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Minimization of urban freight distribution lifecycle CO_2e emissions: Results from an optimization model and a real-world case study

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ABSTRACT

This research models urban freight distribution services lifecycle CO_2e emissions. A lifecycle emissions minimization model for the fleet size and composition problem is presented and applied to a real-world case study. The model explicitly incorporates parking and idling emissions which are significant in multi-stop urban distribution routes. Lifecycle emission elasticities as well as the impact of logistics constraints such as route duration and vehicle cargo capacity are estimated and analyzed. Policy implications and tradeoffs between electric tricycles and conventional diesel vans are discussed.

1. Introduction and motivation

Greenhouse gas emissions (GHG) from transportation related activities account for more than a quarter of total U.S.A. GHG emissions (NCFRP, 2013). Many countries, states, and cities around the world have adopted ambitious GHG reduction plans. For example, the City of Portland, Oregon, Climate Action Plan (CAP) has bold GHG reduction targets (CP, 2015).

Portland CAP acknowledges that in the City of Portland moving goods and people accounts for nearly half of the GHG emissions. Portland CAP also highlights the importance of improving the efficiency of freight movements in the Portland region. In response to the CAP, the Portland Bureau of Transportation (PBOT) prepared a Central City Sustainable Freight Strategy (CCSFS) to identify freight problems and to address the challenges of accommodating sustainable, safe, and efficient goods movement in an increasingly dense central city environment. The CCSFS report recommends that the City evaluates opportunities to provide incentives, explores the feasibility of waiving fees for cleaner vehicles, and fosters sustainable policies related to cleaner vehicles, truck loading and parking, street design, and zoning.

The utilization of cleaner commercial vehicles is one of the most popular strategies to increase the sustainability of commercial operations in dense urban areas (Anderson et al., 2005). Although many research papers and CAPs recommend the adoption of cleaner and/or alternative freight delivery vehicles, there is no published research that has evaluated *lifecycle* emissions of medium and small commercial vehicles in dense urban areas. The existing research have mainly focused on commercial vehicles *operational* CO_2 emissions or long-haul freight. Vehicle miles traveled (VMT), fuel type, and engine type do have a major impact on the amount and type of emissions emitted from a commercial vehicle. However, in urban areas, emissions related to searching for parking or idling while parking may also be significant.

This research is motivated by CAPs that call for cleaner commercial vehicle incentives and for the lack of studies focusing on urban commercial vehicles lifecycle emissions. In this research, lifecycle emissions are not only modeled but also estimated for a real-world urban delivery company that operates in Portland, Oregon. The real-world case study compares lifecycle emissions of conventional diesel vans and electric cargo tricycles.

The specific contributions of this research are the following: (a) a lifecycle emissions minimization model for the fleet size and composition problem, (b) the explicit incorporation of parking and idling emissions, (c) the analysis of lifecycle emission elasticities for different vehicle types and operations, and (d) a discussion of effective urban freight GHG reduction policies based on real-world data. After the literature review this research presents a lifecycle emissions minimization model, a case study, and a discussion of elasticity values and policy implications. The paper ends with a section of conclusions.

2. Literature review

Life cycle assessment (LCA) is also known as a ‘cradle-to-grave’ assessment. LCA separates emissions along life cycles or phases: extraction of raw materials from the earth, raw materials processing,

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manufacturing, distribution, product use, and disposal or recycling at the end of the product life (Von Blottnitz and Curran, 2007). We examine commercial vans and electric tricycles in three distinct phases: (a) vehicle phase (VP), emissions associated to raw material extraction to disposal but without considering vehicle utilization, (b) well-to-tank (WTT) phase or emissions associated to the lifecycle of fuel/electricity production and distribution, and (c) tank-to-wheel (TTW) phase or vehicle utilization or operational emissions.

Trucking TTW or operational emissions are strongly related to VMT but also to congestion and travel speed. Traffic congestion has a great impact on fuel efficiency and CO_2e emissions because there is a rapid non-linear growth in fuel consumption when travel speed falls below 30 mph (Figliozzi, 2011). Stop-and-go traffic conditions also increase emission rates. Engine idling is also an important source of emissions. Idling is ubiquitous at ports and intermodal stations as well as urban areas; idling trucks in the U.S.A. consume 20 million barrels of diesel fuel and generate 10 million tons of CO2 annually (USDOT, 2010). Idling fuel consumption ranges from 0.36 gal/hour to 0.93 gal/hour for small/mid-size commercial engines an up to 1.8 gal/hour for large commercial engines (Brodrick et al., 2002; Frey and Kuo, 2009). Idling has been ignored in many analyses. However, some studies suggest that idling is significant, for example heavy-duty line-haul truck engines idle 20–40% of the time the engine is running – depending on season and operation (Rahman et al., 2013). In an urban context, reducing idling is also a common strategy to reduce GHG emissions (Arvidsson et al., 2013).

A strategy to reduce freight transportation emissions is to switch to vehicles with a smaller carbon footprint and/or to utilize electric vehicles (Pelletier et al., 2014). Some researchers have analyzed electric passenger vehicles lifecycle emissions; a relatively high lifetime mileage is a key parameter to ensure emissions reductions (Hawkins et al., 2013) or economic feasibility (Figliozzi et al., 2011). Regarding commercial vehicles, Sen et al. (2017) recently compared battery electric heavy-duty trucks against conventional diesel trucks. Results show that heavy-duty electric trucks outperform all other engine types if the electricity is generated from renewable energy sources (Sen et al., 2017).

Smaller vehicles such as tricycles have a smaller production and disposal carbon footprint and they can be cost competitive in urban areas where parking or access to destinations is difficult, average speeds are relatively low, the depot is centrally located, and customers are densely distributed in a small delivery area (Tipagornwong and Figliozzi, 2014; Figliozzi and Tipagornwong, 2017). However, tricycles cannot compete with traditional vehicles when customers require long travel distances or large/heavy deliveries. Illegal parking, double parking, and the congestion caused by parking activities are high in dense urban areas (De Cerreño, 2004; Kladeftiras and Antoniou, 2013). Fostering the adoption of alternative vehicles that do not require street parking, such as tricycles, reduces emissions indirectly by reducing congestion, VMT cruising for parking, and illegal double parking events that reduce roadway capacity (Figliozzi, 2017).

Conway et al. (2014) analyzed two tricycle delivery services in New York City and significant emissions reductions were estimated assuming that human powered cargo tricycles replaced a five-year-old cargo van. Utilizing data from a tricycle company, Saenz et al. (2016) determined that tricycles emissions are almost 40 times smaller than a conventional van per mile traveled and that lifecycle emissions are lower for tricycles. In general, the tradeoffs among vehicle types are not evident when several smaller vehicles can be replaced by larger vehicles. Saenz et al. (2016) did not optimize lifecycle emissions and did not analyze parking, idling, emissions elasticities, or the policy implications of their results. Choubassi et al. (2016) analyzed the economic competitiveness of mail delivery services utilizing cargo tricycles and also concluded that high customer density and bicycle friendly urban environments are key for the economics feasibility of tricycle deliveries.

Small tricycles can be successfully coupled with urban consolidation centers that reduce travel distance to customers; by reducing travel distances and increasing load factors urban consolidation centers can increase the emissions efficiency of pick-up and delivery operations (Dablanc et al., 2013). For example, the Chronopost Concorde urban consolidation center located in downtown Paris showed a significant CO_2 emissions reduction; two-thirds of the CO_2 emissions reduction was due to the use of an electric van fleet for final deliveries (Gonzalez-Feliu et al., 2014; Schliwa et al., 2015). Browne et al. (2011) evaluated a trial in which office supply was delivered from a London suburb depot to downtown customers. During the trial diesel vans were replaced by electric vans and tricycles operated from a consolidation center close to downtown; deliveries were first trucked and later transferred to electric vehicles for last-mile delivery. The operation of the electric vehicles did not result in any fossil fuel consumption or GHG emissions because the electricity used by the electric vehicles was generated by renewable sources. Results showed that total distance traveled was reduced by 20% and the CO2e emissions per parcel fell by 54%. A recent case study in Paris presents a detailed analysis of the impact of freight policies that restrict car/truck traffic (i.e. promotes bicycle utilization) in Paris (Koning and Conway, 2016). This study concludes that the utilization of human powered or electric assisted tricycles can have a major impact on the reduction of externalities such as local pollutants and congestion costs.

Summarizing, there are important tradeoffs between utilization levels, operational characteristics, and vehicle types. The tradeoffs are harder to analyze when alternative and/or smaller vehicles utilize electric engines and when parking/idling levels are included in the analysis. Next section presents a novel vehicle type lifecycle emissions minimization model.

3. Lifecycle emissions and fleet optimization model

Unlike previous research efforts that focuses on fleet optimization models to minimize long-term costs (Jabali et al., 2012), the optimization model presented in this research focuses on lifecycle emissions minimization. Other research efforts have focused on the minimization of operational emissions (Figliozzi, 2010). To parsimoniously include routing constrains a continuous approximation model is utilized to estimate route distances and durations and to formulate route constraints (described in subsection (a)). These constraints are later utilized in the optimization model contained in subsection (b). In the following sections the optimization model is applied to a real-world case study.

3.1. Route description and constraints

Continuous approximation methods use estimations that are based on the spatial (and/or temporal) density of demand rather than on precise information about the location and demand of each customer. This planning-level approximation is useful for deriving analytical insights about the relationships between parameters and capturing key variables affecting costs (http://www.sciencedirect.com/science/article/pii/S1366554512000658, Langevin et al., 1996). Continuous approximations have been widely utilized to solve and/or provide policy or managerial insights into many logistics and transportation problems.

Daganzo (1984) proposed an approximation for capacitated vehicle routing problems and Figliozzi (2008) tested and proposed an approximation that works for routes with different types of constraints (including time windows) and routes with a wide range of customers per route. Tipagornwong and Figliozzi (2014) modified this approximation model to incorporate specific characteristics of tricycles. For instance, tricycles can deliver faster than traditional vehicles because they do not search for parking. A new term was added to account for the distance traveled to find an empty parking space when vans are utilized. The distance approximation is the following:

$$VRP = k_a\sqrt{nA} + 2\bar{r}m + n\cdot l_{park}$$

where

- VRP= distance traveled for a fleet of vehicles (km);
- $\bar{r}$= average distance between customers and depot (km);
- n= number of customers;
- m= number of vehicles,
- A= service area size (km^2)
- k_a= service area circuitousness factor
- l_{park} = average distance to find a parking space.

The parameter k_{a} accounts for customers' geographic distribution and circuitousness of the service area.

3.2. Lifecycle emissions optimization model

The lifecycle emissions model is presented below. The optimization model is novel because it includes all phases in vehicle production and recycling and incorporates route constraints and parking characteristics of tricycles and vans. The model determines the best combination of vehicle type and number of customers per vehicle type.

3.2.1. Set

I= {van, tricycle}, set of vehicle types (for van i = 1 and for tricycle i = 2).

3.2.2. Decision variables

n^i= Number of customers served by vehicle type i
m^i= Number of vehicles type i that serve n^i customers

3.2.3. Parameters

E^i_{tot}= Total emissions for vehicle i (lbs.CO_2e)
e^i_{mat}= Emissions of material processing for vehicle i (lbs.CO_2e/lbs. vehicle)
e^i_{prod}= Emissions of vehicle i production/disposal (lbs.CO_2e/lbs. vehicle)
e^i_{bat}= Emissions of battery production/disposal (lbs.CO_2e/lbs. battery)
e^i_{wtt}= Emissions of WTT phase for vehicle i (lbs.CO_2e/gallon or lbs. CO2e/kWh)
e^i_{ttw}= Emissions of TTW phase for vehicle i (lbs.CO_2e/gallon or lbs. CO2e/kWh)
c^i_{trav}= Per – mile fuel or electricity consumed by vehicle i traveling (mile/gallon or mile/kWh)
c^i_{park}= Per – mile fuel consumed while finding a parking (mile/gallon)
c^i_{idle}= Per – hour fuel consumed while idling (gallon/hour)
l^i= Average distance traveled to serve route of vehicle type i (miles/tour)
w^i_{tar}= Vehicle i tare weigh (lbs.)
w^i_{bat}= Battery weigh (lbs.)
b^i= Number of batteries for vehicle type i (2 for tricycles and 1 for vans)
w^i_{cap}= Payload capacity for vehicle i (lbs.)
w_d= Average unit customer demand or delivery size (lbs.)
v^i_{in}= Average speed of vehicle i inside the service area (mph)
v^i_{out}= Average speed of vehicle i outside the service area (mph)
t^i= Total route time of vehicle i (hours)
t^i_{ser}= Average customer service time from vehicle i (hours)
t_{max}= Maximum daily working time (hours)
y^i= Life expectancy of vehicle i (years)
y^b= Life expectancy of batteries (years)
d_{year}= Days of service per year

3.2.4. Objective

$$\min \sum_i E^i$$

$$\sum_i E^i = \sum_i \Bigg[\frac{[(e^i_{mat} + e^i_{prod})m^i\cdot w^i_{tar}]}{y^i} + \frac{d_{year}[e^i_{bat}\cdot b^i\cdot w^i_{bat}]}{y^b} + \frac{d_{year}(e^i_{wwt} + e^i_{ttw})m^i\cdot l^i}{c^i_{trav}} + h\frac{d_{year}(e^i_{wwt} + e^i_{ttw})n\cdot l^i_{park}}{c^i_{park}} + j\,[\,d_{year}(e^i_{wwt} + e^i_{ttw})\,n^i\cdot t^i_{ser}\cdot c^i_{idle}\,]\Bigg] \qquad [1]$$

3.2.5. Constraints

$$\sum_i n^i = n \qquad [2]$$

$$t_{max}m^i \geq t^i m^i = \frac{k_1\sqrt{n^iA}}{v^i_{in}} + \frac{2\bar{r}}{v^i_{out}} + n^i\cdot t^i_{ser} + h\cdot n^i\cdot t^i_{park} \qquad [3]$$

$$m^i \geq \frac{n^i\cdot w_d}{w^i_{cap}} \qquad [4]$$

$$l^i = k_1\sqrt{n^iA} + 2\bar{r} \qquad [5]$$

$n^i \in$ Set of positive integers [6]

$m^i \in$ Set of positive integers [7]

$h = 1$ in the (i) van scenario, otherwise $= 0$ [8]

$j = 1$ in the (ii) van scenario, otherwise $= 0$ [9]

Equation (1) is the objective function, this objective function can be broken down into five parts:

(a) Annualized material assembly, production & disposal emissions $\frac{\left[\left(e^i_{mat} + e^i_{prod}\right)m^i\cdot w^i_{tar}\right]}{y^i}$
(b) Annualized battery material, production & disposal emissions $\frac{d_{year}[e^i_{bat}\cdot b^i\cdot w^i_{bat}]}{y^b}$
(c) Utilization phase emissions associated to distance traveled $\frac{d_{year}(e^i_{wwt} + e^i_{ttw})m^i\cdot l^i}{c^i_{trav}}$
(d) Utilization phase emissions associated to parking (first scenario) $h\frac{d_{year}(e^i_{wwt} + e^i_{ttw})n\cdot l^i_{park}}{c^i_{park}}$
(e) Utilization phase emissions associated to idling (second scenario) $j\,[\,d_{year}(e^i_{wwt} + e^i_{ttw})\,n^i\cdot t^i_{ser}\cdot c^i_{idle}\,]$

Equation (2) ensures that all customers are served. Equation (3) is the route duration constraint. Equation (4) is the vehicle capacity constraint. Equation (5) estimates the average route length per vehicle. Equations (6) and (7) restrict the number of customers and routes to the set of positive integers. Equations (8) and (9) are needed to adjust the objective function and constraints when utilizing different van scenarios (h = 1 for no-idling but extra travel to find parking and j = 1 for idling but no extra travel or time to find parking).

The number of potential solutions growths exponentially as a function of the fleet size. The model evaluates not only cases with one vehicle type (i.e. only vans or tricycles) but also all intermediate combinations – mixed fleets with one or more diesel vans plus one or more tricycles. As the problem size (fleet) grows, the number of alternatives may grow exponentially. The model presented in this section was utilized to estimate the number of vans that minimizes lifecycle emissions while satisfying all the constrains associated to serving the case study customers. The number of tricycles was given by the case study and verified by the model. Mix fleet alternatives were not superior to the all tricycle alternative in terms of total emissions. The case study data are described in the following section and the results of the model in a later section.

4. Case study description

We compare commercial vans and electric tricycles lifecycle emissions based on real-world company data. B-Line Sustainable Urban Delivery 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 such as pickup and consolidation of materials for recycling. B-Line only utilizes electric-human powered cargo tricycles for deliveries and pickups. Most of B-Line delivery stops are located in Portland downtown. B-Line is financially viable and since its launch in 2009 has not receive any subsidies or tax incentives that support its operations. B-line is main tricycle delivery service in Portland though there is also a catering tricycle delivery service company called Portland Pedal Power (PPP, 2017); in December 2016 UPS started a small tricycle delivery trial in Portland (UPS, 2016).

B-Line depot is located only 2 miles from downtown Portland and in the heart of the eastside industrial area where many wholesale, warehousing, and distribution services are located. As shown in Fig. 1, all streets around the B-line depot are designated as truck routes. B-Line routes are complex because tricycle 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 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. In Portland tricycles can be parked legally on sidewalks in front of the delivery location. In contrast, conventional vehicles usually spend extra time and/or distance to find an available parking space. Most B-line customers, restaurants or bakeries, do not have a dedicated off-street loading facility.

Table 1
Average service characteristics and planning parameters.

Delivery Characteristic or Parameter	
Number of daily deliveries	80
Delivery area size	8 sq. miles
Depot-delivery area distance	2 miles
Customer demand	65 lbs.
Working hours	8 h
Total distance traveled per day	82 miles
Customer service time	10 min
Delivery days per year	360 days

B-Line partners transport their products from their respective warehouses to the B-Line depot and then B-Line delivers the products by tricycle. B-line operates seven days per week. 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 were 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. Values of the k_a coefficient can be calibrated empirically to the delivery service area; in this research the coefficient was calibrated to B-Line data. The model presented in Section 3 was solved in a few seconds utilizing Solver and B-line data.

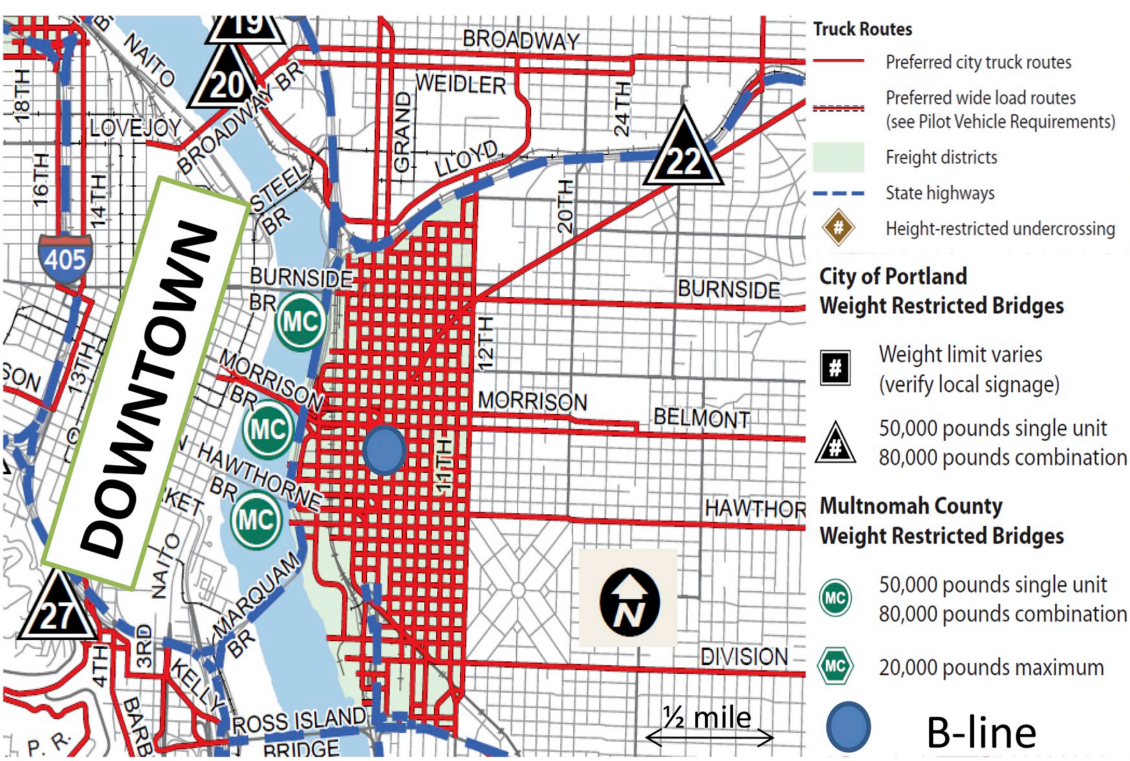

Fig. 1. B-Line distribution warehouse, partners and customers location in downtown Portland.
Adapted from Portland Truck Map (PBOT, 2017)

5. Lifecycle assessment

We divide commercial vans and electric tricycles LCA in three distinct phases: (a) vehicle phase, 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.

5.1. Vehicle phase (VP)

This section focuses on the vehicle cycle assessment only and does not includes emissions associated to vehicle utilization or the energy source. 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, 2016). 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, 2016).

B-Line operated six tricycles made by Cycles Maximus. Diesel vans are the natural competitor for tricycles given the relative small tricycle capacity. In this study we assume that tricycles can be replaced by a

RAM ProMaster 2500, a typical commercial van sold in the USA market. Table 2 presents a summary of the key vehicle characteristics. The tricycle has a relatively small engine and human power provides a non-negligible contribution (technically an electric assist vehicle).

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 production, materials and disposal emissions rates are shown in Table 3. There are energy losses when batteries are charged and utilized, the 0.7 coefficient accounts for these losses.

Additional batteries are necessary for the tricycle 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. B-Line operated six tricycles made by Cycles Maximus and 12 Lead Acid AMG batteries made by Odyssey Battery. Two batteries are needed for each tricycle.

5.2. Energy phase (WTT)

This section focuses on the energy sources and does not includes emissions associated to vehicle utilization or the vehicle production and disposal. The well-to-tank 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 4.

Table 2
Vehicle characteristics.

Characteristic	Electric tricycle	Diesel cargo van
	Cycles Maximus	RAM ProMaster 2500
Gross Vehicle Weight Rate	1100 lbs.	8941 lbs.
Curb Weight	500 lbs.	4781 lbs.
Battery Weight	77.8 lbs.	
Engine Size	250 Watts	3.6 L V-6
Max Payload	600 lbs.	4160 lbs.
Range	30 miles	465 miles

Table 3
Vehicle emissions parameters.

Parameter	Electric tricycle	Diesel cargo van
	Cycles Maximus	RAM ProMaster 2500
$e_{vehicle\ material}$	4.108 lbs CO2e/lbs vehicle	3.995 lbs CO2e/lbs vehicle
$e_{assembly+disposal+recycling}$	1.247 lbs CO2e/lbs vehicle	1.247 lbs CO2e/lbs vehicle
$e_{battery}$	3.93 lbs CO2e/lbs battery	–
Life time (years)	5 years	12 years
Charger efficiency	0.7	–

Although electric tricycles do not produce direct emissions, greenhouse gas emissions from electricity generation may be substantial. Electric vehicles indirectly produce emissions at power plants. Emissions factors are taken from the eGRID database that includes transmission and distribution losses (USEPA, 2016). The eGRID output emission rates and grid gross loss factor which accounts for transmission and distribution losses are shown in Table 5. 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. It is noted that Table 5 does not addresses issues related to nuclear energy long-term disposal and/or contaminations.

Electric energy sourcing can be a key factor. A recent LCA study of medium duty delivery trucks showed that the regional electricity mix source greatly affect electric trucks LCA emissions profile (Zhao et al., 2016).

5.3. Utilization phase (TTW)

This is the tank-to-wheel (TTW) or utilization/operation phase. Previous studies have found that the vast majority of life-cycle GHG emissions are emitted during the TTW phase. In this study emissions related to vehicle maintenance are omitted because their value is negligible comparison with other life-cycle stages.

During several years B-Line staff have collected 1150 observations related battery energy parameters before and after each route. Utilizing this data, we estimated a median fuel economy of 48.65 W-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 drain small amounts of power and there are some efficiency losses when the battery is charging; an efficiency level of 85% is typical

Table 4
Energy emissions parameters.

Parameter	Electric tricycle	Diesel cargo van
	Cycles Maximus	RAM ProMaster 2500
$e_{well-to-tank}$	0.846 lbs CO2e/kWh	5.108 lbs CO2e/gallon
$e_{tank-to-wheel}$	–	22.72 lbs CO2e/gallon

Table 5
Energy sources, grid gross loss and CO2e emissions. Source: US EPA.

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

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.

A fuel economy of 18 miles per gallon is assumed for the van during urban delivery operations. According to USEPA (2014), emissions are estimated to be 22.72 lbs. CO_2e/gallon of diesel. The amount of emissions in the utilization phase is a function of gallons consumed or distance traveled and fuel efficiency. Access to parking turns out to be a key variable to estimate total lifecycle 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 in front of the delivery destination. In case (i) there are additional emissions due the additional distance traveled and also a time penalty is added to the route time; penalties of 200 feet and 3 min are assumed in case (i). The value of 200 ft is derived from observations in Portland, the average distance between available commercial parking and delivery location. The three minutes is an estimate based on the additional time spent by a driver to reach a customer location (the bicycle can park at the door and the unloading of the cargo is faster). It is also assumed a fuel efficiency of 8 mpg while searching for parking (traveling at a lower speed). In case (ii) there are no emissions associated for additional distance traveled but there are emissions associated to engine idling while the customer is serviced. The estimated fuel consumption of an idling engine is 0.6 L/hour per liter of engine displacement (ECOMOBILE, 2015), hence, a 3.6 L engine consumes 0.57 gallons/hour. To be conservative a smaller rate of 0.4 gallons/hour is assumed (Brodrick et al., 2002). Table 6 summarizes all the operational parameters.

6. Case study results

The results indicate it is better to utilize only tricycles that to reduce lifecycle emissions, according to the model the current B-line structure is optimal to reduce carbon emissions. To determine vans lifecycle emissions the model is run only allowing the utilization of vans. For both vehicle types, because fleet size is determined by cargo capacity and/or route duration constraint, the fleet size per vehicle type will not change if the objective function is to minimize fleet costs. The results indicate that for tricycles vehicle capacity and route duration constraints are binding; equations [4] and [3] respectively. Route duration is the only binding constraint for vans and the model reduces vans emission when compared to Saenz et al. (2016) results.

Table 6
Operational parameters.

Characteristic	Electric tricycle	Diesel cargo van
	Cycles Maximus	RAM ProMaster 2500
Fuel economy (city)	48.65 W-hour/mile	18 mpg
Fuel economy (find a parking)	–	8 mpg
Idle fuel consumption	–	0.40 gallon/hour
Distance to find parking (ft.)	0 ft.	200 ft.
Time to find parking (min)	0 min	3 min
Average speed inside service area	7 mph	10 mph
Average speed outside service area	7 mph	30 mph

Table 7
Emissions per customer served (lbsCOe/customer).

Source	Tricycle		Van			
	Portland Elec. Gen. Profile	Denver Elec. Gen. Profile	Parking (200 ft)	Idling 100%	Idling 50%	Idling 25%
Vehicle (VP)	0.13	0.13	0.20	0.20	0.20	0.20
Batteries	0.04	0.04	0.00	0.00	0.00	0.00
Electricity (“WTT”)	0.07	0.15	0.00	0.00	0.00	0.00
Diesel WTT	0.00	0.00	0.24	0.56	0.39	0.30
Tank-to-Wheel	0.00	0.00	1.07	2.47	1.72	1.34
Total	0.23	0.32	1.51	3.23	2.30	1.84

Due to the small size and payload of electric tricycles, nine tricycle routes are needed to serve all customers (there are morning and afternoon routes). Because of the tricycles lower payload, a tricycle route has fewer deliveries and is shorter that a van route. Two vans can serve all customers by doing just one route each.

Table 7 compares 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 and there is no idling. The fourth column represents van emissions when vans park in front of the business (double park if necessary) and idle during customer service time. The fifth and sixth columns represent a smaller percentage of idling time (50 and 25 percent respectively). 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, almost a 25 percent less than the distance traveled by tricycles.

Tricycle lifecycle emissions are substantially lower than van lifecycle emissions. Even the emissions using “dirty” electricity (Denver generation profile) are more than four times lower than van emissions. Utilizing Portland's electricity generation profile, tricycle emissions due to electricity consumption (operating emissions) only account for 29% of total tricycle emissions. The remaining 71 percent are due to tricycles and batteries production and recycling. Using Denver electricity generation profile, tricycle operating emissions reached 41%. By contrast, in the case of diesel vans, operating emissions (due to fuel consumption) represent more than 85% of the total emissions and up to 94% in the 100% idling scenario.

Idling has a major impact; in this case study vehicles spend more time at the customers than actually traveling between customers. Because customer service time is 10 min there is a maximum of 4.5 h of idling time per day per van. Even if the van idles only 25% of the customer service time, fuel consumption and emissions are significantly higher.

Electricity consumption during electric-tricycles operations is on average 48.65 W-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 kW h; this figure makes the diesel fuel economy of 18 mpg equivalent to 0.53 miles per kilowatt-hour. B-line tricycles are almost 40 times more energy efficient than diesel vans on a per mile basis. However, this figure is reduced significantly when more tricycles are needed due to load or time windows constraints.

7. Elasticity analysis

The elasticity analysis was conducted to analyze the relative impact of key parameters. The elasticities were obtained using numerical approximations (1% change) utilizing this function:

$$E(y, x) = \frac{\frac{\partial y(x)}{\partial x}}{\frac{y(x)}{x}}$$

where:

y= lifecycle annual emissions function for a particular vehicle type
x = variable under study (e.g. service time or fuel efficiency)
$E(y, x)$= variable x lifecycle annual emissions elasticity

An elasticity analysis is useful to rank how input data changes are likely to affect annual lifecycle emissions changes. For the tricycle, the elasticity values are shown in Table 8 (sorted from largest to smallest). Increasing the number of customers by 1% results in a 0.56% increase of total emissions, i.e. there are economies of scale with regard to number of customers. This value is closely followed by the circuitousness factors that affects distance traveled in the service area. Service time, distance depot-service area, area size and customer demand are in a second tier. A 1% increase in tricycle energy efficiency results in a 0.40% decrease in total emissions. The impact of travel speed is also important and of a similar order of magnitude (in absolute terms) as customer demand size; both route duration and cargo capacity are binding constrains for tricycles. Hence, more powerful tricycles with a higher payload and engine size can reduce lifecycle emissions by traveling faster and/or carrying more cargo when time windows and/or capacity constraints are binding.

For the van, the elasticity values for the no-idling scenario are shown in Table 9 (sorted from largest to smallest). Emissions are very sensitive to the number of customers but still there are some economies of scale. Vans are less efficient on a per mile basis, hence all the variables associated to distance traveled or area size have higher elasticities. Customer demand has zero elasticity because the cargo capacity constraint is not binding. Van fuel efficiency is the most important factor to reduce total emissions (same absolute value as number of customers).

The elasticity values for the 100% idling scenario are shown in Table 10 (sorted from largest to smallest). When vans idle while serving customers total emission elasticities are greatly affected. Emissions are very sensitive to the number of customers (closer to 1 or elastic) and the elasticities increase for any parameter related to service time and/or idling. On the other hand, distance related parameters and van fuel efficiency while traveling are not as important as in the previous scenario because idling is causing most of the emissions (compare with Table 7).

Table 8
Tricycle emissions elasticity analysis.

Variable	Elasticity
Number of customers	0.58
Circuitousness factor	0.54
Service time	0.33
Depot-service area distance	0.29
Service area size	0.27
Customer demand size	0.24
Tricycle Speed	−0.28
Tricycle energy efficiency	−0.40

Table 9
Van emissions (NO idling) elasticity analysis.

Variable	Elasticity
Number of customers	0.74
Circuitousness factor	0.62
Service area size	0.31
Depot-service area distance	0.16
Service time	0.09
Idle fuel efficiency	0.00
Customer demand size	0.00
Speed outside service area	0.00
Speed inside service area	−0.04
Van fuel efficiency	−0.74

Table 10
Van emissions (idling) elasticity analysis.

Variable	Elasticity
Number of customers	0.90
Service time	0.69
Idle fuel efficiency	0.36
Circuitousness factor	0.22
Service area size	0.11
Depot-service area distance	0.05
Customer demand size	0.00
Speed outside service area	0.00
Speed inside service area	−0.01
Van fuel efficiency	−0.27

If vehicles idle a high percentage of the customers service time, it is possible that idling generates more emissions than actual VMT. The breakeven point between distance travel and idling time can be readily estimated utilizing the following expression.

$$d_{park} \;\; r_{park} = r_{idl} \; t_{idl}$$

where:

r_{park}= fuel consumed while finding a parking (gallons/mile)
d_{park}= distance traveled cruising for parking or to access the business loading zone (miles)
r_{idl}= fuel consumed while idling (gallon/hour)
t_{idl}= time idling (hour)

For example, in our case if the van idles 10 min, idling consumes 0.4 gallons per hour, and the fuel efficiency searching for parking at a low speed is 8 miles per gallon, the breakeven distance is 0.53 miles. Idling at a customer is equivalent to driving 0.53 extra miles at a low speed or 1.2 extra miles driving at a normal speed (during normal conditions the van averages 18 miles per gallon). In the case study there are 80 customers on average, in the case of 100% idling this is 40 or 96 “equivalent” miles with a fuel efficiency of 8 mpg and 18 mpg respectively. The total distance traveled by vans is 65 miles. These figures explain why a small amount of idling rapidly increases total lifecycle emissions and significantly alters elasticity values.

The results from the case study and the elasticity analysis suggests that a few key variables drive lifecycle emissions. For tricycles, vehicle related emissions and for vans fuel efficiency. For both vehicles, route constraints, capacity and time duration, are also significant. It is also important to highlight the key limitations of this research. GREET values are averages valid for the US and for technologies available at the time of the GREET study. As energy sources and vehicles (vans and tricycles) evolve it is important to update these values. The results are also specific to Portland and B-line customer base. To obtain a full understand of lifecycle emissions tradeoffs and their policy implications, additional studies are necessary to evaluate CO2e lifecycle emissions in other cities and with other companies.

8. Policy implications

The case study results clearly show that tricycles generate less lifecycle emissions than diesel vans. Climate action plans are correctly emphasizing a shift towards cleaner and smaller delivery vehicles. The elasticity results also provide some valuable clues regarding actions that can result in CO_2e emissions reductions.

8.1. Urban design

Urban design can greatly reduce emissions per customer by densifying delivery areas, reducing circuitousness factors and by allowing depots that are close to or within the delivery areas. Tricycle circuitousness factors are reduced by policies that promote a well-connected network of wide bicycle lanes. Pedestrian areas and wide sidewalks that can be safely utilized by both foot traffic and tricycles is also a positive design element. Land use policies that preserve land near downtown zoned for warehousing or distribution may be critical to ensure that VMT does not grow for vans and/or to make tricycle deliveries possible.

8.2. Economic feasibility

The elasticity analysis indicates that there are important economies of scale, as more customers are served in a given area the emissions per customer decrease. There is a perfect alignment between urban design elements that reduce emissions and that increase tricycles' economic feasibility. These elements have already been mentioned in point (a): dense delivery area, relatively small delivery size/weight per customer, low circuitousness factor, and local depots that are close to or within the delivery areas. Hence, an urban design that favors tricycles will reduce need for green vehicles subsidies or special incentives. For conventional vehicles, there may be an economic incentive to increase fuel efficiency when fuel prices are high but the speed of fleet replacement may be slow. In some cases a rebound effect may be possible, i.e. more efficient vehicles reduce delivery costs and may result in higher VMT (Winebrake et al., 2012).

8.3. Vehicle size regulations

Tricycles have significant capacity and speed limitations. A van can carry almost seven times more pounds per route than a tricycle. The ratio between vehicles lifecycle emissions is also approximately seven, i.e., the emissions associated to the production and disposal of seven tricycles is equivalent to the emissions associated to the production and disposal of one van. There is a point where tricycles lower emission rates per mile or vehicle are not enough to compensate multiple tricycle delivery trips/vehicles when there are time window constraints, high travel speeds, and/or heavy loads. Tricycles will not be economically feasible either because more drivers (more wages) will be needed to deliver the same amount of cargo. More powerful tricycles with a higher payload and engine size can increase the competitiveness of tricycles but may have other negative side effects. If tricycles are adopted, since most of the tricycle lifecycle emissions are in the vehicle phase a more efficient design (e.g. more payload with less vehicle weight or more payload with a higher proportion of recyclable materials) can further reduce lifecycle emissions. Any measures that discourage large truck access are positive for tricycles but the tradeoffs between number of vehicles and emissions must be carefully analyzed to avoid undesirable effects.

8.4. Parking

Parking is a key factor in dense urban areas when conventional vehicles are utilized. For policy makers, fostering the adoption of alternative vehicles that do not require street parking, such as tricycles, indirectly reduces congestion by reducing cruising for parking or illegal double parking. Cruising for parking or the congestion created by double parking will not be reduced by a gradual replacement of old diesel commercial vehicles by similar sized electric vehicles. In terms of parking, tricycles do have an advantage in dense urban areas without off-street loading/unloading zones. Easier and faster parking reduces tricycle emissions but also increases the economic competitiveness of tricycles by reducing customer service time.

8.5. Idling

If vehicles idle a high percentage of the customers service time, it is possible that idling generates more emissions than actual VMT as discussed in the Elasticity Analysis section. A small amount of idling rapidly increases total lifecycle emissions and significantly alters elasticity values, hence, from a public policy perspective, reducing unnecessary idling can result in high payoffs that may be equivalent to the introduction of cleaner vehicles. Driver education can result in less emissions and also savings for the carrier. Besides idling, the highest reduction in van emissions is obtained by increasing vans fuel efficiency.

The importance of idling may decrease over time as the fleet of older diesel vehicles is replaced by newer or alternative vehicles. It should be noted that electric vehicles do not idle and also that newer diesel engines can automatically shut off while parked or not moving.

8.6. Other externalities and vehicles

Policy makers may support and advocate the use of smaller and environmentally friendly vehicles like tricycles for reasons related to safety, overall urban area livability, and improved air quality/health conditions for urban citizens. In this study only greenhouse gases that affect global warming were estimated, but it is important to highlight that tricycles improve cities air quality by shifting tailpipe emissions from densely populated downtown areas to more remote power plant areas. A recent case study concludes that the utilization of human powered or electric assisted tricycles can have a major impact on the reduction of externalities such as local pollutants and congestion costs (Koning and Conway, 2016). A comprehensive analysis of all the positive impacts of cleaner vehicles may better support the justification of tax incentives and subsidies.

8.7. Alternative vehicles/technologies

Finally, given the exponential growth of the package delivery industry and the potential introduction of new delivery modes such as unmanned aerial vehicles (UAV) or drones (Hackenberg et al., 2018), policy makers may also support and advocate the use of tricycles for parcel delivery since they generate less CO_2e emissions than drones in urban areas (Figliozzi, 2017).

9. Conclusions

This research has analyzed the lifecycle carbon footprint of urban deliveries. A lifecycle emissions minimization model was presented. The lowest lifecycle emissions are obtained by utilizing small tricycles for relatively small loads, in dense service areas, and when the depot is located close to the delivery area. As load size or travel distance grows, the relative efficiency of conventional vans increases. To minimize emissions, different vehicle types should be seen as potentially complementary options (jointly optimized) rather than incompatible options.

The analysis of a real-world case study in Portland, Oregon, showed that lifecycle emissions per customer are at least six times smaller when tricycles are utilized. Utilizing the “dirtiest” USA electricity generation profile lifecycle CO_2e emissions per customer are at least four times smaller when tricycles are utilized. For conventional vehicles, lifecycle emissions increase substantially if vehicles idle at some or all customer locations and when conventional vehicle fuel efficiency is low. On the other hand, tricycle lifecycle emissions are mostly generated by the vehicle production and disposal. Hence, more efficient tricycles in terms of payload, speed, and production/disposal energy intensity can further increase tricycle benefits.

Local and state governments which seek to reduce urban freight transportation externalities can provide incentives to encourage the use of small electric vehicles in urban areas based on estimated lifecycle emissions savings. Incentives are not restricted to monetary or tax incentives, for example incentives to foster tricycle delivery can include a first class bicycle network with high connectivity and wide bicycle lanes or local policies that increases the allowable power or payload of tricycle vehicles. The findings of this research have important implications in terms of urban design, vehicle regulations, parking, and idling policies. However, the proper quantification of alternative policy costsand benefits as well as the optimal tricycle power/payload limits should be the focus of future research endeavors.

This real-world case study utilizes data from an economically viable tricycle delivery company. The case study results cannot be extrapolated or extended to other urban areas or settings without recalculating route constraints and tradeoffs regarding number of vehicles, miles traveled, and idling time. There are complex interrelations among the variables and it is crucial to study both lifecycle emissions and the economic feasibility of alternative vehicles and technologies before adopting GHG reduction policies. Future research efforts should also include the impact of tricycle on externalities such as non-CO2 pollution, congestion, health, and safety.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.tranpol.2018.06.010.

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