White Paper

Delivery First/Last-Mile Emissions Estimation Tool (FLEET) Vehicle Analysis

Examining Logistical and Economic Benefits of Electrified Last-Mile Goods Delivery Vehicles

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Table of Contents

List of Acronyms

ADV	Autonomous Delivery Vehicle
CO_2e	Carbon Dioxide Equivalent
E-Bike	Electric Bicycle
E-Cargo	Electric Cargo
FLEET	First/Last-Mile Emissions Estimation Tool
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
kWh	Kilowatt-Hour
lbs.	Pounds
NEV	Neighborhood Electric Vehicle
PM	Particulate Matter
ZE	Zero-Emission

Figures and Tables

Figures

Tables

I. Introduction

Last-mile deliveries play a critical role in driving the U.S. economy and meeting consumer demands for goods. Over the past decade, these demands have grown rapidly due to factors such as the dramatic increase in e-commerce and behavior changes accelerated by the COVID-19 pandemic. At the same time, frequent and dispersed deliveries using internal combustion engine (ICE) vehicles contribute to greenhouse gas (GHG) emissions and local air pollution. Innovation in zero-emission (ZE) technologies for last-mile deliveries presents an important opportunity to fuel the economy while mitigating these issues. To guide companies seeking to add ZE vehicles to their fleets, CALSTART developed the Delivery First/Last-Mile Emissions Estimation Tool (FLEET), available at https://globaldrivetozero.org/tools/deliveryfleet. This white paper uses the first iteration of Delivery FLEET to examine a selection of vehicles representing a diverse cross-section of alternative fuel and lightweight delivery options and assess their suitability as last-mile delivery vehicles.

The overarching goals of this white paper are threefold:

1. To identify how environmental and operational variables impact the appropriate vehicles in each circumstance;
2. To estimate the equivalent number of each ZE vehicle needed to achieve the same delivery output as one of three baseline vehicles; and
3. To quantify the fuel expense savings and GHG reductions resulting from the replacement of one of three baseline vehicles with new ZE technology.

This paper examines three distinct ICE baseline vehicles: a Class 2 extended-wheelbase cargo van (Mercedes Sprinter), a Class 3 midsized step van (Isuzu Reach), and a Class 4/5 full-sized step van (Freightliner MT45). Each baseline vehicle represents a different segment of last-mile delivery vehicles commonly used by logistics companies. This document walks through the current state of each of the ZE technologies examined, highlights expected strengths and weaknesses of each ZE vehicle type, and examines the basic analysis resulting from Delivery FLEET.

II. Vehicle Types and Models

Electric Cargo (E-Cargo) Bikes

Typically larger and more powerful than conventional electric bicycles, e-cargo bikes have been deployed in various forms and configurations around the world. E-cargo bikes are manufactured in two primary models: cargo tricycles and conventional two-wheeled cargo bikes. Compared to two-wheeled bikes, cargo tricycles offer higher cargo capacities and greater stability while sacrificing range and decreasing maneuverability. Compared to cargo tricycles, two-wheeled electric bicycles (e-bikes) offer reduced vehicle footprints, higher ranges, and slightly lower upfront costs at the expense of cargo capacity. **Figure 1** shows pictures of a Larry vs Harry Bullitt front-loader e-bike (left) and a Babboe Centaur cargo trike (right) both deployed for FedEx.

Figure 1: FedEx Front-Loader E-Bike (left) and E-Cargo Trike (right) (Curbside, 2021)

Several case studies have explored and quantified the benefits that e-cargo bikes can provide compared to conventional delivery vans. Primary among these benefits are logistical efficiency, lower vehicle cost, and reductions in GHG and fuel costs.

In terms of logistical efficiencies, an examination of nearly 930 individual deliveries undertaken by a delivery company operating in urban and peri-urban London found that an individual e-cargo bike offered a lower total travel time, higher average speed, and higher rate of package deliveries per hour than a cargo van was expected to return (Verlinghieri, 2021). A project monitoring approximately 350 individual cargo bikes in Manhattan also ascertained that cargo bikes may be able to replace delivery vans on a 2:1 or 1:1 basis, typically averaging 20 service miles per day across four to eight individual trips (New York City DOT, 2021).

Many of these benefits can be traced to the ability of e-bikes to avoid urban congestion by utilizing bike lanes to travel and, in places where the practice is legal, to avoid issues with parking the vehicle by simply moving it to the sidewalk or another space out of the flow of traffic. Additionally, a fleet of cargo bicycles has the ability to execute multiple delivery routes simultaneously while maintaining an increased rate of package delivery, significantly increasing overall fleet efficiency when compared to a single heavily laden cargo van (Verlinghieri, 2021).

Given their mechanical simplicity and lower materials usage, e-bikes cost significantly less than full cargo vans; a review of MSRPs indicate that e-cargo bikes are typically one-sixth to one-fourth the cost of a cargo van. Additionally, e-cargo bikes are significantly more energy efficient than cargo vans, which reduces their fueling costs and avoids the carbon emissions and particulate matter (PM) issues associated with ICEs. A study from urban Portland, Oregon, notes that e-cargo trikes replacing cargo vans resulted in a 51% to 72% reduction in carbon dioxide equivalent (CO_2e) emissions (Saenz, 2016).

However, there are limitations to e-bikes when compared to cargo vans that require careful consideration of how to balance utility, economics, and logistics, and which may require additional infrastructure and/or policy changes to fully realize the benefits of e-bikes. E-bikes have significantly shorter ranges, lower speeds, and lower cargo capacities than cargo vans, and have been found to be best suited for dense urban environments (Cherry, 2019). Within urban environments, a hub-and-spoke deployment model in which vans deliver packages to a local "hub" is frequently cited as the most efficient method of distribution. The local microhub configuration capitalizes on the e-bikes' limited range by placing them directly in the regions they intend to serve rather than requiring trips to a satellite warehouse; however, the additional construction involved in setting up a microhub can decrease the value proposition of e-bikes. Additionally, the efficacy of last-mile e-bike delivery can vary widely from city to city based on local laws, the condition of infrastructure (e.g., the quality, width, and safety of bike lanes), and environmental conditions such as traffic congestion.

Figure 2: All-Weather E-Cargo Trike with Mirrors and Windshield-Roof Combination (Coastercycles, n.d.)

For this study, CALSTART assessed 14 different models of electric-assisted bikes: five bakfiets/front-loader e-bikes and nine cargo trikes. Utilizing the aforementioned studies and based on real-world usage, the minimum acceptable vehicle range was assumed to be around 18-20 miles per day; thus, all bikes analyzed are capable of meeting that target under manufacturer-provided specifications, though these specifications assume ideal conditions and are not adjusted for range reductions in cold weather (Cherry, 2019; Verlinghieri, 2021). Cargo trikes were taken as a preference due to their larger cargo capacities, more readily available all-weather options as seen in **Figure 2** above (including canopies and doors), and moderate upfront cost, but the high fuel efficiency and compact footprint of front-loading e-bikes merited their inclusion in the analysis (**Table 1**).

Table 1: E-Cargo Bike Makes and Models in FLEET Analysis

Make and Model	Bike Type
Larry vs Harry Bullitt e6100	Front Loader E-Bike
Urban Arrow Cargo Shorty	Front Loader E-Bike
Urban Arrow Cargo L	Front Loader E-Bike
Urban Arrow Cargo XL	Front Loader E-Bike
Yuba Bikes Supercargo CL with Rhino Box	Front Loader E-Bike
Bunch Bikes The Original	E-Cargo Trike
Coaster Cycles Venture	E-Cargo Trike
Coaster Cycles Parcel AW	E-Cargo Trike
Coaster Cycles Freighter	E-Cargo Trike
Coaster Cycles Freighter AW	E-Cargo Trike
RadPowerBikes RadBurro Cargo Box	E-Cargo Trike
Urban Arrow Tender 1000	E-Cargo Trike
Urban Arrow Tender 1500	E-Cargo Trike
Urban Arrow Tender 2500	E-Cargo Trike

Neighborhood Electric Vehicles (NEVs)

Similar in size and footprint to a golf cart and significantly smaller than a typical light-duty vehicle, fully electric NEVs are commonly certified as Department of Transportation-legal for operation on streets with speed limits lower than 35 miles per hour. Their moderate-to-long operating ranges, significant cargo capacity, narrow profiles, and short wheelbases make them versatile vehicles that are both ideal for tight urban spaces and for longer trips (**Figure 3**).

Figure 3: Tropos Motors Able XR NEV with Cargo Box (Tropos Motors, n.d.)

NEVs serve as an intermediate gap between e-cargo bikes and full-size electric vans, providing an efficient, weather-proof, and hardy platform in a significantly smaller vehicle footprint than a cargo van. Their size allows them to utilize parking spots that are otherwise inaccessible to vans while carrying more cargo than an e-cargo bike. Due to NEVs' lower upfront cost, fleets may be able to deploy a larger number of vehicles to expand the fleet's ability to deliver a greater number of packages in parallel. Additionally, NEVs' larger size allows for a bigger battery that extends the vehicle's range, enabling the vehicles to reach more remote areas of an urban environment, and for a larger cargo compartment to better handle oversized and/or heavy packages.

However, NEVs are less suited for congested urban environments, as they are legally distinct from bicycles and are thus unable to leverage bicycle infrastructure unless it has been specifically expanded for NEV usage as well. NEVs are also constrained by similar range limitations to e-bikes and may benefit from the microhub-and-spoke model outlined above in order to maximize their limited ranges. Included in this analysis were five distinct models of NEVs and one all-weather variant (**Table 2**).

Table 2: NEV Makes and Models in FLEET Analysis

Make and Model
Innova EV Dash EV Delivery +
Tropos Motors ABLE XR
Tropos Motors ABLE ST
MOTO-Electric Industrial Buddy LSV
MOTO-Electric Bubble Buddy Utility LSV
Polaris/GEM eL XD Cargo (Winterized/Non-Winterized)

E-Cargo Vans

These vehicles are intended to function as one-to-one direct replacements for common cargo vans, including the Mercedes-Benz Sprinter, Ford Transit, and RAM ProMaster. These fully electric options are heavy-duty and capable, offering long ranges suitable for accessing the furthest reaches of an urban-suburban region and large amounts of storage to allow for extended field deployment times (**Table 3**). However, their prices are roughly double that of NEVs, and their large physical footprints limit their mobility and parking options in dense urban environments.

Table 3: E-Cargo Van Makes and Models in FLEET Analysis

Make and Model
Arrival L3 Van (Class 3)
BrightDrop EV600 (Class 3)
Canoo MPDV1 40kWh (Class 1)
Ford eTransit Long Wheelbase Mid-Roof (Class 3)
GreenPower Motor Company EV Star Cargo (25-foot wheelbase) (Class 3)
GreenPower Motor Company EV Plus Box Truck (Class 4)

Autonomous Delivery Vehicles (ADVs)

Figure 4: FedEx Roxo ADV (FedEx, 2019)

Advancements in LIDAR (Light Detection and Ranging), image recognition, and machine learning have allowed for significant development of ADVs. ADVs are designed to operate mostly independent of human control and provide for a labor-light approach to local deliveries, primarily in high-density environments such as business districts and mixed-use developments. ADVs relevant to this report are small robots capable of individual deliveries. Companies including Starship Technologies, Coco, and Nuro operate in several metropolitan areas around the United States. FedEx has tested its Roxo robot (**Figure 4**) in Memphis, Tennessee; Frisco, Texas; and Manchester, New Hampshire, basing the vehicle out of local retailers and restaurants to boost response times within a 3-to-5-mile radius of the base (Ames, 2020).

Small ADVs have several key benefits over conventional cargo vans, e-bikes, and even transportation network company drivers (e.g., Uber, Lyft, etc.). Larger ADVs have been identified as a potential replacement for cargo vans; where environments are conducive to such a deployment, ADVs may be able to accompany couriers between buildings, reducing the need to search for parking and improving overall productivity (McKinsey & Company, 2018). Beyond reducing the labor needed to complete small deliveries, having ADVs already present at existing microhubs significantly reduces response time and can help local businesses expand their reach and market presence by providing an "a la carte" delivery option, as the Coco Delivery service has in Santa Monica's Zero Emission Delivery Zone. For local deliveries, the electric powertrains present in ADVs reduce emissions associated with courier travel by right-sizing the vehicle, removing the store-bound leg of the courier's journey, and reducing the vehicle's time in traffic congestion by leveraging the sidewalk space.

ADVs, however, face a complicated road forward. Due to their small size, they are largely limited to hyperlocal deliveries (within 10 miles), which restricts their utility in replacing cargo vans. Their upfront cost is relatively high when examining their small cargo compartments. Perhaps most pressingly, in several urban jurisdictions, including San Francisco and New York City, robots have been restricted from using the sidewalk, which narrows ADVs' effectiveness as local legislation may force the robots into the street or disqualify them from operating within city limits at all. New York City Mayor Bill de Blasio echoed labor unions' fear that the robots may lead to delivery person job losses. Additionally, concerns exist about how well ADVs share sidewalks and roads with pedestrians and fellow drivers. In the second edition of its Blueprint for Autonomous Urbanism, the National Association of City Transportation Officials cautions that a proliferation of delivery robots on city sidewalks may negatively impact pedestrian experiences, particularly in areas with high sidewalk usage such as dense urban areas (NACTO, 2019).

III. Methodology

Building on CALSTART's literature review examining the current state of the light electric vehicle market and existing deployments of innovative solutions to last-mile deliveries, the authors explored three types of electrified last-mile transportation and quantified the strengths and weaknesses of each individual mode of transportation.

Overview

The authors identified the previously discussed selection of makes, models, and configurations for each vehicle type. Vehicles examined included 14 e-bikes (five front-loader e-bikes and nine cargo tricycles), nine NEVs, and four e-cargo vans.

Using these vehicles, the authors constructed a dataset of vehicle attributes, drawing on data from product specification sheets and manufacturer conversations to associate characteristics with individual vehicles. The following attributes were collected from published or publicly available sources:

- **Vehicle Manufacturer**
- **Vehicle Model**
- **Vehicle Class**: Selected from cargo trike, front-loader e-bike, NEV, and e-cargo van.
- **Vehicle Cost**: The manufacturer's recommended sale price (MSRP) of the vehicle before any applicable tax credits or rebates. Used to inform the expected upfront cost of the vehicle.
- **Vehicle Battery Size**: The rated capacity of the vehicle's onboard battery given in kilowatt-hour (kWh).
- **Vehicle Maximum Electric Range**: The maximum electric-only rating of the vehicle, typically estimated by the manufacturer.
- **Vehicle Weight Capacity**: The rated capacity of the vehicle's cargo platform, given in pounds (lbs.).
- **Total Cargo Area Volume**: In cubic feet and calculated from cargo platform dimensions if not explicitly given.
- **Vehicle Length and Width (in feet)** and **Overall Vehicle Footprint (in square feet)**

Additionally, vehicle fuel efficiency (in miles per kWh) was calculated by dividing the kWh of the vehicle's onboard battery by the maximum rated range. Based on conversations with FedEx, a typical daily mileage of 140 miles was assumed for all baseline ICE vehicles.

To represent a vehicle's expected real cargo capacity, two additional metrics were calculated by assuming the volume and weight of an average package to be 1.5 cubic feet and 1.5 lbs.

- **Maximum Total Daily Packages (Volume)** gives the maximum number of packages able to be stored inside the vehicle's cargo compartment by dividing the cargo compartment's volume, in cubic feet, by 1.5 cubic feet.
- **Maximum Total Daily Packages (Weight)** similarly gives the maximum number of packages able to be supported by the vehicle's cargo platform by dividing the cargo platform's weight rating, in lbs., by 5 lbs.

ICE Baseline Vehicle

To quantify fuel and emissions savings, CALSTART needed to identify a suitable and representative ICE baseline vehicle that would broadly reflect the current makeup of the FedEx fleet. The baseline vehicle would provide currently existing service conditions that the electric alternative vehicles would be expected to meet. The baseline vehicle would also provide fuel and maintenance costs and GHG emissions in tonnes CO_2e that the alternative vehicles would be expected to reduce.

In conversations with FedEx, the Mercedes Sprinter cargo van (**Figure 5**) was identified as a reasonable point of comparison. In examining the wide diversity of body, chassis, and motor options available for the Sprinter line, a brief review of ex-FedEx fleet vans and anecdotal observations indicated that of the currently available models, the most applicable configuration was a configuration of a 3500XD trim featuring a 170-inch wheelbase with a high roof. The four-cylinder diesel motor was chosen for its fuel efficiency, low price, and to provide a worst-case scenario as a point of comparison for the electric alternatives.

Figure 5: Mercedes Sprinter 3500XD, 170-Inch Wheelbase with High Roof Configuration (Mercedes-Benz, n.d.)

To provide further detail, two additional ICE vehicles were identified at higher vehicle classes than the Class 2 Sprinter van. These include the Isuzu Reach (a Class 3 mid-sized step van) and the

Freightliner MT45 (a Class 4-5 full-sized step van). All three ICE baseline models have been used by FedEx for last-mile deliveries (**Table 4**).

Table 4: Relevant Specifications of ICE Baseline Vehicles

Baseline Vehicle Model	2021 Mercedes Sprinter 3500XD 170-Inch Wheelbase, High Roof	Isuzu Reach 14-Foot Mid-Sized Step Van	Freightliner MT45 Full-Sized Step Van
Vehicle Class	2	3	4-5
MSRP (est.)	$48,405	$60,000	$100,000
Fuel Type	Diesel	Diesel	Diesel
Miles per Gallon (est. by FedEx)	14	11	10
Fuel Tank Size (gallons)	24.5	33	45
Maximum Estimated Range (miles)	343	363	450
Maximum Cargo Capacity (weight, lbs.)	5,309	3,408	6,340
Maximum Cargo Capacity (volume, cubic feet)	380.1	490	892

IV. Model Development and Interpretation

In developing the model, several generalized assumptions were crucial in providing reasonable estimates of expected savings and the abilities of individual vehicles to fill the ICE baseline functionalities, which are briefly outlined as part of **Table 5**.

Table 5: Assumptions, Default Assumption Values, Units, and Data Sources for Assumptions

Metric	Value	Unit	Source
Economic and GHG Savings			
U.S. GHG Grid Intensity (eGrid 2019)	889.2	lbs./MWh	eGrid 2019
Biodiesel Emission Factor (CO_2)	9.45	kg CO_2/gallon	EPA Emissions Factors, April 2021
Biodiesel Emission Factor (CH_4 + N_2O)	0.029871	kg CO_2e/mile	EPA Emissions Factors, April 2021
Diesel Cost (U.S. Average)	$3.30	$/gallon	EIA, November 2021
Electricity Cost (U.S. Average)	$0.1399	$/kWh	EIA, October 2021
Logistics Comparisons			
Baseline Target Range	140	miles	FedEx
Baseline Volume Capacity (100% Utilization)	Class 2: 281 Class 3: 490 Class 4/5: 892	cubic feet	Calculated from baseline vehicle specifications
Baseline Daily Package 5-lbs. Packages Delivered	Class 2: 1061 Class 3: 3408 Class 4/5: 6340	lbs.	Calculated from baseline vehicle specifications

Economics and GHG Calculations

The economics portion examines the overall projected fuel and GHG savings of each examined vehicle, using the standard inputs and the following assumptions:

- Equivalency is set to whichever metric (weight, range, or package volume) leads to the highest number of equivalence trips, assuming that routing software is appropriately sizing packages for vehicles and optimizing for vehicle storage (i.e., oversized packages are being routed to delivery vans as normal; e-bikes are given the smallest packages).
- Vehicles will deliver 100% of each baseline vehicle's maximum utilization over the course of a day.
- Vehicles will accept reductions in the effective service area if they can successfully deliver the packages and return back to the origin point without needing to recharge.
- New technologies start from the same origin as the baseline vehicle (i.e., 100% of both the baseline vehicle's range and the light-duty electric vehicle's range go to delivering packages and travel time is not accounted for).

Overall, all alternative vehicles displayed significant amounts of CO_2e abatement and substantial fuel savings over the ICE baseline vehicle seen in **Figures 6 and 7** below.

Under these conditions, and without accounting for labor and maintenance costs, **e-cargo bikes are expected to achieve simple payback of their upfront cost in approximately a year of operation**. Factoring in the cost of labor is extremely likely to reduce the economic appeal of e-bikes; however, the cost of labor may be outweighed by a reduction of expenditures on maintenance and repairs compared with larger vans, as well as a potential increase in logistical efficiency due to better congestion avoidance and significantly easier parking availability.

NEVs are anticipated to pay for themselves in an average of 2.5 years. While not as nimble and maneuverable as e-bikes, NEVs may be well-positioned to complement e-cargo bikes as an energy efficient and heavy-duty alternative for peri-urban spaces where NEVs may be able to better leverage their advantages on parking and maneuvering through traffic due to their small footprint.

E-cargo vans are generally expected to pay for themselves in 5-6 years under this scenario. While e-cargo van fuel cost savings and GHG reductions are smaller than e-cargo bikes and NEVs, they are still a considerable improvement upon the baseline vehicles. Further, the similar weight and volume capacities of these vehicles compared with their ICE counterparts enable them to be deployed across a broader range of applications with similar labor requirements.

Figure 6: Spread of Modeled Reductions in GHG Emissions by Vehicle Type vs. Class 2 Baseline Vehicle (left), Class 3 Baseline Vehicle (center), and Class 4/5 Baseline Vehicle (right)

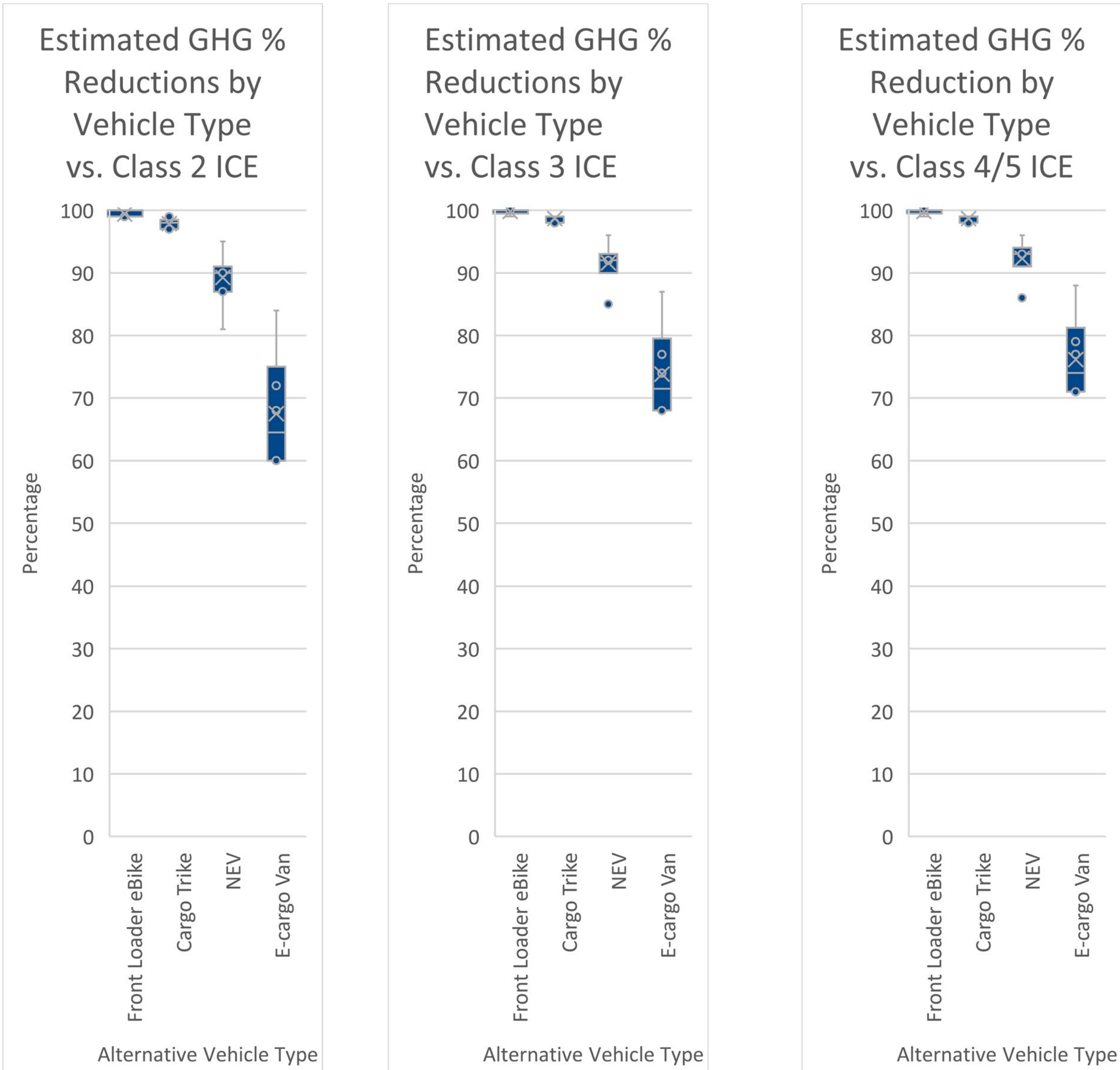
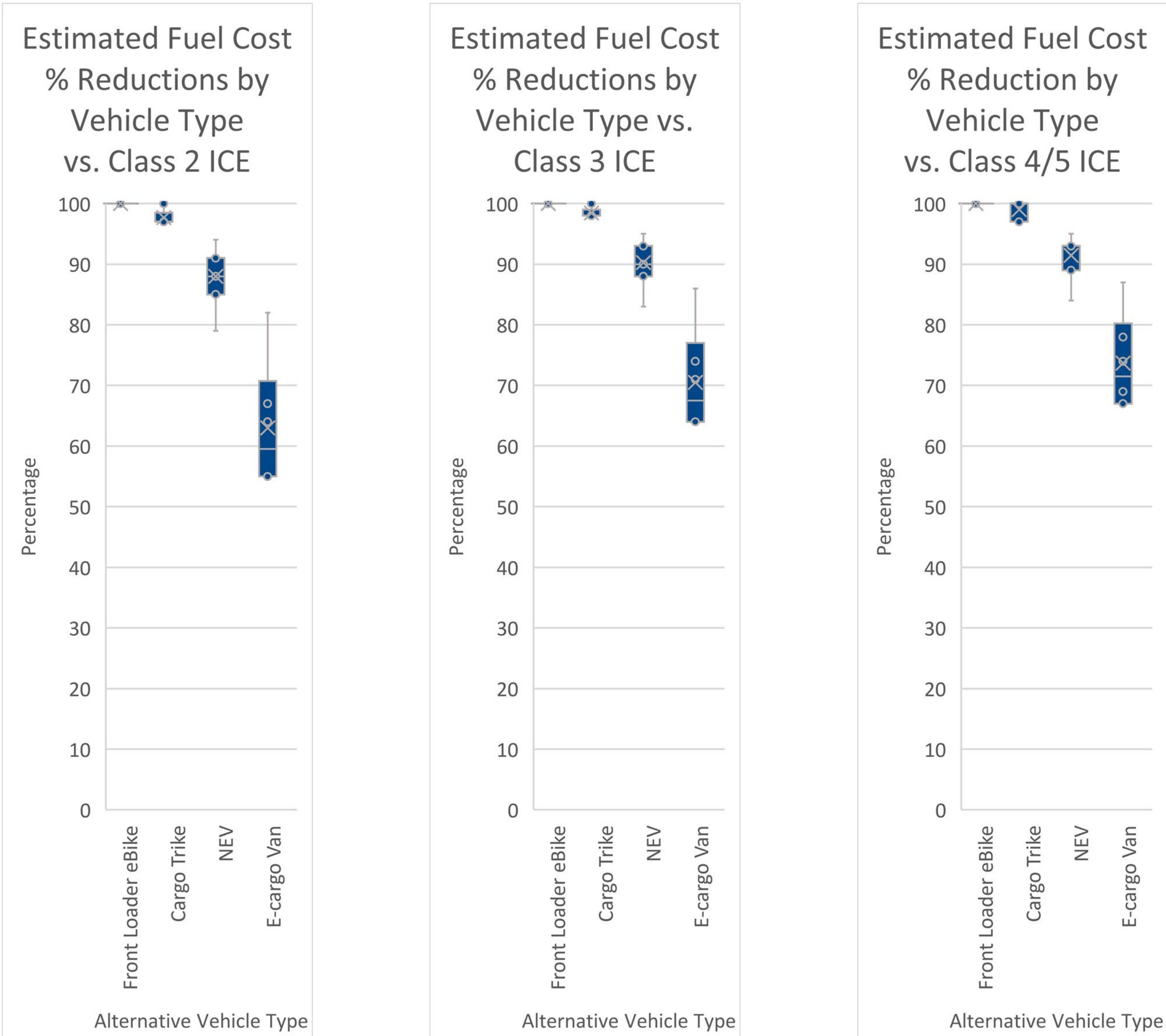


Figure 7: Spread of Modeled Reductions in Fuel Costs by Vehicle Type vs. a Class 2 Baseline Vehicle (left), Class 3 Baseline Vehicle (center), and Class 4/5 Baseline Vehicle (right)



Logistics (Cargo Capacity, Mobility + Handling)

While measurable attributes such as fuel savings and GHG emissions are straightforward to calculate and compare, equally important are less qualitative attributes: how environments and internal logistics can inform the appropriate choice of vehicle, how new technologies can replace baseline vehicles in terms of functionality and service level, and how local infrastructure and policy can influence the effectiveness of each vehicle type.

Environmental Considerations

As part of the right-sizing process, the authors examined the characteristics of built environments that can influence how vehicles are used and interact with their surroundings, as well as to better consider what characteristics were most likely to play outsized roles in determining vehicle suitability. Most of these primary considerations and potential impacts on the overall analysis can be summed up as functions of **increasing urbanization**; these environmental considerations are enclosed below as **Table 6**.

Table 6: Environmental Characteristics and Overall Importance to FLEET Analysis

Considerations	Importance of Consideration	Relevant Vehicle Characteristics	Appropriate Vehicles
Residential Density	High density means fewer stops, with a high volume of packages	Range, cargo capacity (volume)	High Residential Density: Cargo Bikes (with microhubs), NEVs, Cargo Vans Low Residential Density: All vehicles
Congestion	Time impacts, increased variation of delays and route time variance	Vehicle footprint, range	High Congestion: ADVs, Cargo Bikes Low Congestion: NEVs, Delivery Vans
Curb infrastructure, including ramps, loading zones, etc.	Ease of dolly/wheeled vehicle movements, parking	Vehicle footprint, vehicle type	High Curb Infrastructure: NEVs, Delivery Vans Low Curb Infrastructure: ADVs, Cargo Bikes
Road infrastructure, including dedicated bike lanes	Ease of vehicle navigation	Vehicle type, footprint	High Road Infrastructure: Cargo Bikes Low Road Infrastructure: NEVs, Cargo Vans
Mixed Use Zoning	Fewer stops, high volume of packages	Range, cargo capacity (weight)	High Mixed Use Zoning: ADVs, Cargo Trikes, NEVs, Cargo Vans Low Mixed Use Zoning: All vehicles
Commercial Density	May alter the appropriate delivery vehicle due to package size and/or weight and time of day restrictions due to businesses being open	Vehicle type, range, cargo capacity (weight), cargo capacity (volume)	High Commercial Density: Cargo Trikes, NEVs, Cargo Vans Low Commercial Density: All vehicles
Weather, all-season temps and precipitation	A determining factor for mode selection, staffing	Vehicle type, configuration	High Weather Variability: ADVs, All-Weather Cargo Bikes, NEVs, Cargo Vans Low Weather Variability: All Vehicles

Operational Considerations

This analysis also considers the aspects of FedEx daily logistics that are likely to additionally impact vehicle suitability for a given environment. As above, many of these considerations can be summed up as functions of the need to **better match baseline utility and expectations**; these considerations are enclosed below as **Table 7**.

Table 7: Logistical Characteristics and Overall Importance to FLEET Analysis

Considerations	Importance	Relevant Vehicle Characteristics
Non-standard / oversized packages	Considerations for weight / height	Cargo capacity (volume), vehicle footprint
Warehouse location	Accounting for travel time to expected delivery zones	Range
Vehicle Capacity	Considerations for economics	Cargo capacity (volume), cargo capacity (weight)
Vehicle Cost	Considerations for economics	Vehicle cost
Technology used for routing and package assignments	Balance between vehicle distributions and right-sizing	Vehicle type, range, cargo capacity (weight), cargo capacity (volume)
Seasonality (weather)	Accounting for range and efficiency; rain, snow, and heat	Vehicle type
Peak Holiday Season	Accounting for increased mobilization and package demand	Range, cargo capacity (weight), cargo capacity (volume)

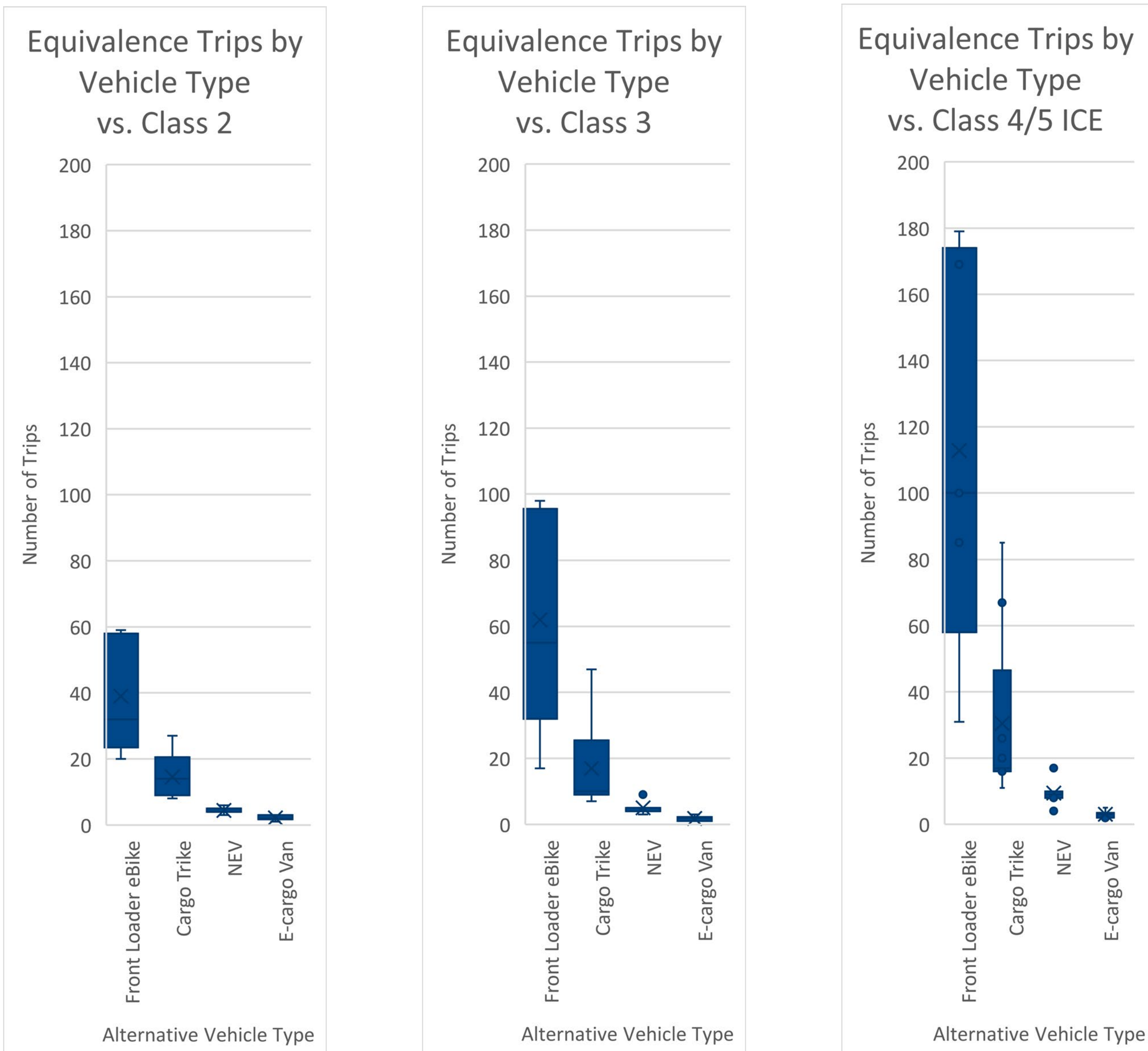
Vehicle Characteristics and Comparisons

This analysis seeks to quantify the logistical benefits of each type of vehicle by assessing three primary metrics.

How many equivalence trips are required for each vehicle to meet the specified level of service?

"Equivalence trips" is the number of individual trips required by each vehicle to meet the same level of services of an ICE baseline vehicle for one of three metrics: Miles Travelled, Daily Package Weight Delivered, or Daily Package Volume Delivered. In other words, if a cargo van is able to deliver 1000 lbs. of boxes in a day and a human being can deliver 10 lbs. of boxes in a day, a human being would need 100 equivalence trips to meet the same level of service. (This level of service can be achieved by a single human being making the same trip 100 times, or 100 human beings making the same trip once). This metric is intended to highlight the ability of each alternative vehicle to meet the desired level of service.

Figure 8: Range of Daily Individual Trips Required to Match 100% Daily Package Delivery Capacity of Baseline ICE Vehicles



Overall, the equivalence trip distributions fell in an intuitive manner (**Figure 8**): the smaller cargo capacities and lower weight ratings of the e-bikes required a greater number of trips than NEVs or e-cargo vans to serve the same target baseline metric. However, within the e-bike category, and even within the front-loader subcategory, there is a significant amount of variation in the amount of service the vehicles can provide. This is due to the flexible nature of the e-bike platform, as manufacturers often offer several variations on a single model with longer wheelbases and larger and wider cargo platforms. The heaviest-duty front-loader e-bikes can come close to, or even exceed, the cargo capacities of the wider and more stable cargo tricycles.

In terms of their ability to match package weight delivered, NEVs offer a compelling option, nearly matching the delivery output of baseline ICE vehicles in some cases. E-cargo vans, which often have similar weight and volume capacities compared with ICE cargo vans, frequently perform at a one-to-one ratio.

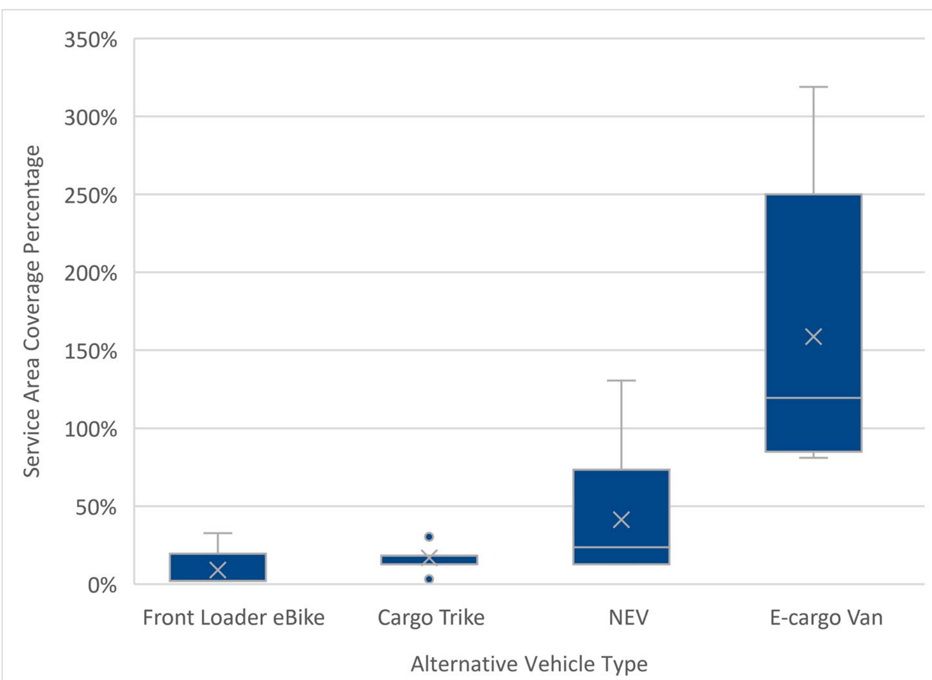
How much total daily package weight or volume can this vehicle deliver across its day?

This metric is intended to highlight the relative strengths of each vehicle. Given an average package size and weight of 1.5 cubic feet and 5 lbs., CALSTART used manufacturer specifications to calculate the number of trips required to match either the baseline vehicle's daily package volume or package weight. Given a specific number of trips required to meet a selected level of service, the remaining metric is multiplied by the required trips in order to determine the vehicle's level of service on the alternate metric. For example: if a cargo bike with a volume capacity of 10 cubic feet and a weight capacity of 100 lbs. seeks to match the weight utility of a van that can deliver 1000 packages per day, the bike would require 10 equivalence trips to match the utility. Each of those 10 trips can deliver 10 cubic feet of cargo; thus, the total daily package volume is 100 cubic feet.

Is the vehicle able to meet the target service area? If not, what percentage of the service area can the vehicle serve?

Here, the analysis seeks to determine where a vehicle's maximum functional range is expected to allow it to serve (**Figure 9**). If a vehicle is able to meet the desired level of service but can only reliably deliver packages within the 25% of the baseline vehicle's service area that is closest to the hub, this can help inform where any potential microhubs are situated or help to avoid putting vehicles into service that will not be able to reach desired delivery zones.

Figure 9: Range of Baseline Service Area Coverage Percentages



Examining how each vehicle type is able to cover the estimated baseline service area can help to inform how vehicles should be deployed and to determine the geographies to which each vehicle's weight and cargo capacities can be best applied. E-bikes averaged 14% of the baseline service area, roughly equivalent to a maximum 24-mile radius from their deployment hub. Combined with their small footprint and ability to leverage bicycle infrastructure, this situates e-bikes well to both rapid-response courier duties and to more traditional last-mile package hauling within urban cores with well-defined grid patterns in order to maximize efficiency. NEVs averaged 36% of the baseline vehicle's service area, equivalent to approximately a 37-mile radius from their deployment hub. With their heavy cargo capacity and slightly longer range, NEVs may be well-suited for a similar duty cycle as e-bikes but for heavier or outsized packages, as well as for reaching the more remote parts of a city. Finally, e-cargo vans, on average, are able to meet or exceed the baseline vehicle's range and may be best suited for duties couriering goods to microhubs, moving goods directly from satellite warehouses to less-dense suburbs and foregoing urban cores, or for delivering large shipments to industrial districts where traffic and parking are smaller issues.

V. Discussion

ADVs

The ADV market is nascent and still in the process of maturing. ADVs' primary benefits lie in their ability to utilize existing stores and businesses as local hubs in order to improve response time, decrease fuel costs and emissions, and right-size vehicles to small-scale and immediate deliveries. However, given their utilization of infrastructure typically reserved for pedestrians, uncertainties exist around how ADVs will scale with demand, and what impacts increasing densities of ADVs will have on the urban experience.

- **Pros:** Rapid response, energy efficient, reduces courier emissions and transit time
- **Cons:** Price
- **Best suited for**: Small deliveries, urban environments, short range (<10 miles)

E-Cargo Bikes

E-cargo bike advantages are most apparent in situations where they are faster or more flexible than vehicles that are limited to travel within traffic lanes, such as areas prone to frequent congestion or where legal parking availability is generally limited. Bicycle policy and road infrastructure can have significant impacts on the safety and efficiency of last-mile e-bike deliveries; areas lacking dedicated bike infrastructure will involve more risk and may require e-bikes to use traffic lanes for travel, restricting their mobility. While CALSTART found that e-bikes emit significantly less GHGs and save fuel compared to the ICE baseline vehicle in the course of operation, e-cargo bikes require several daily equivalence trips in order to match the baseline service level due to their limited cargo capacities. Depending on routes and shift lengths, this is likely to require additional labor for the multiple deployed vehicles, which will reduce overall cost savings.

- **Pros:** Ability to execute parallel delivery routes simultaneously, excellent ability to save fuel and GHG emissions over baseline vehicles, reduces transit time in congested environments, operators do not usually need a commercial driver's license
- **Cons:** Increased labor costs, less effective in environments lacking bike infrastructure, vehicles may make operators more vulnerable to adverse weather conditions
- **Best suited for**: Small deliveries, congested urban environments, short-moderate range (<25 miles)

NEVs

NEVs can bridge the gap between e-cargo bikes and full-size delivery vans, offering a substantial portion of the baseline vehicle's cargo capacity and range at a lower upfront cost and a smaller, easier-to-park footprint. A downside to NEVs is that, like e-bikes, there is a need to deploy multiple vehicles to match the baseline service level. Areas offering dedicated NEV infrastructure (e.g., micromobility travel lanes) will significantly improve vehicle mobility and efficiency, potentially rivaling or exceeding that of e-cargo bikes, though these lanes are rare at the time of writing. This analysis finds that NEVs emit significantly less GHGs and save fuel compared to the ICE baseline vehicle but are not expected to completely avoid many of the core logistical problems facing delivery vehicles (congestion, parking issues, etc.). Similar to e-cargo bikes, NEVs have limited ranges and may benefit from operating out of microhubs situated within targeted delivery zones to maximize their productive range utilization. Additionally, the need to deploy multiple vehicles to match the baseline level of service may increase labor costs.

- **Pros:** Large cargo handling capacity, ability to execute parallel delivery routes simultaneously, excellent ability to save fuel and GHG emissions over baseline vehicles
- **Cons:** Increased labor costs, only able to partially address logistical issues (parking, congestion), higher upfront cost
- **Best suited for**: Urban environments accommodating NEV travel, cities with designated delivery zones, moderate-density delivery regions

E-Cargo Vans

E-cargo vans are designed as "drop-in" replacements for baseline vehicles, offering significant cargo capacities and long ranges at higher upfront costs. While e-cargo vans closely match the baseline vehicles in terms of utility and can offer reduced fuel costs and emissions, the same logistical inefficiencies that affect the baseline vehicle will be prevalent with electrified versions of cargo vans. E-cargo vans will still face issues with finding parking and traffic delays in congested regions, and there are concerns around the additional weight of the batteries increasing danger in vehicle-versus-pedestrian collisions. However, in situations where large volumes of cargo need to be transported to low-to-moderate traffic regions or shuttle packages to an intermediate delivery hub, e-cargo vans can represent a cost-effective, efficient solution.

- **Pros:** Large cargo handling capacity, long ranges, moderate ability to save fuel and GHG emissions over baseline vehicles
- **Cons:** High upfront cost for vehicles and charging equipment, logistical inefficiencies still apply
- **Best suited for**: Peri-urban/exurban delivery routes with low congestion, goods transfer from regional warehouses to microhubs, oversized or otherwise difficult-to-handle packages

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