Formulation of the Parallel Scheduling Vehicle Routing Problem

M. Kaplan[a,b,*], K. Heaslip[b]

[a] Virginia Tech, Blacksburg, VA, USA
marcyk1@vt.edu, kheaslip@utk.edu
[b] Center for Transportation Research, University of Tennessee Knoxville, Knoxville, TN, USA
* Corresponding author

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1 INTRODUCTION

Technology innovation is transforming the last-mile package delivery industry at a rapid pace. Last-mile delivery poses significant challenges in terms of costs, which can account for up to 75% of the total delivery process (Devari et al., 2017; Gevaers et al., 2009). Also, last-mile delivery causes significant environmental impacts, with rising consumer demand exacerbating these issues through increased congestion and emissions (Savelsbergh and Woensel, 2016). Delivery professionals must find ways to leverage these emerging technologies to meet the unique needs of communities. This research integrates the strengths of individual emergent delivery technologies with package characteristics and community needs to meet the demand for equitable, accessible, and inclusive delivery that is also cost-effective. These new opportunities include electric vans, autonomous delivery vehicles (ADVs), drones, and truck-drone systems.

To improve the viability of cost-effective, accessible, and efficient package delivery, delivery professionals need a system model that exemplifies how technology integration can reduce delivery cost. As part of this research, a new Vehicle Routing Problem (VRP) called the Parallel Scheduling Vehicle Routing Problem (PSVRP) is defined to model a fleet of electric vans, ADVs, drones, and truck-drones. It is intended to generalize the Parallel Drone Scheduling VRP (PDSVRP) and therefore is closely related (Mbiadou Saleu et al., 2022, 2018; Murray and Chu, 2015; Ulmer and Thomas, 2018). In general, a PSVRP is where multiple fleets of different types of vehicles are coordinated to deliver packages to a set of customers. The overarching aim is to define a formulation that can minimize operational costs by strategically deploying these varying assets in different scenarios involving disparate customer quantities, customer distributions, depot locations, and package weights.

2 METHODOLOGY

2.1 PSVRP Problem Specification

The PSVRP is a new VRP type that has not been defined previously. However, it is intended to generalize the PDSVRP and therefore is closely related. In a PSVRP, multiple fleets of different types of vehicles are coordinated to deliver packages to a set of customers. In this research, the PSVRP includes a fleet of vans, ADVs, drones, and truck-drones (Figure 1). All vehicles are electric and start and end at the depot, which can represent a distribution center, warehouse, or local store. The vans start at the depot, deliver to each of its assigned customers, and then end at the depot. The ADVs operate similarly but do not have a driver. The drone only delivers one package at a time and returns to the depot after each delivery because they have a more limited flight range. The truck-drone is a system where the truck and the drone assigned to the truck operate in tandem. The truck in the truck-drone system complete deliveries in the same manner as the van and ADV. The drone in the truck-drone system either travels on top of the truck and does not make a delivery, or the drone can depart from the truck at one node, make a single delivery, and rendezvous with the truck at the next node. When the drone travels on top of the truck, it does not use any energy.

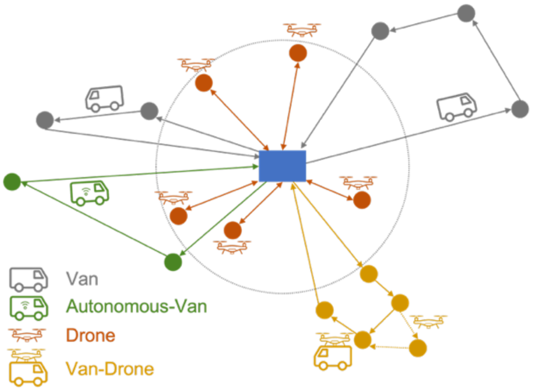

Figure 1 – *The PSVRP Example Solution*

The Mixed-Integer Linear Program (MILP) formulation of the PSVRP is given. The PSVRP formulation defines the objective function and constraints designed to ensure the PSVRP model performs as it would in a real-world implementation. The objective of the PSVRP is to minimize the cost of delivery while utilizing fleets of electric vans, ADVs, drones, and truck-drones. The cost is minimized but is subject to several constraints that ensure the model simulates a real-world environment as closely as possible.

2.2 Solution Methodology

A solution methodology must be developed to solve the formulation defined in the previous section by determining the best routes for the fleet of vehicles. Adaptive Large Neighborhood Search Algorithm (ALNS), introduced by Ropke and Pisinger (2006), is used in this research to solve the PSVRP. Before ALNS can be applied, a complete initial routing solution needs to be developed to solve this 2-echelon VRP. First, a route that includes vans, ADVs, and drones is constructed using the Nearest Neighbor Algorithm. Next, this partial initial solution is improved using a local search heuristic. After, truck-drones are added to the initial solution for nodes where they can further reduce delivery cost. Lastly, this initial solution is further improved with a local search heuristic that tests different string placement. This four-step process creates the initial solution that is implemented in the ALNS after. The ALNS includes three destroy and two repair heuristics: random destroy, worst destroy, cluster destroy, greedy repair, and regret repair.

The ALNS is used to solve the PSVRP for several instances. The instances that are tested were created to trial a wide variety of different scenarios that could be present. The different numbers of customers tested are 10, 50, 100, 250, and 500. Customer demand is defined by package weight. Package weight choices are divided into three categories: small (0 to 5 pounds), medium (5 to 20 pounds), and large (20 to 50 pounds). Four package weight distributions are tested: 1) 33.33% small, 33.33% medium, 33.33% large, 2) 86% small, 7% medium, 7% large, 3) 7% small, 86% medium, 7% large, and 4) 14% small, 43% medium, 43% large. Each of these 20 instances are tested on a 40 x 40 grid with a uniform random customer distribution for both the multi-modal electric van, ADV, drone, and truck-drone fleet, and the base case diesel truck. This allows new delivery technology to be compared to current delivery methods. The electric van, ADV, drone, and truck-drone vehicle specifications, which are the characteristics that each vehicle will have in the instances that are tested, are defined based on existing vehicles in the real world. A diesel truck base case scenario is used to compare the results.

3 RESULTS AND DISCUSSION

The results of solving the PSVRP for all 20 scenarios with the electric van, ADV, drone, and truck-drone combination, and the base diesel truck, are shown in Table 2. Each scenario is run 10 times. The Mann-Whitney U Test statistical analysis was conducted to determine where the cost and emissions difference was statistically significant comparing the new fleet combination to only using diesel trucks. Analysis on the ALNS' performance and trends for which vehicle modes were used, impact of customer number, and impact of package weight distribution was conducted as well.

Table 1 – *ALNS Performance of Each Scenario*

Scenario	z_{cost}	μ_{cost}	z_{emis}	μ_{emis}	$\mu_{cost\ base}$	$\mu_{emis\ base}$	p-value$_{cost}$	p-value$_{emis}$
10-1	83.52	108.90	75.60	98.76	112.33	180.63	0.4272	0.0002***
10-2	15.62	89.12	99.40	98.00	118.50	190.55	0.0257*	0.0002***
10-3	87.78	113.33	79.38	102.58	108.50	174.47	0.4268	0.0002***
10-4	85.07	106.72	77.96	96.70	119.33	191.89	0.0537	0.0002***
50-1	219.63	229.68	200.82	211.10	239.33	384.85	0.0886	0.0002***
50-2	141.78	196.49	200.71	220.27	258.83	416.20	0.0002**	0.0000***
50-3	211.89	227.82	193.31	208.53	245.33	394.50	0.0312*	0.0002***
50-4	214.99	232.24	196.21	212.13	241.50	388.33	0.1857	0.0000***
100-1	293.87	313.05	277.11	295.14	340.33	547.26	0.0017**	0.0002***
100-2	296.96	311.81	290.23	302.95	345.00	554.76	0.0004***	0.0002***
100-3	286.13	312.43	265.94	288.57	338.17	543.77	0.0013**	0.0002***
100-4	298.51	313.97	277.69	290.26	342.50	550.74	0.0017**	0.0002***
250-1	467.09	498.34	447.96	478.16	519.33	835.09	0.0113*	0.0002***
250-2	242.59	446.96	483.52	563.47	514.83	827.85	0.0017**	0.0022**
250-3	271.02	465.74	438.58	499.42	514.33	827.05	0.0028**	0.0028**
250-4	481.01	509.94	448.73	475.98	518.00	832.94	0.5702	0.0002***
500-1	702.19	762.43	675.07	732.39	762.33	1225.83	0.9705	0.0000***
500-2	385.77	710.09	714.66	886.96	763.67	1227.98	0.2121	0.0004***
500-3	699.09	729.56	648.49	679.10	778.50	1251.83	0.0008***	0.0002***
500-4	711.47	767.30	670.13	719.57	767.83	1234.68	0.7336	0.0002***

Note: Cost is in United States dollars ($) and emissions is in pounds of carbon dioxide per mile (lb CO_2/mi); z_{cost} and z_{emis} is the best cost and emissions of the 10 runs, respectively; μ_{cost} and μ_{emis} is the average cost and emissions, respectively; $\mu_{cost\ base}$ and $\mu_{emis\ base}$ is the average cost and emissions, respectively, for the base scenario of diesel trucks; p-value$_{cost}$ and p-value$_{emis}$ is the p-value from the Mann-Whitney U Test for cost and emissions, respectively, to compare the electric van, ADV, drone, and truck-drone fleet to the fleet with only diesel trucks.
Significance Codes: '***'0.001 '**' 0.01 '*' 0.05.

The integration of new delivery technologies (i.e., electric vans, ADVs, drones, and truck-drones) in the PSVRP provides better route planning than more traditional delivery modes because each delivery mode can be applied to the delivery scenario most optimal for its capabilities. The above results highlight the benefit of integrating new delivery modes, especially for environmental benefit. The results also indicate that the cost difference is significant in approximately half of the scenarios. The scenarios with the least and the most customers may not experience a cost reduction from the integration of electric vans, ADVs, drones, and truck-drones. However, several of the scenarios where the 86% small, 7% medium, 7% large package weight distribution was used showed significance in cost. This could be due to the ability for drones and ADVs to deliver a greater percentage of packages since they can only carry lighter weights. Since, these modes are autonomous, their cost is less. The routing benefits of the PSVRP also improve service quality because by optimizing routes, companies can ensure timely deliveries, enhancing customer satisfaction.

4 CONCLUSIONS

Overall, the multi-modal fleet in a PSVRP with electric vans, ADVs, drones, and truck-drones can often make better routing decisions than a traditional delivery fleet because the vehicles have varying capacities, sizes, and capabilities. An additional benefit of this varied fleet is that it can work harmoniously to overcome geographical challenges. For example, a drone can overcome challenging topography by flying over it, while an electric van can make deliveries in more urban areas. The PSVRP formulation provides a powerful tool for optimizing logistics operations; however, its effectiveness can be limited by computational complexities, real-world dynamics, the quality of available data, and implementation cost. Adapting the PSVRP to real-world dynamic changes, such as traffic conditions, customer cancellations, or vehicle breakdowns, can be challenging. The challenge with modeling real-world scenarios increases with limitations regarding data availability, especially since the modes presented in this study are newer.

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