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Lifecycle modeling and assessment of unmanned aerial vehicles (Drones) CO_2e emissions

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ABSTRACT

There are no studies that model the potential effectiveness of Unmanned Aerial Vehicles (UAVs) or drones to reduce CO_2e lifecycle (including both utilization and vehicle phase) emissions when compared to conventional diesel vans, electric trucks, electric vans, and tricycles. This study presents a novel analysis of lifecycle UAV and ground commercial vehicles CO_2e emissions. Different route and customer configurations are modeled analytically. Utilizing real-word data, tradeoffs and comparative advantages of UAVs are discussed. Breakeven points for operational emissions are obtained and the results clearly indicate that UAVs are more CO_2e efficient, for small payloads, than conventional diesel vans in a per-distance basis. Drastically different results are obtained when customers can be grouped in a delivery route. UAV deliveries are not more CO_2e efficient than tricycle or electric van delivery services if a few customers can be grouped in a route. Vehicle phase CO_2e emissions for UAVs are significant and must be taken into account. Ground vehicles are more efficient when comparing vehicles production and disposal emissions per delivery.

1. Introduction

Transportation accounts for a large share of total GHG emissions in most developed countries (Hertwich and Peters, 2009). Unmanned aerial vehicles (UAVs) have the potential to reduce costs and delivery times, but their potential impact on energy consumption and greenhouse gas (GHG) emissions is currently understudied. The real-world analysis conducted in this research is based on UAVs with electric engines because safety, noise, and pollution problems are likely to hinder the urban deployment of UAVs with internal combustion engines. However, the modeling approach can be applied to any type of UAV.

The focus of this research is on emissions tradeoffs between UAVs and different types of ground delivery vehicles. It has been correctly argued that the analysis of transportation systems energy and emissions levels should include not only direct tailpipe emissions but also emissions associated to vehicle production and disposal, the fuel/energy source, and required transportation infrastructure (Chester and Horvath, 2009). Lifecycle assessment (LCA) of vehicle emissions provides a more comprehensive view of transportation emissions that the traditional approach based on tailpipe emissions.

LCA separates emissions along life cycles or phases: extraction of raw materials from the earth, materials processing, manufacturing, distribution, product use and disposal or recycling at the end. We compare last-mile UAVs and ground vehicles lifecycle CO_2e emissions in two distinct phases: (a) vehicle utilization and (b) vehicle production/disposal. In this research ground vehicle emissions associated to utilization includes well-to-tank (WTT) – the lifecycle of fuel production and distribution – and tank-to-wheel (TTW) or direct tailpipe emissions. These concepts are extended for the aerial vehicle or aircraft with an electric engine; for the UAV

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WTT emissions are replaced by generation-to-battery (GTB) and TTW emissions are replaced by battery-to-propeller (BTP) emissions. The vehicle phase (b) includes emissions from materials extraction and processing, manufacturing, distribution, and vehicle disposal or recycling but without considering vehicle utilization.

Unlike previous research efforts, this research compares UAV emissions not only against conventional diesel vehicles but also against more environmentally friendly electric trucks and electric tricycles. In addition, both operation and vehicle CO_2e (carbon dioxide equivalent) emission phases are analyzed. The focus is on the derivation of breakeven points for the utilization phase as a function of the number of customer deliveries and other logistical parameters such as relative energy efficiency, service area size, and depot-service area distance. Vehicle phase emissions per delivery are also estimated and compared with emissions from the utilization phase.

2. Literature review

Potential advantages and disadvantages of UAVs have been already considered by logistics companies. For example, the logistics services company DHL has identified higher last-mile efficiency, reduction of accidents, and faster deliveries as key potential UAV benefits; key potential challenges associated to UAVs are security, privacy, congestion, and regulatory concerns (Heutger and Kuckelhaus, 2014). Recently, UAVs have been featured frequently in the media following announcements made by large corporations such as Amazon (Anderson, 2014) but less frequently in the logistics academic literature.

The academic literature has already documented the advantages that UAVs can provide to deliver medicines in remote locations (Thiels et al., 2015). Other researchers have analyzed UAVs potential applications and challenges (Mohammed et al., 2014) and some authors have focused on the regulatory barriers that can preclude large UAV deployments (Boyle, 2015).

The academic literature discussing UAVs pros and cons or attempting to model UAV performance is rather scant. D'Andrea (2014) provided a succinct and preliminary discussion and modeling of UAV energy usage and delivery costs. Payload, lift-to-drag ratio, headwind, and travel speed do have a significant impact on UAV performance (D'Andrea, 2014).

Regarding UAV operational emissions, Goodchild and Toy (2017) compared VMT and CO_2 emissions when deliveries are made by UAVs and conventional trucks. Real-world land use data and a GIS based approach was utilized to estimate customer locations and travel distances. The impact of different UAV energy consumption and emission levels were analyzed numerically. Truck emissions were a function of travel distance, vehicle year, and travel speed. Results suggest that UAVs emit less emissions when customers are located close to the depot and trucks emit less for faraway customers. The authors suggested that UAVs and trucks can complement each other. The idea of utilizing both UAV and trucks to improve overall delivery efficiency has also been analyzed by several authors but focusing on the actual design of routes and logistics systems (Mathew et al., 2015; Murray and Chu, 2015; Wang et al., 2017). Unlike this research, Goodchild and Toy (2017) do not estimate vehicle phase emissions or compare UAVs against cleaner ground vehicles such as tricycles or electric vehicles. In addition, this research provides detailed analytical formulas to estimate UAV emissions as a function of distance of payload or the number of stops (one-to-one and one-to-many service configurations).

Regarding UAV energy consumption, Choi and Schonfeld (2017) model the impact of battery capacity on payloads and flight ranges. Numerical analysis is utilized to optimize the drone fleet size and minimize delivery costs. This study concludes that UAV deliveries are more economical in areas with high customer density and that improved battery technology can significantly reduce UAV fleet size. There are tradeoffs associated to delivery speeds but clear benefits from longer hours of operation. Many papers in the applied electronics and engine control areas have focused on UAV technology, software, and design issues; these papers, for example Bristeau et al. (2011), are not reviewed herein because they are not directly relevant to the topic discussed in this paper.

Summarizing, there is a consensus in the literature that remote areas and dense urban areas are seen as promising environments for UAV deployment. Unlike previous research efforts, this research compares UAV emissions not only against conventional diesel vehicles but also against more environmentally friendly electric trucks and electric tricycles. Another contribution of this research is the analysis of vehicle production and disposal CO_2e emissions and the derivation of formulas to estimate breakeven points for one-to-one and one-to-many route configurations. To the best of the author's knowledge, there are no scholarly articles that have analyzed and compared lifecycle CO_2e emissions of UAVs and different ground vehicle types.

3. Modeling UAV steady flight energy consumption

Before estimating UAV emissions it is first necessary to estimate UAV energy consumption. There are many factors that affect airborne vehicles energy consumption. Drag, lift, weight, and thrust forces act over any self-propelled airborne vehicle such as airplanes, helicopters, and UAVs (Anderson and Eberhardt, 2001).

Maintaining a steady level flight requires a balance of forces, i.e. an equilibrium of all the forces acting upon an airborne vehicle. According to Newton's second law, any object moving in a steady level trajectory at a constant velocity has zero acceleration, all forces applied to the aircraft are balanced. For an airborne vehicle in a steady level trajectory there are four relevant forces: (i) weight, the force of gravity that acts in a downward direction, (ii) thrust, the force that propels the airborne vehicle in the direction of motion, (iii) lift, the force that acts at a right angle to the direction of motion through the air, and (iv) drag, the force that acts opposite to the direction of motion. When there is zero acceleration, level flight at a constant velocity, the lift balances the weight and the thrust balances the drag (Anderson and Eberhardt, 2001; D'Andrea, 2014).

$$\mathrm{L} = \mathrm{W}, \mathrm{D} = \mathrm{T} \text{ and } \frac{\mathrm{L}}{\mathrm{D}}\mathrm{T} = mg$$