Assessment of the Carbon Footprint Reductions of Tricycle Logistics Services

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This research assessed the greenhouse gas emissions of a tricycle logistics company (B-Line) that is providing last-mile distribution services in downtown Portland, Oregon. The main research goal was to compare the carbon footprint of a tricycle logistics service with that of a traditional urban logistics company. The tricycles use electric engines; traditional urban logistic companies use diesel-powered vehicles. Emissions associated with power and fuel consumption, along with vehicle and battery production, assembly, and disposal, were quantified. Real-world GPS and warehouse data were recorded to evaluate B-Line operations, and different scenarios were analyzed to assess emissions reductions. A conservative approach was taken to avoid overstating emissions savings. The results show that total greenhouse gas emissions, including B-line's and its partners' operations, expressed as carbon dioxide equivalent (CO_2e), are reduced between 51% and 72%. If the comparison includes only B-line's deliveries, the tricycles' CO_2e emissions are five times lower than diesel vans' emissions.

More than ever cities need to be sustainable to achieve a better quality of life for their citizens. According to a United Nations report from 2014, 54% of the world's population now lives in urban areas (*1*). In the United States, more than 80% of the population already lives in urban areas (*2*). Because of urbanization and more frequent deliveries, the number of commercial vehicles and traffic are both steadily increasing (*3*). The Federal Highway Administration (FHWA) states that there has been an increase of 21% in terms of total vehicle miles of travel (VMT) within urban areas from 1996 to 2006. More specifically, a faster growth of freight traffic in urban areas has been detected; the share of freight vehicles increased from 4.8% to 5.2%.

Roadway capacity and parking spaces are very limited in dense and congested urban areas. Passenger and freight transportation compete for the same space. Trends in logistics (higher frequency of deliveries and smaller order size because of just-in-time delivery systems) are now increasing negative transportation externalities such as traffic congestion, poor road safety, crashes, energy consumption, air and noise pollution, and total miles traveled.

Several empirical studies confirmed that urban freight vehicles account for 6% to 18% of total urban travel (*4, 5*). Further, 21% of CO_2 emissions come from urban freight vehicles (*6, 7*). The transportation sector is responsible for 28% of total greenhouse gas (GHG) emissions in the United States, so the contribution of urban freight transportation to GHG emissions is extremely relevant to sustainability efforts. In addition, urban freight vehicles (commonly powered by diesel engines) are known to have serious effects on public health. Diesel motor vehicles are a major source of air contaminants produced during combustion, such as nitrogen oxides (NO_x), which react to form smog and acid rain (*8*). There are other air contaminants that increase health risks, such as sulfur oxides (SO_x), carbon monoxide (CO), and particulate matter (PM) (*9*).

Governments are seeking to mitigate negative freight externalities by cutting GHG emissions and other air pollutants. One possible strategy to tackle the negative effects of urban freight is the electrification of urban delivery vehicles (*10*). In congested urban areas, delivery trucks have low fuel economy because they spend a great portion of their time idling (*11*). In addition, electric motors are more efficient than internal combustion engines in an urban environment in which average driving speed is low (*12*). Another advantage is that systematic recharging and battery swapping are feasible because these delivery vehicles take similar routes every day and after each route return to the company garage (*13*). Hence, the switch from a fossil-fuel-combustion fleet to an electric-powered fleet seems a suitable way of reducing urban emissions. One of the great advantages of vehicles' electrification is that it would bring the transportation and the electric sectors into a kind of partnership and shift emissions from vehicles in urban areas to remote power stations, improving cities' air quality.

In particular, electrically assisted cargo tricycles could play a role in reducing GHG emissions from the freight transportation sector. Cargo tricycles are an ideal low-emissions alternative for transporting light goods in city centers not only because of their lack of tailpipe emissions but also because of their small size and easy access to compact, congested towns and cities. Unlike conventional diesel-powered vans, cargo tricycles can legally use bicycle paths and lanes, allowing for faster access to congested downtown or pedestrian areas (*14*). An advantage of cargo tricycles is that their operations are not significantly affected by congestion or by a lack of loading and unloading areas. Other advantages are noise reduction through the use of quieter vehicles, improved safety for pedestrians, and fewer conflicts in traffic with passenger cars and other road users in general (*15*).

Although there has been extensive research into cargo tricycles' benefits, most research efforts have ignored vehicle production and disposal emissions when evaluating environmental impacts. To the best of the authors' knowledge, there is no published carbon footprint assessment of a tricycle logistics company.

This research explores the potential of electric urban delivery tricycles to reduce GHG emissions over their service lifetime for urban delivery operations. B-Line is a tricycle logistics company that is currently providing warehousing, pickup, and delivery services in downtown Portland, Oregon (*16*). The researchers were able to record and analyze several days of detailed GPS route and warehouse data

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Transportation Research Record: Journal of the Transportation Research Board, No. 2570, Transportation Research Board, Washington, D.C., 2016, pp. 48–56.
DOI: 10.3141/2570-06

from B-line operations. The goal was to compare B-Line's carbon footprint with the carbon footprint of the traditional pickup and delivery companies. Because freight that is delivered by tricycle is often light in weight and small in size, diesel vans are the natural competitor.

Although electric tricycles do not produce tailpipe emissions, GHG emissions from electricity generation are substantial. And even though electric tricycles may have greater tank-to-wheel (TTW) efficiency than conventional diesel-powered vans in city delivery operations, the overall energy efficiency of electric tricycles depends on their life-cycle energy use, including upstream electricity generation and transmission efficiency. An assessment of tricycle and diesel van life-cycle emissions was carried out, ranging from the extraction of raw materials from the earth to vehicle manufacturing, use stage, and recycling or disposal at the end. For the use phase, B-Line operations were analyzed to study how delivery services could be provided by more traditional diesel-powered fleets.

The next section presents a brief literature review; the following sections present the methodology used to compare different vehicle technologies, a case study, and results.

LITERATURE REVIEW

To understand a tricycle logistics service, it is essential to break down and analyze the characteristics of cargo tricycles. It is also essential to quantify their environmental effect when serving as last-mile vehicles in urban distribution.

Characteristics of Cargo Tricycles

Cargo tricycles are often electric-assisted. La Petite Reine and Cycles Maximus are two important manufacturers of cargo tricycles. On a regular basis, the tricycle payloads are between 331 lb and 600 lb, and their maximum speed is approximately 10 mph (*17*). Differences between cargo tricycles and diesel vans can be identified in Table 1, where specifications of a typical cargo tricycle and van are shown.

Cargo tricycles have many advantages. Because of their small size, tricycles require minimal parking space and can be parked legally on- and off-street, on sidewalks, or inside a business (*14*). A diesel van must be parked on the street, which increases the walking time and distance to make a delivery and commonly requires the vehicle to idle while waiting for parking. The driver of a delivery van either has to cruise for a free parking space or double park, which is illegal, and this increases cost, emissions, and traffic congestion. The time it takes to serve a customer can be reduced if tricycles are used.

In terms of maneuvering throughout urban areas, tricycles also tend to have a distinct advantage over vans because there are often dedicated bicycle lanes that a tricycle can use to bypass traffic congestion. Further, the possibility of simplifying and shortening the route by crossing pedestrian areas or riding up one-way streets on a sidewalk in the opposite direction makes a tricycle the perfect vehicle to deliver in dense downtowns. A tricycle also has better fuel economy because of its lower weight and because riders have to pedal. Wilson et al. stated that an average fit man or woman could pedal a bicycle with the power output of 75 W without suffering fatigue for seven hours (*28*). The human contribution is not insignificant, because the power exerted by the rider could reduce necessary battery size by around 500 W-h during a seven-hour day, and battery capacity is around 850 W-h.

TABLE 1 Specifications of Typical Diesel Van, Tricycle, and GREET Emissions Rates

Specification	Electric Tricycle Cycles Maximus	Diesel Cargo Van GMC Savana 2500
Price	\$6,200[a]	\$41,500[b]
Battery size–tank size	864 W-h[a]	31 gal[b]
Battery capacity	72–92 A-h[a,c]	na
Gross vehicle weight rate	1,100 lb[d]	8,600 lb[b]
Curb weight	500 lb[d]	6,118 lb[b]
Battery weight	77.8 lb[c]	na
Maximum payload	600 lb[d]	2,482 lb[b]
Cargo volume	60 ft^3[d]	239.7 ft^3[b]
Range	30 mi[a]	465 mi[e]
Maximum speed	10 mph[f]	50 mph[h]
Fuel economy (city)	25–50 W-h/mi[d]	15 mpg[g]
$e_{\text{vehicle material}}$	4.108 lb CO_2e/lb vehicle[i]	3.995 lb CO_2e/lb vehicle[i]
$e_{\text{assembly+disposal+recycling}}$	1.247 lb CO_2e/lb vehicle[i]	1.247 lb CO_2e/lb vehicle[i]
e_{battery}	3.93 lb CO_2e/lb battery[j]	na
$e_{\text{well–to–tank}}$	0.923 lb CO_2e/kW-h[k]	5.108 lb CO_2e/gal[i]
$e_{\text{tank–to–wheel}}$	na	22.72 lb CO_2e/gal[l]

NOTE: na = not applicable.
[a]Cycles Maximus (*18*).
[b]GMC Vans Savana Cargo (*19*).
[c]Odyssey Batteries (*20*).
[d]Provided by B-Line (*16*).
[e]Based on the fuel economy.
[f]Conway et al. (*17*).
[g]Typical urban area maximum speed.
[h]*2014 Vehicle Technologies Market Report*, U.S. Department of Energy (*21*).
[i]GREET model (*22*).
[j]Sullivan and Gaines (*23*) and Rantik (*24*).
[k]USEPA eGRID (*25*).
[l]USEPA (*26, 27*).

Although there are many advantages to cargo tricycles, there are also several disadvantages. Because tricycles have limited payload and volume capacity, there are times where freight is not deliverable because it exceeds the vehicles' limit in weight or volume or both. Limited travel range and low speed in free-flow conditions are also crucial disadvantages. Therefore, tricycles are suitable as an urban delivery vehicle only in certain circumstances, that is, for small volumes of relatively light parcels when a diesel van delivery process is constrained by the limitations of the urban structure.

Decarbonizing the Last Mile

Cargo tricycles are mostly used in the last mile of the logistics chain, defined as the distribution of goods from an urban distribution center to final customers. Existing research efforts into the use of cargo tricycles within urban last-mile logistics are still scattered (*29–31*). Most studies are limited to the European context because cargo tricycle delivery is better suited to the narrow streets of old towns than to boulevards. Popular examples are located in Brussels, Belgium, London, and Paris (*17, 32*).

Most research effort has been focused on identifying a market niche within the logistics sector (*29*). In terms of environmental effects, the body of research is relatively thin. However, there are some studies and some companies that have made emissions savings data available. For instance, GNewt Cargo, a delivery company in London, has been independently verified to cut CO_2 emissions per parcel delivered by 62%, according to its website (*33*). Ecopostale, a Belgian company, estimates that there are 29 tons of carbon dioxide equivalent (CO_2e) savings when their delivery service is compared with that of a traditional delivery company (*34*); and Txita, a tricycle delivery company of San Sebastian, Spain, estimates the saving in CO_2e, compared with the use of commercial vans, at 14 tons on the basis of 59,247 parcels delivered in two years (*35*). A Dutch study estimated possible annual savings for the Netherlands of 21,000 tons of CO_2 (*36*).

Browne et al. evaluated a trial in which office supplies were delivered from a suburban London depot to downtown customers (*15*). During the trial, diesel vans were replaced by small electric vans and tricycles operated from a micro-consolidation center close to downtown. A truck was needed to transport cargo from suburban London to the distribution center in downtown London. Then, six tricycles and three electric vans took the cargo from the distribution center to the final customers. The operation of these electric vehicles did not result in any fossil fuel consumption or GHG emissions because the electricity used by these electric vehicles was produced from renewable sources. The result showed great benefits: total distance traveled was reduced by 20% and the CO_2e emissions per parcel fell by 54%. GNewt Cargo was the operator of the micro-consolidation center, tricycles, and electric vans (*33*).

Conway et al. evaluated two case studies in New York City, assuming that Cycles Maximus cargo tricycles replaced the daily operation of a five-year-old cargo van (*37*). The total annual CO_2 and PM10 savings were 19 to 21 tons and 3.5 to 4 lb, respectively, because of cargo tricycle operations in New York City. Because the Cycles Maximus tricycles in use by the case study operators were fully human-powered, emissions savings were evaluated by estimating emissions rates for comparable motorized urban delivery vehicles using EPA's Motor Vehicle Emission Simulator (MOVES) model (*38*). Neither a life-cycle assessment nor a comparison with alternative diesel vehicles was performed.

METHODOLOGY

A carbon footprint (GHG emissions assessment) quantifies the total emissions that contribute to global warming caused by an organization or project (*39*). The assessment quantified GHG emissions of carbon dioxide, methane (CH_4), and nitrogen oxides and then converted these emissions into carbon dioxide equivalents (CO_2e), typically with a time horizon of 100 years, using the global warming potential values recommended by the Intergovernmental Panel on Climate Change (*40*).

The GHG Protocol is the "most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions," according to the GHG Protocol website (*41*). The GHG Protocol defines direct and indirect emissions, distinguishing between emissions from sources that are controlled by the company studied and emissions that are the consequence of the company studied but occur at sources controlled by other organizations. Three broad categories are also defined: (*a*) all direct GHG emissions, (*b*) indirect GHG emissions from consumption of purchased heat or electricity, and (*c*) other indirect emissions, such as the extraction and production of purchased materials and fuels, transport operations in vehicles not controlled by the organization, electricity-related activities (e.g., transmission and distribution losses), outsourced activities, and so on.

This study included GHG emissions associated with energy use and fuel consumption, along with vehicle and battery production, use, and disposal, in an attempt to estimate the most comprehensive carbon footprint assessment. In this context, life-cycle assessment (LCA) of systems should be introduced. LCA (also known as a cradle-to-grave assessment) assesses multiple environmental impact categories. These may include global warming effects of GHG emissions and may also include human health impacts, ecosystem and resources impacts, land use, and so on. A carbon footprint assessment separates the inputs into three categories; LCA commonly separates the inputs into life-cycle stages ranging from extraction of raw materials from the earth to manufacturing, distribution, product use, and recycling or disposal at the end. Life-cycle stages should be analyzed from the perspective that each stage depends on the one before it. LCA helps to avoid shifting environmental problems from one place to another by considering the entire life cycle system.

In this study, the carbon footprint of a tricycle logistics company was compared with the footprint of a traditional pickup-and-delivery company covering the broadest GHG Protocol scope; that is, including all life-cycle emissions associated with the production, use, and disposal of vehicles. Thus, two commercial vehicles were considered: a conventional diesel-powered cargo van with an internal combustion engine, such as the GMC Savana 2500, and an electric-powered cargo tricycle, such as the Cycles Maximus cargo tricycle. The vehicle specifications are shown in Table 1. Commercial vans and electric tricycles were examined in three distinct phases: (*a*) vehicle cycle (from raw material extraction to disposal, considering different vehicle compositions); (*b*) well-to-tank (fuel or electricity production and distribution); and (*c*) tank-to-wheel (vehicle use operation, where only fossil fuel vehicles produce tailpipe emissions). To execute an LCA, several software tools are available. For transportation analyses in particular, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is a widely known option (*22*). Other data used in this study were collected from publicly available sources, such as the U.S. Environmental Protection Agency and the eGRID database (*42*).

Vehicle Life Cycle

There are several stages in the vehicle life cycle: extraction of raw materials (including aluminum, iron, plastic, and copper), transportation of those materials to factories where alloys are developed, refinement of raw materials and production of final materials, transportation of those materials to assembly plants, production of vehicles at the vehicle assembly factories, transport and distribution of vehicles to dealers, and disposal or recycling. The GREET 2014 model was used to estimate GHG emissions from vehicle manufacturing (not including the tricycle battery) (*22*). The GREET model contains hundreds of parameters with default values drawn from national or regional statistics or industrial practice. Detailed documentation of the system boundary and assumptions in relation to industrial processes and technologies is available in GREET publications. Detailed environmental impacts are provided for numerous materials and manufacturing processes, and the GREET model breaks down different vehicle technologies into their constituent systems, components, and parts, considering mass and material composition.

GREET uses vehicle weight as the functional unit. Vehicle weight and vehicle materials, assembly, and disposal emissions rates are shown in Table 1. In this research, an electric cargo tricycle was modeled as a pickup truck with electric vehicle conventional materials because the GREET model does not include the electric tricycle vehicle type. This is not ideal, but it is a conservative estimation because all other electric vehicle technologies have smaller emissions rates. The commercial diesel van was modeled as a pickup truck with an internal combustion engine and conventional materials.

Battery Life Cycle

Electric tricycles typically use lead-acid (PbA) batteries. Although the lead-acid battery is the oldest type of rechargeable battery, it is still attractive because of its low cost and high specific power. Valve-regulated lead-acid (VRLA) batteries do not require constant maintenance, unlike the initial "flooded" design. The absorbed glass mat (AGM) type dominates VRLA market share because of its extremely high energy-to-weight density and excellent overall performance. Sullivan and Gaines conducted a full process-based LCA of the VRLA battery (*23*). In comparison with other battery technologies, the PbA battery has the lowest cradle-to-grave emissions footprint because of highly successful recycling processes and infrastructure (*43*). Currently, new PbA batteries range from 60% to 80% recycled content. Rantik analyzed the recycling processes for PbA batteries (*24*). On the basis of the global warming potential values recommended by the International Panel on Climate Change to convert CH_4 and N_2O, it is estimated that PbA battery life-cycle GHG emissions are 3.93 kg CO_2e per kg. Battery weight and emissions rate are also shown in Table 1.

Use Phase

The majority of life-cycle GHG emissions are emitted during the use phase. In this carbon footprint comparison between electric tricycles and commercial vans, emissions from vehicle maintenance are omitted; they are assumed to be similar or that the difference is minimal in comparison with other life-cycle phases.

Well-to-Tank: Emissions of Energy Supply Chain

Diesel Fuel Supply Chain Life cycle GHG emissions for a typical fuel such as diesel include several stages: petroleum pumping, extracting, transporting, refining in factories, dispensing, and distributing through to diesel stations. The diesel supply chain is the most polluting stage in the life cycle of a vehicle (*44*). It has been estimated that around 20% of the life-cycle GHG emissions of fossil fuels such as gasoline and diesel are emitted during extraction, transport, and refining processes (*45*). These upstream GHG emissions were estimated by the GREET model, taking gallons of diesel as the functional unit (*22*). The diesel GHG emissions factor is estimated and shown in Table 1.

Electricity Supply Chain Electricity consumption does not produce GHG emissions at the point of use but in centralized plants where the electricity used to charge tricycle batteries has been produced. The Emissions and Generation Resource Integrated Database (eGRID), published by the U.S. Environmental Protection Agency, is an internationally recognized source of data on GHG emissions and other criteria pollutants associated with electricity generation in the United States (*46*). The eGRID emissions factors are mainly valuable for GHG emissions assessments (*25*).

The eGRID output emissions rates are related to the generation of electricity at the power plant, not to consumption of electricity; as a result, these values do not consider transmission and distribution losses or imports and exports between subregions. However, eGRID provides a grid gross loss factor that can be used to estimate emissions associated with these losses (*46*). Three different electricity generation scenarios were considered to account for variability in the electric generation profiles across the 50 states. Thus, Table 2 shows the fuel profiles and emissions rates for three U.S. cities: Portland, Oregon, New York, New York, and Denver, Colorado. It was assumed that coal is the energy source with the highest emissions rates and these three cities were chosen to represent areas with low, medium, and high percentages of coal-based electricity. Emissions rates are provided for three GHG that are emitted in significant amounts because of the production of electrical energy: CO_2, CH_4, and NO_2. Grid gross loss (GGL) factors are also displayed in Table 2.

Tank-to-Wheel: Use Phase Modeling

The TTW considers the tailpipe emissions caused by fuel consumption. The diesel fuel consumption value shown in Table 1 relies on EPA's fuel economy estimates (*21*). According to EPA, the amount of tailpipe carbon dioxide emitted from burning one gallon of diesel is 10,180 g of CO_2 (*26*). In 2011, EPA estimated at 0.988 the ratio of CO_2 emissions to total GHG emissions, in order to express CO_2, CH_4, and nitrous oxide (N_2O) as carbon dioxide equivalents (*27*). Therefore CO_2e emissions are estimated as 22.72 lb. CO_2e per gallon of diesel.

The fuel economy of the electric tricycle should be calculated by measuring battery energy capacity (in watt-hours) before and after following a typical route for which the distance is known. Because these measurements should be made for the batteries, not for the

TABLE 2 Energy Sources, Grid Gross Loss Factor, and CO_2e Emissions Rates for Three U.S. Cities, Along with National Averages

Region	GGL (%)	Hydro (%)	Other (%)	Nuclear (%)	Oil (%)	Gas (%)	Coal (%)	CO_2 Emitted (lb/MW-h)	CH_4 Emitted (lb/GW-h)	N_2O Emitted (lb/GW-h)	CO_2e Emitted (lb/MW-h)
Portland, Oregon	8.2	43.6	5.6	3.4	0.3	14.3	31.3	843	16	13	847
New York, New York	5.8	0.0	0.5	39.9	1.3	57.4	0.0	622	24	3	624
Denver, Colorado	8.2	3.9	5.7	0.0	0.0	17.1	73.0	1,899	23	29	1,906
U.S. average	6.5	6.2	2.7	19.6	1.0	24.0	44.8	1,232	24	18	1,239

electric motor, electricity losses as a result of the batteries' energy inefficiency are included in this factor. However, efficiency losses in battery charging are not taken in account. Stevens and Corey developed a test procedure to examine battery charging efficiency as a function of battery state of charge (SOC) (*47*). Results indicated that from 0% SOC to 84% SOC, the average overall efficiency is 91%, and that at SOCs above 84% the incremental efficiency is only 55%. Overall, an efficiency level of 85% is often assumed. In this study, a charging efficiency level of 70% was assumed, to avoid overstating tricycle fuel efficiency.

The use phase GHG emissions per mile (lb/mi) were calculated for each vehicle by using Equation 1 for electric tricycles and Equation 2 for diesel commercial vans.

$$\frac{CO_2e}{\text{mile}} = \frac{\text{kW-h}}{\text{mile}} \times \left(\frac{ERg}{1 - GGL} \times \frac{1}{\eta} \right) \quad (1)$$

$$\frac{CO_2e}{VMT} = \frac{1}{\text{mpg}} \times \left(\frac{CO_2e_{\text{tailpipe}}}{\text{gallon}} + \frac{CO_2e_{\text{upstream}}}{\text{gallon}} \right) \quad (2)$$

where

VMT = vehicle miles traveled,
ERg = eGRID generation-based output emissions rate (lb/kW-h),
GGL = eGRID grid gross loss factor (decimal), and
η = charging efficiency (decimal).

CASE STUDY

A case study was conducted using real-world data from Portland, Oregon to investigate potential GHG emissions savings. This was done through the use of a tricycle logistics service. Portland is known as one of the most bicycle-friendly cities in the United States. There are many bike paths throughout the city, which makes biking convenient. In addition, the Portland downtown area is relatively flat, which makes it possible for delivery companies such as B-Line to thrive. B-Line Sustainable Urban Delivery (*16*) was founded in February 2009. The company delivers a wide variety of products, such as produce, baked goods, coffee beans, bicycle parts, and office supplies. They deliver to restaurants, coffeehouses, bicycle shops, and other businesses using electric- and human-powered cargo tricycles. Most of B-Line's customers are located in downtown Portland (Figure 1).

B-Line's distribution warehouse is located in the Eastside, only two miles from downtown Portland. Because the company is near the edge of downtown, it could be considered to be an urban distribution center. B-Line currently provides delivery services for eight

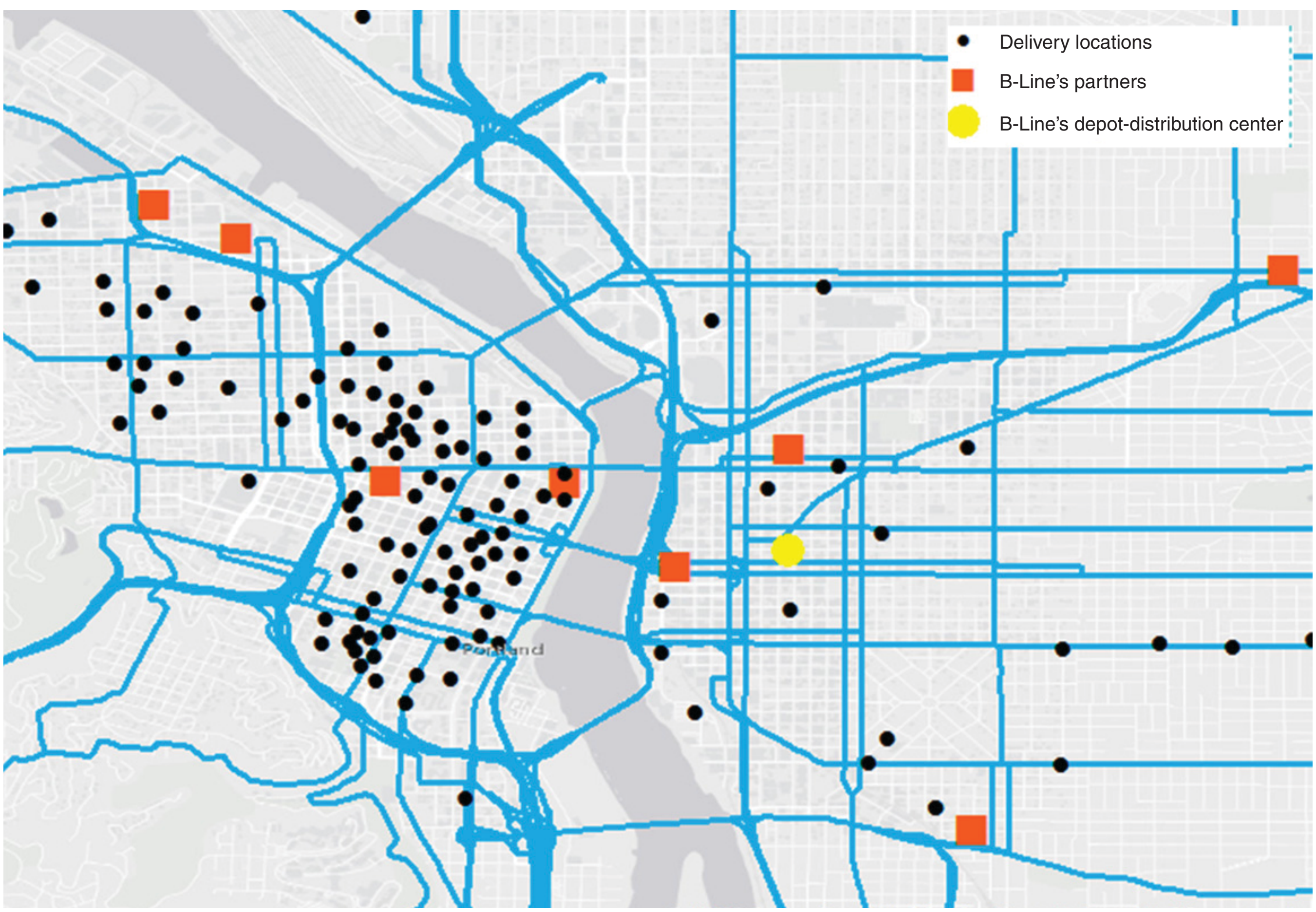

FIGURE 1 Distribution of B-Line's partners and customers in Portland, Oregon.

companies. Two of its major partners transport their products from their warehouses to B-Line's distribution center every morning between 6 a.m. and 9 a.m. Two other companies transport goods once a week. The remaining four partners are located in or close to downtown, so that B-Line picks up products at these partners' locations and then distributes them to the final customers. Routing at B-Line is complex because it involves traditional distribution with route distance and route duration constraints as well as intermediate pickup and delivery of goods at other partners' and customers' locations. As is the case for many other urban delivery companies, B-Line provides both forward and reverse logistics services. The backhaul is in many cases used to consolidate (that is, bring back to the B-Line depot) waste material for recycling.

On May 2015, researchers shadowed the operations of the B-Line company in Portland, Oregon. The data that were recorded and analyzed included several days of detailed B-Line GPS routes and warehouse operations. A summary of some key average values that describe a single day of B-Line operations is provided:

- Customer demand weight: 65 lb
- Service time: 10 min
- Daily number of customers: 80
- Total distance traveled: 82 mi
- Tricycle traveling speed: 7.4 mph

B-Line owns six tricycles, along with 12 lead-acid AGM batteries that weigh 77.8 lb. each. Two batteries are needed for each tricycle. During a tricycle's route, one battery is in use and the other is at the B-Line distribution center, ready to be swapped for the used battery on the tricycle's return to the center. This is done to avoid low SOC, which can damage a battery and shorten its useful life. Battery charger effects were excluded from this assessment because of their low weight and consequently insignificant effect on GHG emissions. The electric tricycle fuel economy was calculated on the basis of B-Line's proprietary information. During more than two years, B-Line staff have measured batteries' parameters before and after each route; the company has more than 1,150 measurements of all of its batteries. From these measurements, a fuel economy median of 48.65 W-h/mi (20.55 mi/kW-h) was calculated. B-Line's carbon footprint can be calculated with the previous data. With the data that were collected from B-Line, researchers created two hypothetical scenarios to analyze the boundary emissions benefits of B-Line in comparison with a traditional diesel-powered fleet.

- Scenario 1 (consolidation factor = 1). In the best case, B-Line would provide the same services as it does now, but with diesel vans instead of tricycles.
- Scenario 2 (consolidation factor = 0). In the worst case, B-Line would not exist, and each of B-Line's partners would have its own commercial van for its logistics operations.

Given the pickup and delivery locations of each day, the researchers, together with the B-Line operations manager, created hypothetical routes that minimized the distance traveled for each scenario. As noted in the literature review, service time per customer when a van is used is likely to be greater than service time per customer when a tricycle is used. This is because tricycles can park on sidewalks whereas cargo vans have to find a secure location to park. Because 80 deliveries must be completed per day, and 10 minutes' service time per customer was assumed, one van was not enough to serve all customers in Scenario 1; two diesel vans were needed. In Scenario 2, the same delivery frequencies and demand weight were assumed for the partner companies. Routes were calculated to start and end at B-Line's partners' locations; it was further assumed that each B-Line partner needed only one van. In both scenarios, neither time windows nor capacity constraints were assumed. This is because a commercial van's payload is much greater than a tricycle's payload. As the exact list of customers typically varies day by day, total daily distance traveled in both scenarios was averaged. The result of minimizing distance was an average total of 36 mi/day for Scenario 1. In Scenario 2, one van from each partner's depot makes its own deliveries and returns to its depot. This routing decision involved 88 mi/day.

A conservative approach was taken in creating the hypothetical routes and calculating the total daily distance traveled in both scenarios. To that end, neither logistics constraints nor a distance penalty for finding a parking spot when making deliveries in downtown was assumed. Using the data from these two scenarios, the carbon footprints could be calculated and a comparison between B-Line's carbon footprint and the carbon footprint of a traditional diesel van delivery company could be made.

1. As noted in the Methodology, carbon footprint assessment, using GHG Protocol Scope 3, should also include all indirect emissions. This implies that GHG emissions caused by B-Line's partners while transporting goods from their warehouses to B-Line's depot should be taken into account. In this approach, B-Line's partners' vehicles' life-cycle emissions were not considered; only fuel supply chain and fuel consumption GHG emissions were included. Of the eight partners B-Line currently delivers for, only two bring their products to B-Line's distribution center. It was calculated that on average, the daily distance covered by these two B-Line partners from their depots to the B-Line distribution center is 25 mi. That should be taken into account in assessing B-Line's carbon footprint in Scenario 1. It was assumed that B-Line's partners use a 15-mpg diesel van for covering those 25 mi.
2. The life expectancy of common delivery vehicles is approximately 12 years (*48*). The life expectancy of freight tricycles is usually shorter; it was assumed to be 5 years.
3. The life expectancy of lead-acid AGM batteries is between 3 and 10 years depending on use. Here, a 4-year life was assumed.
4. Warehouse life cycle GHG emissions impacts were not included in this comparison. It was assumed that these facilities (space for loading and unloading, storage, parking for vehicles overnight, and walk-in cooler) are similar for both B-Line's actual operations and Scenario 1. This is a conservative approach because diesel vans are larger than tricycles, thus more space is needed to park overnight and to load and unload cargo.

RESULTS

Some of the final results of the study are presented in Figure 2, which shows that CO_2e emissions from the tricycle delivery system fall between 51% and 72%, depending on the cargo consolidation factor. That result was found using the Portland electricity emissions rate. However, large emissions savings could be found even in the case of carbon-intensive electricity generation, where GHG emissions were reduced by at least 46%. However, the distance traveled increased substantially. The B-Line daily mileage accounted for 82 mi, plus 25 mi covered by its partners. If B-Line service were

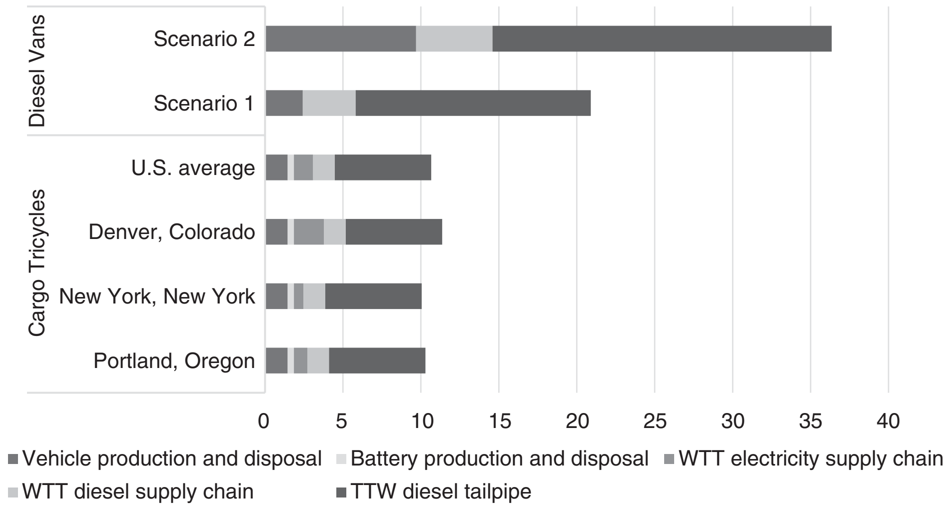

FIGURE 2 CO_2e emissions per year (metric tons) (WTT = well to tank).

provided with vans, they would travel 36 mi. That situation implies a 43% reduction in mileage.

B-Line avoids between 10 tons and 26 tons of CO_2 emissions per year. However, most GHG emissions are caused by B-Line's partners in transporting goods from their warehouses to the B-Line depot. These 25 mi/day account for more than 64% of the B-Line GHG emissions if all indirect emissions from consumption of purchased fuels and electricity, transmission and distribution losses, and vehicle production and disposal are taken into account.

If the emissions from B-Line's partners are ignored, a greater difference between the tricycle logistics company's emissions and a traditional company's emissions can be observed. Figure 3 shows CO_2e emissions per delivery. The impact of partners' emissions on B-Line's carbon footprint can be perceived. If transport activities of the partners were not included, a huge reduction could be seen: six tricycles and 12 batteries have only 20% of the carbon footprint of two diesel vans—that is, emissions are five times lower.

DISCUSSION AND CONCLUSIONS

A conservative approach was taken to avoid overstating emissions savings. Diesel van fuel economy, a key variable, is often lower than 15 mpg when operating in congested urban areas. Moreover, the extra distance traveled by vans searching for and finding parking (and the resulting emissions) was not considered. The emissions resulting from idling while waiting for a parking spot or when double-parking, even though significant, were not taken into account either (*14*).

Despite the conservative approach, the results show a high reduction of GHG gas emissions when diesel vans are replaced by electric tricycles. In Portland's electricity mix, CO_2e emissions fell by at least 51%. But even in a region with a large electricity emission rate, CO_2e emissions are cut by half. These emissions reductions are somewhat similar to those found in other research efforts. Browne et al. evaluated the use of an urban distribution center and electric

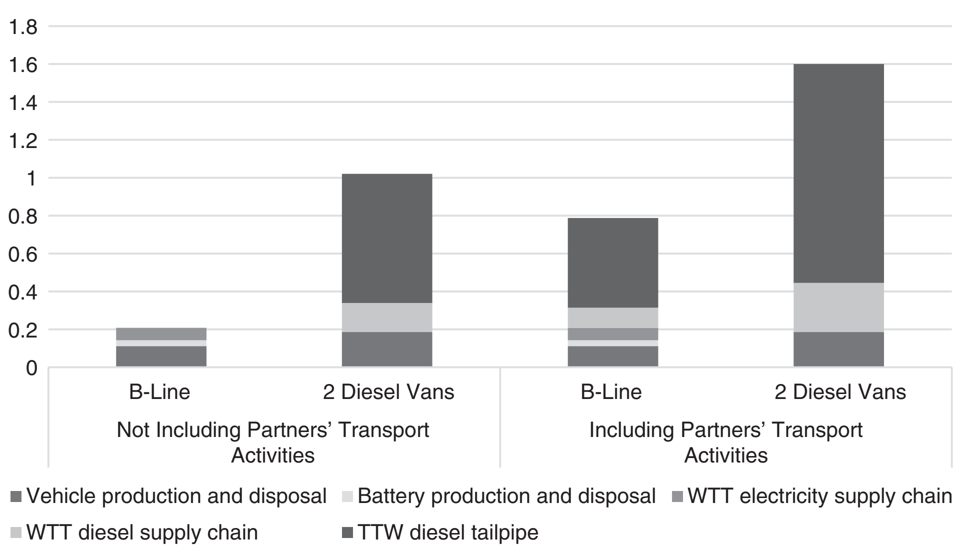

FIGURE 3 CO_2e emissions per delivery (lb).

vehicles in London and came to the same conclusion (*15*). CO_2e emissions were cut by 54%.

An important trade-off between cargo tricycles and diesel vans was found with respect to total distance traveled versus CO_2e emissions. Cargo tricycles reduce CO_2e emissions because of the cleaner energy source, but limited carrying capacity translates to longer total travel distance. On the other hand, trucks can take advantage of economies of scale, which reduce total travel distance, although the per mileage CO_2e emission is still greater than that of cargo tricycles.

High urban density and congestion levels are important factors because in these circumstances van traffic speed and miles per gallon are reduced and emissions and route time are increased. In densely congested areas, where freight transportation externalities are high, tricycle competitiveness and benefits are maximized. Because tricycles' service time is shorter and their speed is slower, they are more efficient when customers are more densely located.

In summary, this research analyzed the carbon footprint of a tricycle logistics company and compared the results with the carbon footprint of a typical diesel-powered delivery company. The results showed that electric tricycles can reduce CO_2e emissions between 50% and 70%, depending on the cargo consolidation factor. If partners' transportation activities are not included, a larger reduction can be achieved: six tricycles and 12 batteries have only 20% of the carbon footprint of two diesel vans—that is, emissions are five times lower.

ACKNOWLEDGMENTS

The authors thank Franklin Jones and the B-Line staff for their openness, cooperation, and support during the data collection effort. This work was supported by the Transportation Technology and People Laboratory at the Maseeh College of Engineering and Computer Science at Portland State University. This work was also supported in part by the Ministry of Economy and Competitiveness of the Government of Spain and the Ibero-American Program for Science and Technology for Development. Support was also received from the Caja Navarra Foundation in Spain.

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The authors are responsible for any errors or omissions.

The Standing Committee on Transportation and Air Quality peer-reviewed this paper.