Embedded Hybrid Truck-Drone Delivery Routing Design for Rural Areas – Project 6

Deliverables and Reporting Requirements for UTC Grants Awarded in 2023 (June 2023)

Exhibit D

Recipient/Grant (Contract) Number: The University of Tennessee; Texas A&M University, Grant No. 69-A3552348338

Center Name: Center for Freight Transportation for Efficient and Resilient Supply Chain (FERSC)

Research Priority: Improving Mobility of People and Goods

Principal Investigator(s): Yang Zhou (TAMU), Bruce Wang (TAMU)

Project Partners:

Research Project Funding: $100,000 Federal and $50,000 non-Federal funding

Project Start and End Date: 07/01/2024 – 06/30/2025

Project Description: According to the U.S. Department of Agriculture, around 14% of the U.S. population lives in rural areas, with a higher percentage of seniors and increased poverty rates compared to urban areas. Rural regions face unique challenges such as sparse population density, limited infrastructure, and geographic isolation, leading to economic and social disparities. To address these issues, logistics companies like DHL and UPS have introduced hybrid truck-drone delivery systems for better service coverage. This hybrid system combines the long-range capabilities of trucks with the flexibility of drones for last-mile delivery, offering potential solutions for rural logistic challenges. However, the success of these systems depends on their efficiency, particularly in solving the truck-drone routing problem to optimize delivery routes.

To make TDRP more tractable, existing studies usually tackle truck-drone synchronization in different ways. Two prevalent methods include using trucks as motherships for drone landing operations (also known as dynamic synchronization) and installing static docking hubs as landing stations. Taking advantage of both methods, as shown in Figure 1, our methodology focuses on synchronizing truck-drones at virtual docking hubs – designated meeting points where trucks park and wait for drone landings. The reason is two-fold: (1) installing docking hubs is expensive and often underutilized, especially in rural areas with dispersed and low delivery demand; (2) dynamic synchronization at arbitrary locations is usually infeasible due to landing restrictions. This project introduces virtual docking hubs, designated meeting points selected from landing-free and parking-free locations. Trucks park at the virtual docking hub, transforming into physical docking points for drones to land and recharge after completing their deliveries.

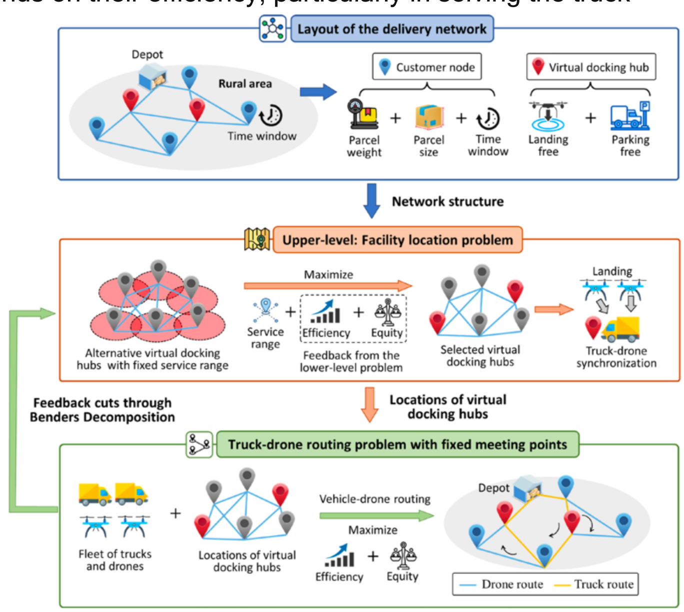

Figure 1. Illustration of research plan

However, the delivery efficiency is highly sensitive to the locations of virtual docking hubs, necessitating the integration of hub location planning into TDRP. This combination further complicates the problem, as it adds another layer of decision-making coupled with routing plans. To manage the complexity, we will formulate TDRP as a two-stage problem using decomposition techniques like Benders Decomposition, which separates the integrated optimization problem into an upper-level facility location problem, and a lower-level truck- drone routing problem with fixed meeting points. We solve these two manageable subproblems iteratively, with the lower-level problem feeding back costs and feasibility to the upper-level problem through continuously generating and adding Benders cuts –

additional constraints that refine the solution space.

In our solution framework, the upper-level problem is provided with a set of potential locations for virtual docking hubs, each assigned varying radii defining their fixed service ranges. The operator determines a subset of these locations as virtual docking hubs for the lower-level problem, with the objective of maximizing the total service coverage and a proxy variable representing the routing efficiency and measures of the lower-level problem. Given that the upper-level problem is relatively tractable - owing to the significantly smaller number of potential hub locations compared to the Origin-Destination nodes in the lower-level problem, we will solve the upper-level problem using advanced optimization solvers such as Gurobi and CPLEX.

With the locations of virtual docking hubs determined, the lower-level problem focus on optimizing routes for trucks and drones to jointly maximize efficiency (minimizing travel time) and service. Here, service waiting time is defined as the deviation of actual service time from its ideal service time (i.e., directly served by a dedicated vehicle using the shortest path). Therefore, we minimize the gap between the longest and shortest service waiting times experienced by different customer, ensuring that all customers receive a consistent service level. To account for the varying levels of urgency among different orders, we will incorporate time-window constraints to prioritize time-sensitive parcels.

In summary, this project aims to propose an embedded hybrid truck-drone delivery system for rural areas. The upper-level problem deals with facility location for virtual docking hubs to maximize service coverage. The lower-level problem addresses an embedded truck-drone routing problem with time windows, aiming to jointly maximize delivery efficiency and service. Our solving framework guarantees convergence to near-optimal solutions. Additionally, sensitivity analysis will be conducted on the efficiency objectives to offer insights into achieving an optimal balance in various rural and delivery resource settings.

The deliverables will comprise: (1) A functional mathematical model and customized solution approach for optimizing efficiency in the rural truck-drone delivery system; (2) Comprehensive documentation of project findings, methodologies, and analyses.

US DOT Priorities: This research aligns with USDOT's goals by ensuring access to essential goods in rural areas through optimized delivery routing. To bridge the aforementioned gaps and align with the FERSC's goal of enhancing multimodal freight system planning and tackling rural issues, this project focuses on developing an embedded hybrid truck-drone delivery routing approach, to simultaneously enhance the efficiency of delivery services in rural communities, offering benefits such as access to essential resource, lower delivery costs, and broader service areas.

Outputs: This research achieves its mission through various levels of effort, including community workshops and demonstrations (e.g., to Navasota and Texas DOT), as well as participation in academic conferences (e.g., TRB, IEEE ITSC), seminars, and journal publications (e.g., Transportation Research Part C). Additionally, the research findings and methodologies will be integrated into educational content, such as the "Transportation Engineering" course taught by PI Zhou and PI Wang. The project outcomes will also be showcased at community events, including Texas A&M Engineering Project Showcase, Civil Engineering Poster Showcase, annual FERSC meeting.

Outcomes/Impacts: This research aims to innovate in the field of efficient delivery systems in rural areas by proposing a hybrid truck-drone model to address the challenges faced by these communities. This study introduces a hybrid delivery system combining trucks and autonomous drones, designed to improve access and reduce delivery costs, thereby enhancing the quality of life for rural residents. The methodology encompasses developing a comprehensive mathematical model for the delivery routing problem, prioritizing service requests based on urgency and necessity. Through the application of advanced decomposition techniques and heuristic algorithms, this research seeks to offer a scalable solution that balances efficiency, potentially revolutionizing delivery services in rural settings. The anticipated outcomes include not only better access to essential services but also operational cost reductions, making this approach a viable model for enhancing rural delivery logistics.