Potential Energy, Fuel Savings and Emission Reduction of Tubular Network

Abstract

The Tubular Network is poised to revolutionize urban logistics by introducing an innovative underground tunnel-based delivery system. This paper undertakes a comprehensive analysis of the energy efficiency, environmental benefits, and cost-effectiveness of the Tubular Network in comparison to existing delivery methods.

Methodology: To gauge the Tubular Network's performance, we utilized the specifications of a standard hoverboard battery, estimating the energy consumption, greenhouse gas emissions, and fuel expenses associated with a tubular shuttle powered by two such batteries.

Key Findings:

1. Energy Efficiency: Our calculations reveal that the tubular shuttle boasts remarkable energy efficiency, consuming only 0.078 MJ per kilometer traveled.
2. Emissions Reduction: When compared to traditional diesel vans and small quadcopter drones, the Tubular Network demonstrates substantial environmental advantages. It reduces greenhouse gas emissions by 94% when compared to diesel vans and by 61% in comparison to quadcopter drones.
3. Cost Savings: From a cost perspective, the Tubular Network stands out as an economical choice, offering a 98% reduction in fuel costs when compared to diesel vans and a 62% reduction in comparison to quadcopter drones.

Overall Efficiency:

In a comprehensive evaluation, our Tubular Network shuttle emerges as the most eco-friendly option in terms of greenhouse gas emissions per unit distance and per package delivered, surpassing traditional trucks, drones, robots, and e-cargo bikes. It also demonstrates exceptional efficiency in terms of energy consumption and fuel costs per unit distance or per package delivered. The Tubular Network is not only a visionary approach to urban logistics but a sustainable, cost-effective, and environmentally responsible solution to modern delivery challenges. This research highlights its potential to reshape the way we approach last-mile delivery, benefiting both urban environments and the economy.

Introduction

Road freight delivery is a large source of greenhouse gas emissions. In the United States, the transportation sector emitted 27% of greenhouse gasses, more than any other industry. Light-duty vehicles held a 57% share of the transportation sector, and medium- and heavy-duty vehicles held a 26% share [1]. Furthermore, road freight consumes roughly half of all diesel produced, and experts predict that road freight activity in 2050 will more than double that of 2015 [2]. To reduce emissions, innovations are needed in the road freight delivery system.

Tubular Network aims to decarbonize the transport of goods. Our tubular shuttle will operate in such above ground or underground tunnels at speeds of 60 miles per hour and will carry payloads of up to 30 pounds. We estimate that the average use case for the shuttle will be half mile deliveries, but our shuttle will be able to make delivery trips of up to five miles one way.

In this white paper, we analyze the 1. energy consumption, 2. greenhouse gas emissions, and 3. fuel costs per unit distance and per package of our tubular shuttle and compare it with various other delivery modes. Our analysis includes conventional delivery vehicles such as medium-duty trucks and light-duty vans (both diesel and electric) as well as electric cargo bikes. We also incorporate comparisons with other delivery robots, namely road autonomous delivery vehicles (RADRs), sidewalk autonomous delivery vehicles (SADRs), and large and small drones.

We utilized the projected specifications of the tubular shuttle currently in development to estimate its energy consumption, greenhouse gas emissions, and fuel costs. Our current tubular shuttle will run on two hoverboard batteries (e.g. Hover-1 Titan batteries or similar). On average, Tubular shuttle will make half mile one-way deliveries on average and five-mile one-way deliveries at maximum. We compared these results with other values from existing literature. Based on this analysis, we find that our tubular network shuttles are more efficient in terms of energy, emissions, and fuel costs per unit distance than all other modes considered and are one of the most efficient modes along these metrics per package delivered.

Results

Energy Consumption

First, we studied the energy consumption of the tubular shuttle in comparison with the other various delivery modes. We found that the tubular shuttle and the small drone have the lowest energy consumptions per unit distance of all the delivery modes examined in this study. In terms of energy consumption per package, the tubular shuttle surpasses all other delivery vehicles except the electric cargo bikes examined in this study. Figure 1A shows the energy consumptions per unit distance for each delivery mode, and Figure 1B shows their energy consumptions per package.

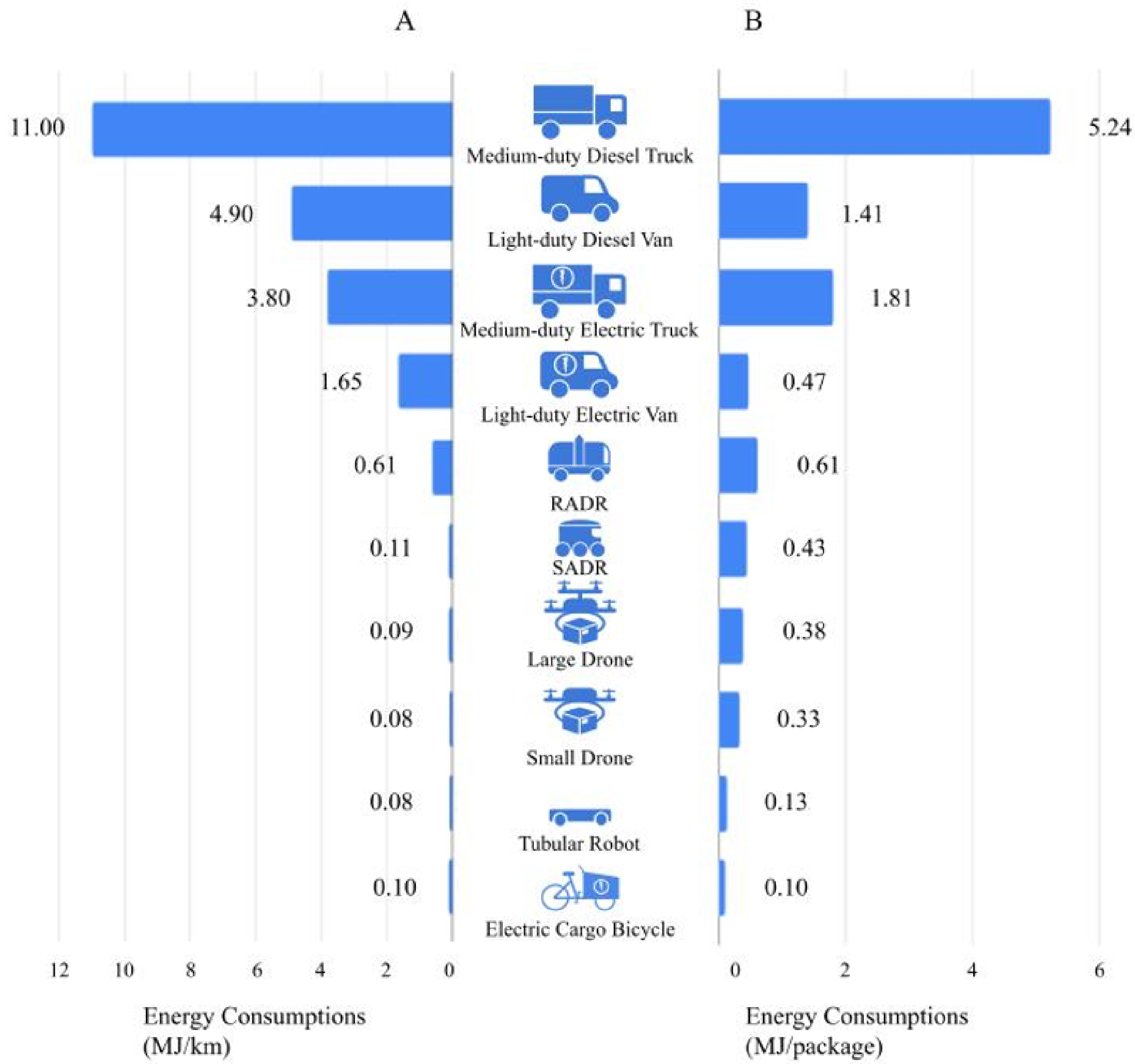

Figure 1 - Energy Consumptions of Various Delivery Modes

Greenhouse Gas Emissions

Next, we examined the greenhouse gas emissions for each delivery mode. In this study, we considered greenhouse gas emissions from fuel and upstream greenhouse gas emissions for both diesel and electricity. As shown in Figure 2A, Tubular Shuttle generated the least total greenhouse gas emissions per unit distance or per package delivered compared to SADR, large drone, small drone, and electric cargo bike. Thus, the greenhouse gas emissions per package of the tubular robot far outpaces all other delivery modes, as seen in Figure 2A and 2B.

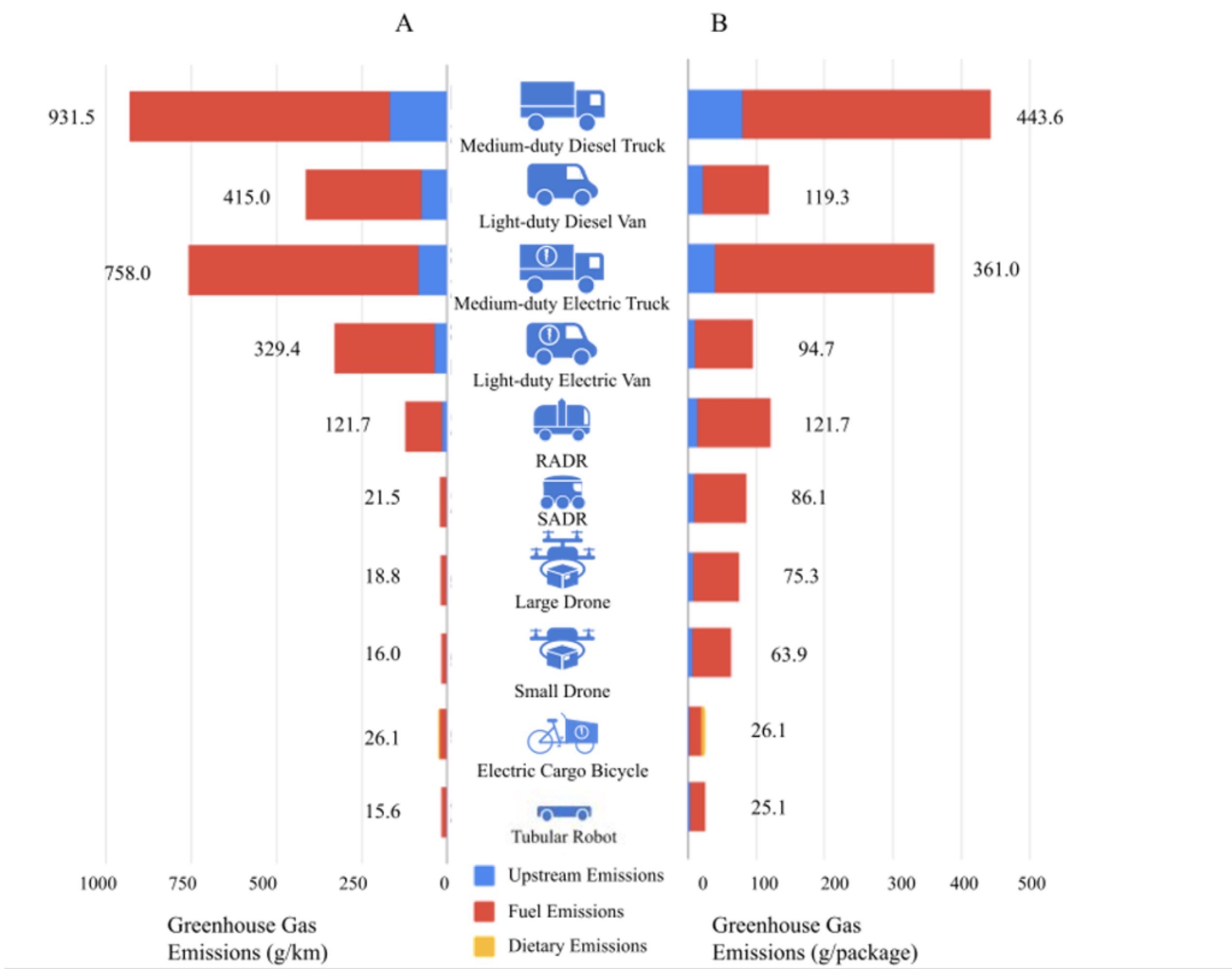

Figure 2 - Greenhouse Gas Emissions of Various Delivery Modes

Fuel Costs

Lastly, we looked at the fuel costs for each delivery mode. Once again, we found that the SADR, large drone, small drone, tubular robot, and electric bike have cheaper fueling costs per unit distance than the other delivery modes but that the electric bike and tubular robot are cheaper than all other delivery modes when examining per package delivery. Figure 3A shows the fueling costs per unit distance of each delivery mode, and Figure 3B shows their fueling costs per package.

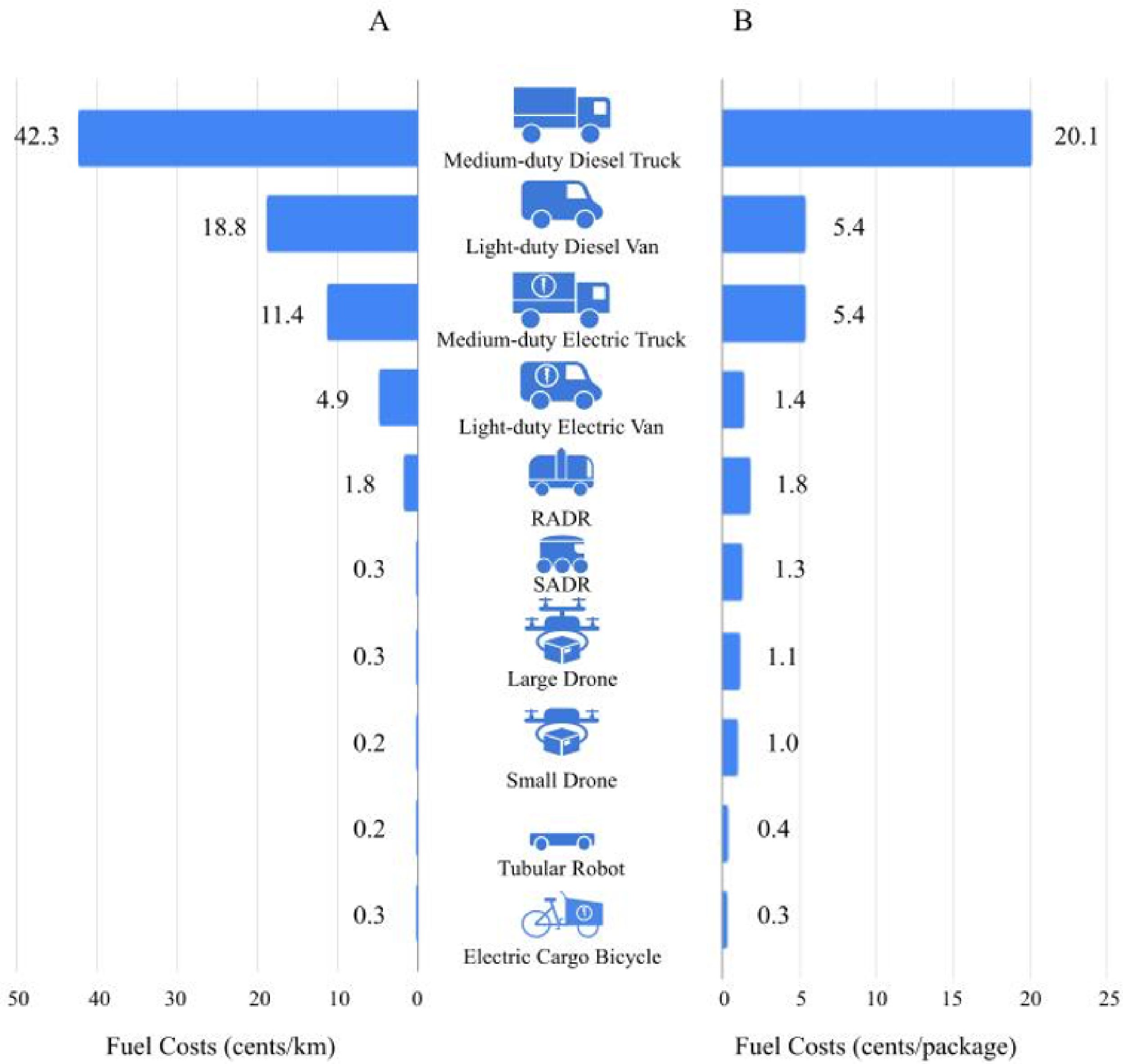

Figure 3 - Fuel Costs of Various Delivery Modes

Discussion

Our groundbreaking tubular robot, designed to transport a 30 lbs. payload at speeds of 60 mph, is set to redefine urban logistics. In this study, we investigate the energy efficiency, environmental impact, and cost-effectiveness of our tubular robot compared to other delivery methods.

Distance-Driven Efficiency

1. Energy Consumption: When evaluating our tubular robot's energy efficiency concerning distance, it consistently outperforms other modes of transportation, boasting lower or equal energy consumption rates.

Package-Centric Benefits:

1. **Greenhouse Gas Emissions**: When focusing on the number of packages delivered, our tubular robots prove to be the most environmentally friendly option across all modes of transportation, including drones and ground delivery vehicles.
2. **Cost Savings**: When compared to conventional delivery vehicles such as diesel trucks and electric vans, the tubular shuttle demonstrates the potential to reduce greenhouse gas emissions per package by an impressive 94% and 73%, respectively. Moreover, it slashes fuel costs per package by 98% and 73%, respectively.
3. **Autonomous Drone Comparison**: In contrast to small autonomous drones, our tubular robots achieve remarkable savings of 61% in greenhouse gas emissions per package and 62% in fuel costs per package.

Economic and Environmental Competitiveness:

Our findings strongly suggest that the Tubular Network, featuring tubular robots, can emerge as both environmentally responsible and economically competitive alternatives to traditional and autonomous delivery vehicles. Moreover, operating within self-contained tunnels, these robots won't contribute to existing traffic congestion, ensuring a smooth and efficient delivery process.

A Cleaner, Affordable Delivery Solution:

The Tubular Network aspires to provide cities with a cleaner and more cost-effective parcel delivery solution. With their impressive performance metrics, our tubular robots are well-positioned to revolutionize urban logistics, benefiting the environment and the economy.

Methods

Energy Consumption Calculations

We calculated the energy consumption per unit distance (e_{dist}) of the tubular shuttle as

$$e_{dist} = \frac{E}{d_{max}}$$

Equation 1

where E is the maximum amount of energy consumed on one delivery trip and d_{max} is the maximum round trip delivery distance. To calculate the value of E for the tubular robot, we utilized the specifications of the Hover-1 Titan hoverboard, which has a battery voltage of 36 V and a battery capacity of 4.0 Ah [4]. This gives a power capacity of 144 Wh, equivalent to 0.144 kWh, or 0.5184 MJ (1 kWh = 3.6 MJ). Since the tubular shuttle contains two hoverboard batteries, the power capacity of the robot is twice that of the hoverboard, or 1.0368 MJ. We applied a transmission loss of 6.5% and charging efficiency of 88% [5], so the estimated maximum amount of energy consumed on one delivery trip (E) is 1.26 MJ. The tubular shuttle is projected to have a maximum delivery distance of 5 miles one way, or 10 miles round trip. Thus, the robot can travel 16.0934 km on a single trip (1 mile = 1.60934 km). Using Equation 1, we calculate that the estimated energy consumption per unit distance (e_{dist}) of the tubular shuttle is 0.078 MJ/km.

To find the energy consumptions per package () for the RADR, SADR, large drone, and tubular robot, we used the equation

$$e_{pack} = \frac{e_{dist}}{S * P}$$

Equation 2

where S is the number of stops per unit distance and P is the average number of packages delivered per stop. We assumed that the number of stops per kilometer was 1 for the RADR and electric bike, 0.25 for the SADR and the large drone, and 0.62 (½ mile one way delivery distance, or 1 stop per mile) for the tubular robot. We also assumed that the average number of packages delivered per stop was 1 for the RADR, SADR, large drone, tubular robot, and electric bike.

For the remaining energy consumptions of the other vehicles, we used values from existing literature. The energy consumptions per unit distance and per package of the medium-duty trucks, light-duty vans, small drone, and electric bike come from Rodriguez et al. [5]. The energy consumptions per unit distance of the RADR, SADR, and large drone come from Figliozzi, where we modeled the RADR off the Nuro, the SADR off the Starship, and the large drone off the MD4-3000 [6]. We applied the 6.5% transmission loss and 88% charging efficiency to the RADR, SADR, and large drone (Rodriguez et al. already applied them to their values) [5]. We summarize all energy consumption computations in Table 1.

Table 1 – Energy Consumption Estimtate

Delivery Mode	**Energy Consumption (MJ/km)**	**Energy Consumption (MJ/package)**
Medium-duty diesel truck [5]	11.00	5.24
Light-duty diesel van [5]	4.90	1.41
Medium-duty electric truck [5]	3.80	1.81
Light-duty electric van [5]	1.65	0.47
RADR (e.g. Nuro) [6]	0.61	0.61
SADR (e.g. Starship) [6]	0.11	0.43
Large drone [6]	0.09	0.38
Small drone [5]	0.08	0.33
Tubular Shuttle	0.08	0.13
Electric Cargo Bike [5]	0.10	0.10

Greenhouse Gas Emissions Calculations

To calculate the greenhouse gas emissions per unit distance from fuel for the RADR, SADR, large drone, and tunnel robot, we multiplied the energy consumptions per unit distance by the national non-baseload output emissions rate, 177.3 g/MJ (1,407 lbs./MWh) [7]. For their upstream greenhouse gas emissions per unit distance, we multiplied the energy consumptions per unit distance by 22 g/MJ, the average upstream greenhouse gas emissions for electricity generation [5]. Greenhouse gas emissions per unit distance from all other vehicles came from Rodriguez et al. [5]. To calculate the greenhouse gas emissions per package, we divided the greenhouse gas emissions per unit distance by the stops per unit distance and average number of packages per stop for each vehicle. For the medium-duty trucks, light-duty vans, small drone, and electric bike, these are given by Rodriguez et al. [5], and for all other delivery modes, we used the values assumed above. Finally, we also include the dietary greenhouse gas emissions associated with the energy emitted by the operator of an electric bike, calculated to average around 6 g/km by the ECF [8] We summarize the results in Table 2.

Table 2 – Greenhouse Gas Emissions Estimation

Delivery Mode	**Fuel GHG (g/km)**	**Upstream GHG (g/km)**	**Dietary GHG (g/km)**	**Total GHG (g/km)**	**Fuel GHG (g/package)**	**Upstream GHG (g/package)**	**Total GHG (g/package)**
Medium-duty diesel truck [5]	762.8	168.7	-	931.5	363.2	80.3	443.6
Light-duty diesel van [5]	339.8	75.2	-	415.0	97.6	21.6	119.3
Medium-duty electric truck [5]	674.3	83.7	-	758.0	321.1	39.9	361.0
Light-duty electric van [5]	293	36.4	-	329.4	84.2	10.5	94.7
RADR (e.g. Nuro)	108.3	13.4	-	121.7	108.3	13.4	121.7
SADR (e.g. Starship)	19.2	2.4	-	21.5	76.6	9.5	86.1
Large drone	16.8	2.1	-	18.8	67.0	8.3	75.3
Small drone	14.2	1.8	-	16.0	56.7	7.2	63.9
Electric Cargo Bike [5][8]	17.9	2.2	6	20.1	17.9	2.2	26.1
Tubular Shuttle	13.9	1.7	-	15.6	22.3	2.8	25.1

Fuel Cost Calculations

To calculate the projected fuel costs per unit distance for each delivery mode, we multiplied each vehicle's respective energy consumption per unit distance by its fuel price per MJ of energy in May 2022. For diesel, this was 3.84 cents/MJ [9] after applying conversion factors of 1 gallon of diesel = 137,381 Btu, 1 kWh = 3,412 Btu [10], and 1 kWh = 3.6 MJ. For transportation-sector electricity, this was 2.30 cents/MJ [11]. Then, we found the fuel costs per package by dividing by the stops per unit distance and average number of packages per stop given above. We give the fuel costs for each delivery mode in Table 3.

Table 3 – Fuel Cost Estimation

Delivery Mode	**Fuel Cost (cents/km)**	**Fuel Cost (cents/package)**
Medium-duty diesel truck	42.3	20.1
Light-duty diesel van	18.8	5.4
Medium-duty electric truck	11.4	5.4
Light-duty electric van	4.9	1.4
RADR (e.g. Nuro)	1.8	1.8
SADR (e.g. Starship)	0.3	1.3
Large drone	0.3	1.1
Small drone	0.2	1.0
Tubular Shuttle	0.2	0.4
Electric Cargo Bike	0.3	0.3

Discussion: Getting to Zero

To attain a genuinely sustainable and zero-carbon emissions transportation system, the optimal approach is the utilization of renewable energy sources. Each Tubular Network shuttle delivery has three carbon emission sources: upstream emissions from fuel production, emissions from direct fuel consumption, and emissions from battery manufacturing, distributed over the battery's lifespan. The adoption of renewable energy sources like wind and solar can substantially reduce upstream and fuel-related emissions compared to the current regional mix of coal, oil, and renewables. While future battery technology may promise a lower carbon footprint in manufacturing, today's battery technologies do not offer emission-free solutions. To establish a "carbon zero" transportation system immediately, despite the reduced upstream and fuel-related emissions, carbon offsets must be acquired to offset the residual emissions and ensure a genuinely carbon-neutral transport system.

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