any external restriction on private behavior will limit the effectiveness of those societal goals (see the work of Holguin-Veras [9] for a more thorough discussion of this relationship). This paper continues to test that theory and quantify the magnitude of the effect of external policies on societal goals.

3. Methods

Optimizing the routing of urban pickup and delivery systems generally relies on solutions to the Vehicle Routing Problem (VRP). The VRP is an extension of the traveling salesman problem (TSP), a problem designed to find the shortest route between a number of destinations. The TSP theory originated with actual traveling salesmen needing to optimize their route for visiting a number of destinations before returning to their origin. The VRP extends the TSP to consider multiple routes over a fleet of vehicles, and the vehicle routing problem with time windows (VRPTW) extends the VRP to consider the influence of permitted time windows for stops on the routing solution. Solutions to this problem can improve any service that relies on routing and scheduling including garbage collection, third party logistics providers (UPS, FedEx), and airport shuttles. In general, this class of problems minimizes a particular cost for a fleet of vehicles picking-up or delivering goods. Traditionally, the costs these tools utilize include monetary, distance, and time costs [10]. Other costs of these services, for example noise and air pollution costs, are not currently paid by the fleet and are rarely reflected in VRP solutions.

Few researchers have developed tools for solving the VRP optimizing on emissions. The following research examines different ways to include emissions within a VRP optimization, though each falls short of solving the problem presented in this paper.

Figliozzi [11] has developed an emissions minimization vehicle routing problem (EVRP) solution which explicitly includes emissions in the cost minimization of a traditional vehicle routing problem with time windows. In this model, emissions are directly related to travel speed. To apply his model, Figliozzi modifies the Solomon [12] benchmark problems for vehicle routing problems with hard time windows to reflect the impact of congestion. His evaluation focuses on the impact of congestion on emissions using a simulated data set and does not apply that evaluation to a sample from an existing delivery provider.

Dessouky, Rahimi and Weidner [13] consider trade-offs between cost, service, and environmental performance for a demand-responsive transit operation. Simulating transit operations with a scheduling heuristic and considering life-cycle impacts to the environment, 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.

Palmer [14] modified a vehicle routing problem solution to account for CO_2 emissions by a grocery delivery service. This 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 model is the closest to date at providing a useful model to consider the trade-offs between emissions and service. Because his model requires as an input the cost of CO_2 it does not allow for insight into the appropriate cost of CO_2 to modify behavior.

Benedek and Rilett [15] developed a traditional passenger assignment model using user equilibrium and system optimal cost functions to optimize on CO, 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.

While each of these researchers have made significant progress toward accounting for the environmental impacts of vehicle routing, none accounts for the trade-offs between cost, service, and emissions while allowing optimization of each.

ArcGIS software allows solving routing and scheduling problems. This software includes a complete road network with address data and link cost functions, but it does not estimate emissions from vehicle activity. This research 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. This 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.

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 here to account for emissions when the problem involves shorter than one-hour stops. Based on EPA standards, an engine with 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 most residential urban pickup and delivery systems do not exceed this one-hour threshold.

While the exact details of the heuristic used in the ArcGIS software is proprietary, their help manual [16] indicates shortest paths are identified with Dijkstra's algorithm [17] and order sequencing is completed with a tabu search heuristic [18]. These solutions are well-regarded for quickly producing reasonable results.

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