ANALYSIS OF TRICYCLE LOGISTICS SERVICES LIFECYCLE GHG EMISSIONS

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ABSTRACT
This paper assesses the carbon footprint of a tricycle logistics company (B-Line) which is currently providing last mile distribution services in downtown Portland, Oregon. B-Line freight tricycles are electric and human powered vehicles with zero tailpipe emissions. Detailed real-world route GPS and warehouse data were recorded to evaluate B-Line supply chain operations and compare tricycle and diesel van emissions. Supply chain data is utilized to construct a lifecycle emissions model that includes power and fuel consumption during deliveries as well as vehicle and battery production, assembly and disposal emissions. The model also incorporates delivery logistics constraints such as time windows, cargo capacity, and customer distribution. Total emissions upper and lower bounds as well as elasticity values are analyzed. Results show that lifecycle emissions per delivery are at least five times lower when tricycles are utilized.
INTRODUCTION

Our earth is warming. According to the EPA (USEPA, 2015a), the earth average temperature has increased by 1.5°F over the past hundred years and this increase is likely due to anthropogenic greenhouse gas (GHG) emissions. EPA projections estimate that the earth temperature will increase between 2 and 11.5°F over this century.

Greenhouse gas emissions from transportation accounted for 27% of total U.S.A. GHG emissions in 2013, and have risen by 16% since 1990. Reducing global transport GHG emissions will be challenging because transportation emissions are strongly coupled with gross domestic product (GDP) growth. Since 2008, truck vehicle miles traveled (VMT) in the U.S. has been increasing as a result of economic growth, more international trade, and more intercity trade (NCFRP, 2013). In 2006, freight movements accounted for 9% of the total U.S. greenhouse gas emissions and 29% of the total GHG emissions coming from transportation-related sources; truck emissions accounted for 68% of this total. Trucking emissions are caused by VMTs but also by idling. Idling is ubiquitous at ports and intermodal stations as well as inner city streets as a result of traffic congestion and during deliveries; idling trucks in the U.S.A. consume about 20 million barrels of diesel fuel and generate 10 million tons of CO₂ annually (Cambridge Systematics, 2010).

Traffic congestion has a great impact on fuel efficiency and CO₂ emissions because of the relationship between vehicle operating speed and the rate of CO₂ per mile traveled. Delivery fleet emissions are linked to distance traveled but also show a rapid non-lineal growth in emissions when speed falls below 30 mph (Figliozi, 2010). Congestion affect emission rates because fuel consumption is a function of both acceleration rates and travel speeds. A strategy to reduce transportation emissions is switch to vehicles with a smaller carbon footprint. Environmental advocates, policy-makers and the trucking industry have great expectations for use of electric commercial vehicles in urban freight movement. Emissions reductions are expected to be high, especially in areas with low speed, high congestion, and high idling rates during deliveries and the last mile of transportation. Smaller vehicles (tricycles) have a smaller production and disposal carbon footprint (USDOE, 2015) but the tradeoffs are not so clear when several smaller vehicles can be replaced by a larger vehicle (e.g. diesel vans). This research analyzes the level of GHG emissions reductions that can be achieved utilizing electric tricycles in urban areas. B-Line (2015) is a sustainable logistics company that is currently operating in downtown Portland, Oregon. B-Line offers customers an urban delivery as well as warehousing and pick-up services. The researchers were able to shadow B-Line drivers, warehouse staff, and mechanics. Several days of detailed GPS route and warehouse data were recorded and filmed/photographed. The main goal of this study is to compare B-Line’s lifecycle GHG emissions against lifecycle GHG emissions of a conventional urban delivery company that utilizes diesel vans. Diesel vans are the natural competitor for tricycles given relative small tricycle capacity. Although
several research efforts have recently evaluated the benefits of tricycle logistics services, most research efforts have ignored vehicle life cycle emissions when evaluating environmental impacts. The existing research have mainly focused on operational CO\textsubscript{2} emissions. To the best of the authors’ knowledge, there is no published tricycle logistics company lifecycle GHG assessments in the existing literature or analyzing emissions elasticity values.

**LITERATURE REVIEW**

A strategy to reduce urban truck traffic is the utilization of urban consolidation centers which seek to remove freight vehicles by finding ways to combine the pick-ups and deliveries of different shippers and different receivers (Dablanc et al., 2013). Urban consolidation centers and companies which provide last mile logistics by using electric vehicles and/or tricycles have been increasingly appearing in European cities (Schiliwa et al. 2015).

A study documents the benefits of the Chronopost Concorde urban consolidation center located in downtown Paris (TURBLOG, 2011). Chronopost is a big French express parcel company and the Chronopost Concorde facility is an urban depot where deliveries are first trucked and later moved to electric vehicles for last-mile delivery; a fleet of 16 electric vehicles is utilized for final deliveries to clients. Chronopost achieved higher productivity, 70 deliveries per route instead of 56, and CO\textsubscript{2} emissions decreased by 60\% in a six-month period. One-third of the decrease was due to the new logistics organization and two-thirds of the reduction was due to the use of an electric van fleet for final deliveries. Browne et al. (2011) evaluated a trial in which office supply was delivered from a suburban London depot to final customers in downtown. During the trial diesel vans were replaced by electric vans and tricycles operated from a consolidation center close to downtown. Deliveries are first trucked and later moved to electric vehicles for last-mile delivery in downtown London. A total of six tricycles and three electric vans delivered the cargo from the distribution center to 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 travelled was reduced by 20\% and the CO\textsubscript{2}e emissions per parcel fell by 54\%. GNewt Cargo was the operator of the micro-consolidation center, tricycles, and electric vans.

Conway et al. (2014) analyzed two tricycle delivery services in New York City. Emissions reductions were estimated assuming that Cycles Maximus cargo tricycles replaced a five-year-old cargo van. The annual savings were between 19 and 21 tons of CO\textsubscript{2}, and between 3.4 and 4 lbs. of PM\textsubscript{10}. In this case study, tricycles were fully human-powered and therefore no emissions are released during their operation. The emissions savings were estimated by using the EPA’s MOVES model.
Unlike previous research efforts, this research analyzes all lifecycle stages of tricycles and vans and also utilizes a highly detailed dataset obtained from shadowing real-world operations of a tricycle logistics company. In addition, a logistic model based on continuous approximations is created and emissions elasticity values are estimated and analyzed.

**CASE STUDY**

B-Line Sustainable Urban Delivery was founded in February of 2009. The company delivers a wide variety of products, such as produce, baked goods, coffee beans, bike parts, and office supplies to restaurants, coffeehouses, bike shops and office buildings. B-line also performs reverse logistic services with the pickup and consolidation of materials for recycling. B-Line only utilizes electric and human powered cargo tricycles for delivery and pickups. Most of the B-Line customers are located in or nearby Portland downtown area. B-Line distribution warehouse is located only 2 miles from downtown Portland as shown in Figure 1.

![Map of B-Line distribution warehouse, partners and customers location in downtown Portland.](image)

**FIGURE 1.** B-Line distribution warehouse, partners and customers location in downtown Portland.

B-Line depot is located near the edge of downtown and can be considered as an urban consolidation and distribution center. B-Line routes are complex because tricycles volume optimization is essential to achieve competitiveness. Routes not only include traditional distribution from the depot with time windows but also pickup at partners and customers locations. Routes may include both pickup(s) and deliveries.
This research only considers the distribution of goods delivered from B-Line’s depot to customers, approximately 90% of the products delivered. For the sake of brevity and to facilitate the comparison of the results with previous research efforts, this research does not analyze the benefits and/or GHG emissions reductions of reverse logistic services for the pickup and consolidation of materials for recycling.

B-Line’s partners transport their products from their respective warehouses to B-Line’s depot and then B-Line delivers those products by tricycle. B-line operates seven days per week. On May 2015, the researchers were able to collect detailed route and warehouse/depot operations data. Detailed vehicle and batteries data was provided by the full-time mechanic at the depot. Partners operations and warehousing consolidation data was provided by the operations manager. Several days of detailed GPS route data was recorded utilizing a smartphone application called ORcycle (http://www.pdx.edu/transportation-lab/orcycle). The GPS data was then mapped and analyzed to estimate route durations, tricycle speeds, and customer service times. Table 1 presents a summary of some key average values that describe the scope of B-Line operations.

<table>
<thead>
<tr>
<th>Characteristic or Parameter</th>
<th>B-Line delivery system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of daily deliveries</td>
<td>80</td>
</tr>
<tr>
<td>Delivery area size (mi2)</td>
<td>8 sq. miles</td>
</tr>
<tr>
<td>Distance from warehouse (mi)</td>
<td>2 miles</td>
</tr>
<tr>
<td>Customer demand (lb.)</td>
<td>65 lbs.</td>
</tr>
<tr>
<td>Working hours (h)</td>
<td>8 hours</td>
</tr>
<tr>
<td>Total distance traveled per day</td>
<td>82 miles</td>
</tr>
<tr>
<td>Customer service time (min)</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Delivery days per year</td>
<td>360 days</td>
</tr>
</tbody>
</table>

**TABLE 1. Delivery service characteristics and planning parameters.**

B-Line owns 6 tricycles made by Cycles Maximus and 12 Lead Acid AMG batteries made by Odyssey Battery. Two batteries are needed for each tricycle; one for the morning route and one for an afternoon route. Batteries are swapped after a route to ensure that batteries do not reach a low state-of-charge which may result in reduced battery life. During several years B-Line staff have collected 1,150 observations related battery energy parameters before and after each route. Utilizing this data, we estimated a median fuel economy of 48.65 watt-hour/mile (20.55 miles/kWh). These measurements were taken from the batteries themselves (not from the electric motor) and electricity losses as a result of batteries energy transmission inefficiency are included in this median number. In addition, chargers and power converters connected to the grid are drain small amounts of power and there are some efficiency losses when the
battery is charging; an efficiency level of 85% is typical in the literature (Stevens and Corey, 1996). In this study, we assume an average charging efficiency level of 70% in order to avoid over-estimating tricycle’s fuel efficiency. Battery chargers life-cycle impacts (materials, production, assembly and recycling) are excluded from this assessment, because of their small number, low weight and long life expectancy.

The goal of this research is to compare lifecycle GHG emissions of tricycles and conventional diesel vans. The specifications of a typical cargo tricycle and the assumed values for a diesel van are shown in Table 2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Electric tricycle</th>
<th>Diesel cargo van</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles Maximus</td>
<td>RAM ProMaster 2500</td>
<td></td>
</tr>
<tr>
<td>Gross Vehicle Weight Rate</td>
<td>1,100 lbs.</td>
<td>8,941 lbs.</td>
</tr>
<tr>
<td>Curb Weight</td>
<td>500 lbs.</td>
<td>4,781 lbs.</td>
</tr>
<tr>
<td>Battery Weight</td>
<td>77.8 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Engine Capacity</td>
<td>-</td>
<td>3.6 liter V-6</td>
</tr>
<tr>
<td>$e_{\text{vehicle material}}$</td>
<td>4.108 lbs CO2e / lbs vehicle</td>
<td>3.995 lbs CO2e / lbs vehicle</td>
</tr>
<tr>
<td>$e_{\text{assembly+disposal+recycling}}$</td>
<td>1.247 lbs CO2e / lbs vehicle</td>
<td>1.247 lbs CO2e / lbs vehicle</td>
</tr>
<tr>
<td>$e_{\text{battery}}$</td>
<td>3.93 lbs CO2e / lbs battery</td>
<td>-</td>
</tr>
<tr>
<td>$e_{\text{well-to-tank}}$</td>
<td>0.846 lbs CO2e / kWh</td>
<td>5.108 lbs CO2e / gallon</td>
</tr>
<tr>
<td>$e_{\text{tank-to-wheel}}$</td>
<td>-</td>
<td>22.72 lbs CO2e / gallon</td>
</tr>
<tr>
<td>Charger efficiency</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>Max Payload</td>
<td>600 lbs.</td>
<td>4,160 lbs.</td>
</tr>
<tr>
<td>Range</td>
<td>30 miles</td>
<td>465 miles</td>
</tr>
<tr>
<td>Fuel economy (city)</td>
<td>48.65 watt-hour/mile</td>
<td>18 mpg</td>
</tr>
<tr>
<td>Fuel economy (find a parking)</td>
<td>-</td>
<td>8 mpg</td>
</tr>
<tr>
<td>Idle fuel consumption</td>
<td>-</td>
<td>0.57 gallon / hour</td>
</tr>
<tr>
<td>Life time (years)</td>
<td>5 years</td>
<td>12 years</td>
</tr>
<tr>
<td>Distance to find parking (ft.)</td>
<td>0 ft.</td>
<td>200 ft.</td>
</tr>
<tr>
<td>Time to find parking (min)</td>
<td>0 min</td>
<td>3 min</td>
</tr>
<tr>
<td>Average speed inside service area</td>
<td>7 mph</td>
<td>10 mph</td>
</tr>
<tr>
<td>Average speed outside service area</td>
<td>7 mph</td>
<td>30 mph</td>
</tr>
</tbody>
</table>

**TABLE 2.** Vehicle characteristics and emissions parameters.
LIFECYCLE ASSESSMENT OF VEHICLES

Life cycle assessment (LCA) is also known as a ‘cradle-to-grave’ assessment. LCA separates emissions along life cycle phases: extraction of raw materials from the earth, process of those materials, manufacturing, distribution, product use and disposal or recycling at the end. We examine commercial vans and electric tricycles in three distinct phases: (a) vehicle cycle, from raw material extraction to disposal but without considering vehicle utilization; (b) well-to-tank or the lifecycle of fuel/electricity production and distribution; and (c) tank-to-wheel or vehicle use operation. This section focuses on the vehicle cycle assessment (a) that does not includes vehicle utilization.

Vehicle production and disposal includes: extraction of raw materials, transport to factories where alloys are developed and final materials are produced, transportation of these parts to assembly plants, production of vehicles at assembly factories, transport and distribution of vehicles to dealers and then, after the use phase, disposal or recycling of vehicles. GHG emissions of these stages are estimated using the GREET model which uses vehicle weight as the functional unit (USDOE, 2015). The GREET model contains hundreds of parameters with default values based on national/regional statics or industrial practice. Detailed documentation of assumptions in relation to industrial processes and technologies are available on GREET publications (USDOE, 2015).

The GREET model does not include the e-tricycle vehicle type, hence, the electric tricycle was modeled as an electric vehicle pick-up truck with conventional materials. The conventional diesel van was modeled as a pick-up truck with an internal combustion engine and conventional materials. Vehicles weight and vehicle production, materials and disposal emissions rates are shown in Table 1.

Additional batteries are necessary for the tricycles operation. Electric tricycles utilize Valve-Regulated Lead-Acid (VRLA) batteries and the estimated the life-cycle emissions of producing VRLA batteries was taken from Sullivan and Gaines (2010). The emissions associated to batteries recycling or disposal stage was taken from Rantik (1999). Combining theses sources, it is estimated that battery lifecycle GHG emissions are 3.93 kgCO2e/kg. Battery weight and emissions rate are shown in Table 1.

LIFECYCLE ASSESSMENT OF ENERGY SOURCES

This is the well-to-tank (WTT) analysis of emissions that includes all the emissions in the energy supply chain. The diesel and the electricity supply chains are analyzed individually.

Life-cycle GHG emissions for fuels such as diesel include several stages: petroleum pumping and extracting, transporting to refineries, production of the final diesel fuel, and then dispensing and distributing through to diesel stations. Around 20% of the diesel life-cycle emissions are emitted during these well-to-tank processes. Using the GREET model and gallons of diesel as the functional unit, the diesel GHG emission factor is estimated and shown in Table 2.
Although electric tricycles do not produce direct emissions, greenhouse gas emissions from electricity generation may be substantial. Electric vehicles produce emissions at power plants where electricity has been generated. Emissions factors are taken from the eGRID database that includes transmission and distribution losses (USEPA, 2015b). The eGRID output emission rates and grid gross loss factor which accounts for transmission and distribution losses are shown in Table 3. The electric generation profiles of three U.S. cities are shown. New York has the “greenest” electricity generation in terms of CO2e, Denver has the “dirtiest”. Portland is below the USA average.

<table>
<thead>
<tr>
<th>Region</th>
<th>GGL Factor (%)</th>
<th>Hydro (%)</th>
<th>Other renewable (%)</th>
<th>Nuclear (%)</th>
<th>Oil (%)</th>
<th>Gas (%)</th>
<th>Coal (%)</th>
<th>CO2e Emitted (lbs/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland, OR</td>
<td>8.21</td>
<td>43.55</td>
<td>5.54</td>
<td>3.44</td>
<td>0.32</td>
<td>14.34</td>
<td>31.3</td>
<td>847.0</td>
</tr>
<tr>
<td>New York, NY</td>
<td>5.82</td>
<td>0.0</td>
<td>0.46</td>
<td>39.9</td>
<td>1.29</td>
<td>57.36</td>
<td>0.0</td>
<td>623.8</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>8.21</td>
<td>3.91</td>
<td>5.71</td>
<td>0.0</td>
<td>0.04</td>
<td>17.15</td>
<td>72.99</td>
<td>1906.2</td>
</tr>
<tr>
<td>USA Average</td>
<td>6.5</td>
<td>6.17</td>
<td>2.68</td>
<td>19.6</td>
<td>1.02</td>
<td>23.97</td>
<td>44.77</td>
<td>1238.5</td>
</tr>
</tbody>
</table>

TABLE 3. Energy sources, grid gross loss (GGL), and CO2e emissions. Source: US EPA

LIFECYCLE ASSESSMENT OF VEHICLE UTILIZATION

This is the tank-to-wheel (TTW) or utilization phase. The vast majority of life-cycle GHG emissions are emitted during the use phase. In this study emissions related to vehicle maintenance are omitted because their value is negligible compared with other life-cycle stages. A fuel economy of 18 miles per gallon is assumed during urban delivery operations, as shown in Table 2. According to EPA (2014), emissions are estimated to be 22.72 lbs. CO2e/gallon of diesel. The amount of emissions in the utilization phase is a function of gallons consumed or distance traveled and fuel efficiency.

A continuous approximation model can be used to estimate total distance traveled by introducing logistics constraints. Dangazo (1984) proposed an approximation for capacitated vehicle routing problems (CVRP) and Figliozzi (2008) modified the approximation model for routes with a few customers per route. Tipagornwong and Figliozzi (2014) modified the approximation model to incorporate specific characteristics of tricycles. For instance, tricycles can deliver faster than traditional vehicles because they can be parked legally on sidewalks in front of the delivery location. In contrast, conventional vehicles need to spend time and distance to find and an available parking space. A new term was added to account for distance to find an empty parking space. The distance approximation is the following:

\[ VRP = k_1 \frac{n - m}{n} \sqrt{nA} + 2rm + n \cdot l_{park} \]

where

- \( VRP \) = distance traveled for a fleet of vehicles (km);
• \( r \) = distance between service area and a depot (km);
• \( n \) = number of customers;
• \( C \) = capacity of a vehicle (number of customer visits per vehicle);
• \( m \) = number of vehicles,
• \( A \) = size of service area (km\(^2\))
• \( k_1 \) = customer distribution coefficient.
• \( l_{park} \) = average distance to find a parking space.

The parameter \( k_1 \) accounts for customers’ location distribution and is a function of customers’ density. Values of the \( k_1 \) coefficient can be calibrated empirically to the delivery service area; in this research the coefficient was calibrated to mimic B-Line’s operation in terms of average daily total distance (82 miles), nine routes and five vehicles.

Access to parking turns out to be a key variable to estimate emissions. In this research it is assumed that the driver of a delivery van have to either (i) cruise to find a free parking space or (ii) double-park illegally in front of the delivery destination. In case (i) there are additional emissions due the the additional distance traveled and also a time penalty is added to the route time; penalties of 200 feet and 3 minutes are assumed respectively. It is further assumed a fuel efficiency of 8 mpg due to the low speed while searching for parking, as shown in Table 2. In case (ii) there are additional emissions because the vehicle is idling while the customer is serviced. Distance and time penalty terms are not included, but a new term accounting for idle emissions is added directly into the emissions model. The estimated fuel consumption of an idling engine is 0.6 liters / hour per liter of engine displacement (Ecomobile, 2015). Hence, a 3.6 liter engine consumes 0.57 gallons / hour, as shown in Table 2.

**EMISSIONS AND LOGISTICS MODEL**

Unlike previous research efforts, the model presented in this research include all stages in vehicle production and recycling and also incorporates logistics restrictions (delivery time, cargo, customer distribution) and parking characteristics of tricycles and vans. In addition, due to the small size and payload of electric tricycles, more than one tricycle can be replaced by a diesel delivery van. Hence, it is necessary to estimate what is the number of vans that minimizes lifecycle emissions for this vehicle type.

The model presented in this section was utilized to estimate the number of vans that minimizes lifecycle emissions while satisfying all the logistics constrains that B-line vehicles must meet. The lifecycle
emissions model is presented below. As explained in the previous section, B-line tricycle data was utilized to calibrate the parameter $k_1$.

**SET**

$I = \text{Set of vehicle types, } i \text{ belongs to the set of vehicle types, } I = \{\text{van, tricycle}\}$

**DECISION VARIABLES**

$R^i = \text{Number of routes of vehicle } i \text{ to serve all customers}$

**PARAMETERS**

$E^i_{\text{tot}} = \text{Total emissions for vehicle } i \text{ (lbs.CO}_2e\text{)}$

$e^i_{\text{mat}} = \text{Emissions of material processing for vehicle } i \text{ (lbs.CO}_2e\text{ / lbs. vehicle)}$

$e^i_{\text{prod}} = \text{Emissions of vehicle } i \text{ production / disposal (lbs.CO}_2e\text{ / lbs. vehicle)}$

$e^i_{\text{bat}} = \text{Emissions of battery production / disposal (lbs.CO}_2e\text{ / lbs. battery)}$

$e^i_{\text{wtt}} = \text{Emissions of WTT phase for vehicle } i \text{ (lbs.CO}_2e\text{ / gallon or lbs.CO}_2e\text{ / kWh)}$

$e^i_{\text{ttw}} = \text{Emissions of TTW phase for vehicle } i \text{ (lbs.CO}_2e\text{ / gallon or lbs.CO}_2e\text{ / kWh)}$

**OTHER PARAMETERS**

$c^i = \text{Per – mile fuel or electricity consumed by vehicle } i \text{ (mile / gallon or mile / kWh)}$

$c_{\text{park}} = \text{Per – mile fuel consumed while finding a parking (mile / gallon)}$

$c_{\text{idle}} = \text{Per – hour fuel consumed at idle (gallon / hour)}$

$m^i = \text{Number of vehicles of type } i \text{ to serve all customers}$

$l^i = \text{Per – tour distance traveled to serve route of vehicle type } i \text{ (miles / tour)}$

$w^i_{\text{tar}} = \text{Vehicle } i \text{ tare weigh (lbs.)}$

$w^i_{\text{bat}} = \text{Battery weigh (lbs.)}$

$b^i = \text{Number of batteries}$

$w^i_{\text{cap}} = \text{Payload capacity for vehicle } i \text{ (lbs.)}$

$w_d = \text{Average unit customer demand (lbs.)}$

$v^i_{\text{in}} = \text{Average speed of vehicle } i \text{ running inside service area (mph)}$

$v^i_{\text{out}} = \text{Average speed of vehicle } i \text{ running outside service area (mph)}$

$t^i = \text{Total route time of vehicle } i \text{ (hours)}$

$t^i_{\text{ser}} = \text{Average customer service time from vehicle } i \text{ (hours)}$

$t_{\text{max}} = \text{Maximum daily working time (hours)}$

$y^i = \text{Life expectancy of vehicle } i \text{ (years)}$

$y^b = \text{Life expectancy of batteries (years)}$

$d_{\text{year}} = \text{Days of service per year}$
OBJECTIVE

Minimize total emissions = material assembly, production & disposal + battery material, production & disposal + use phase + find parking (only first scenario) + idle service time (only second scenario)

\[ E_{tot} = \left( \frac{e_{mat}^i + e_{prod}^i}{y_i} \right) m^i \cdot w_{tar}^i + d_{year} \left( \frac{e_{bat}^i \cdot b^i \cdot w_{bat}^i}{y^b} \right) + d_{year} \left( \frac{e_{wwt}^i + e_{tww}^i}{c^i} \right) R^i \cdot l^i + h \cdot d_{year} \left( \frac{e_{wwt}^i + e_{tww}^i}{c_{park}} \right) n \cdot t_{park}^i + j \cdot d_{year} \left( \frac{e_{wwt}^i + e_{tww}^i}{c_{park}} \right) n \cdot t_{ser}^i \cdot c_{idle} \]

[1]

\[ l^i = \frac{k_1 n - m^i}{n \cdot R^i} + 2^\bar{r} \]

[2]

\[ t^i = \frac{k_1 n - m^i}{R^i \cdot v_{in}^i} + \frac{2^\bar{r}}{v_{out}^i} + n \cdot t_{ser}^i + h \cdot n \cdot t_{park}^i \]

[3]

\[ m^i \geq \frac{R^i \cdot t^i}{t_{max}} \]

[4]

Subject to

\[ R^i \geq \frac{n \cdot w_{d}}{w_{cap}} \]

[5]

\[ t^i \leq t_{max} \] [6]

\[ b^i \geq 2m^i \] [7]

\[ R^i \in \text{Set of positive integers (natural number)} \] [8]

\[ m^i \in \text{Set of positive integers (natural number)} \] [9]

\[ h = 1 \text{ For the first scenario, otherwise } = 0 \] [10]

\[ j = 1 \text{ For the second scenario, otherwise } = 0 \] [11]

Equation 1 is the objective function. Equation 2 is the length of a route, starting from a depot, serving customers, and returning to the depot. Equation 3 is the duration of a vehicle route. Equation 4 is the minimum number of vehicles needed to serve all customers. Equation 5 is the vehicle route capacity.
Equation 6 is the working time constraint. Equation 7 is the minimum number of batteries for a tricycle. Equations 8 and 9 restrict the number of vehicles and routes to the set of positive integers. Equations 10 and 11 make one scenario at a time.

**MODELING RESULTS**

Nine tricycle routes are needed to serve all customers: four tricycles make two routes and one tricycle just make one. On the other hand, three vans can serve all customers by doing just one route each. Even though the distance traveled by vans is smaller, the total emissions are several times higher. The total daily distance traveled by diesel vans is 63 miles (of which 3 miles are extra distance to find parking), almost a 25 percent less than the distance traveled by tricycles. Because of the tricycle’s lower payload, a tricycle route has fewer deliveries and is shorter.

Figure 2 compares total emissions per customer in pounds of CO2e. The left columns represent lifecycle tricycle delivery emissions and the right columns lifecycle van delivery emissions. The third column represent van emissions when vans travel 200 ft to find parking; the fourth column represent van emissions when vans double park and idle. Tricycle lifecycle emissions are substantially lower than van lifecycle emissions. Even the emissions using “dirty” electricity are at least five times lower than van emissions. Utilizing Portland’s electricity generation profile, tricycle emissions due to electricity consumption (operating emissions) only account for 28% of total tricycle emissions. The remaining 72 percent are due to tricycles and batteries production and recycling. Using Denver’s electricity generation profile, operating emissions account for 47%. By contrast, in the case of diesel vans, operating emissions (due to fuel consumption) represent 82% of the total emissions in the first scenario, and more than 92% in the second scenario.

Idling can have a highly significant impact in urban logistics when the routes have many customers and customers are nearby; vehicles spend more time at the customers than actually traveling between customers. Because customers service time is 10 minutes on average a total of 4.5 hours of idling time per day per van was calculated.

Another important outcome of this study is that from the first time, to the best of the authors’ knowledge, electricity consumption during electric-tricycles operations has been measured: 48.65 watt-hour per mile, or 20.55 miles per kilowatt-hour. Diesel vans fuel economy is assumed to be 18 miles per gallon. The EPA estimates that the energy content of one gallon of diesel is equivalent to 33.7 kWh, and that makes diesel fuel economy of 18 mpg equivalent to 0.53 miles per kilowatt-hour. This makes B-line tricycles almost 40 times more energy efficient than diesel vans.
Elasticity Analysis of per customer emissions

An elasticity analysis is useful to understand what variables are likely to affect total lifetime emission changes. All parameters in the elasticity analysis are related to logistics and transportation constraints, as shown in Figure 3.

Emissions are very sensitive to number of customers or number of daily deliveries and customer distribution because these variable increases significantly the distance traveled. The emissions of vans are very sensitive to fuel efficiency but when vans double park (D-P) the elasticity value is almost 1/3 lower. When vans double park emissions are very sensitive to fuel consumption while idling and the service time duration. In general, any variable related to distance traveled affect more vans than tricycles, except for distance between depot and service area. Tricycles return more often to the depot (shorter routes), hence they are penalized for this additional distance.
FIGURE 3. Per customer emissions elasticity analysis.

CONCLUSIONS

This research has analyzed the carbon footprint of a tricycle logistics company that is currently providing delivery services in Portland, Oregon. Results show that emissions per customer are at least 5 times smaller when tricycles are utilized. With Portland’s electricity profile, tricycle lifecycle CO$_2$e emissions per customer are around seven times smaller than diesel vans lifecycle CO$_2$e emissions per customer. Utilizing the “dirtiest” USA electricity generation profile lifecycle CO$_2$e emissions per customer are five times smaller when tricycles are utilized.

High customer density is one of the most important variables to reduce emissions. Due to the fact that tricycles service time is shorter and their speed is lower, dense congested urban areas where transportation externalities are higher, maximize tricycles’ environmental benefits. Higher congestion levels, lower road capacity, and extensive bicycle networks improve tricycle logistics services environmental benefits and competitiveness. Idling at customers can drastically increase vans emissions.

Local and state governments which are concerned about freight urban transportation externalities should incentive the use of small electric vehicles in urban delivery operations. On a per mile basis, tricycles have CO$_2$e emissions rates that are 40 times smaller than vans’ CO$_2$e emission rates. In this study only
greenhouse gases which affect global warming are estimated, but it is important to highlight the contribution of tricycles logistics services to improve cities’ air quality by shifting tailpipe emissions from downtown areas to more remote power plants.
REFERENCES


RANTIK (1999) Life cycle assessment of five batteries for electric vehicles under different charging regimes, The Swedish transport and communications research board.


