An Evaluation of Environmental Impacts of Different Truck Sizes in Last Mile Distribution in the city of São Paulo, Brazil

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Abstract. Motivated by regulations that have prohibited the traffic of large freight vehicles in an inner area of 100 km² in the city of São Paulo, Brazil, in this paper we evaluate the impact of this policy on CO2 emissions by delivery vehicles. These emissions are estimated for two different sizes of freight vehicles under different operational scenarios: the so-called VUCs (4 ton Urban Freight Vehicles) and larger rigid trucks (9 ton). Using different customer densities, drop sizes, and distribution center distances obtained from a sample survey, as well as Daganzo’s continuous approximations for trip lengths and the NTM method, trade-off curves have been constructed. From these curves, it can be seen that bigger vehicles are, on most cases, a better choice than VUCs regarding emission, showing that this policy cannot be generalized for every supply chain.

Keywords: Urban Freight, Environmental Impacts, Freight Policies, CO2 emissions.

1 Introduction

According to the United Nations, São Paulo is the largest city in the Southern Hemisphere [1]. With more than 4.5 million cars, trucks and buses flowing every day [2], heavy congestion, noise, vibration, traffic accidents and air pollution affect everybody. According to the Environment Agency of the State of São Paulo [3], motor vehicles were responsible for the emission of 260,000 t of air pollutants in 2014, almost 90% of total emissions in the metropolitan region of São Paulo. Trucks generated 11% of that total (28,000 t), but accounted for less than 3% of the total fleet. Additionally, high levels of air pollution in São Paulo reduce life expectancy by one and a half years [4].

Even though freight vehicles have a significant contribution to road congestion and CO2 emissions, they also supply goods to more than 200,000 commercial establishments across the municipality of São Paulo [5]. These goods satisfy, every day, the consumption and service needs of its 11 million citizens. Planning and implementing actions and policies that seek to balance the need for goods and environmental concerns, have increasingly been identified as a fundamental role in a modern city [6].

To reduce the congestion and mitigate its environmental impacts, São Paulo authorities have implemented initiatives such as license plate rotation for passenger cars and commercial vehicles, and restricted hours in which is allowed the circulation of trucks. Roughly, those restrictions apply within the Maximum Traffic Restriction Zone (Zona Máxima de Restrição de Circulação - ZMRC). The ZMRC comprises an inner and denser area of 100 km², with a higher concentration of traffic, stores and service in São Paulo City. Traditional trucks are prohibited to circulate within or across the ZMRC during specific periods: Mondays to Fridays between 5 am and 9 pm and on Saturdays between 10 am and 2 pm. Since 2008, smaller trucks, known as “Veículos Urbanos de Carga” or VUC (acronym for urban freight vehicle) are allowed to drive throughout the city with no time restrictions, except the license plate rotation. They are much more agile than larger trucks, thus merge better with car traffic, but are also less productive. As most customers insisted in daytime deliveries, this has resulted in a significant growth of the VUC fleet: 67% over the last ten years [7], against an increase of 6% of other freight vehicles.

In this context, this paper aims to analyze and estimate the environmental impact of this policy, from a CO2 emissions point of view, which in practice substituted VUCs for regular trucks. The remainder of the paper is organized as follows. Section 2 presents essential literature of both carbon emissions and length of delivery routes estimations. In Section 3, we detail the proposed model for estimating CO2 emissions. Section 4 describes the values used for the model parameters. Results are presented and discussed in Section 5. Finally, section 6 makes final remarks and outlines some directions for future research.
2 Carbon emission methods in transportation activities and delivery route length

In this paper, we use CO2 emissions estimation methods that are activity-based, i.e., the emission factors are estimated based on a reference model and a database that relates a particular transportation activity to the emissions caused by that activity. In the GHG Protocol methodology, the required parameters in order to estimate emissions (if fuel consumption information is not available) are freight distance traveled (ton x kilometer) and type of vehicle (individual type emission factors). The most common database is the data provided by the United States Environmental Protection Agency - EPA (GHG Protocol Calculation Tools) [8]. Unfortunately, EPA uses the same emission factor regardless of the type of vehicle or type of road and travel speed, by assuming an average unity fuel consumption for the diesel trucks [9][10]. This methodology does not include a specific load factor, and therefore is based on an average utilization per truck.

An alternative activity-based methodology is the one developed by the Network for Transport Measures NTM in Europe [11]. The NTM methodology, at the highest level of aggregation, is also based on an average utilization per truck, but type of road and type of vehicle are required to estimate fuel consumption. At the next level of detail, NTM methodology requires detailed parameters: fuel consumption, distance traveled and weight per shipment. Fuel consumption is a function of the type of truck/trailer, the load factor and the type of road. Velásquez et. al. [12] have shown that higher resolution modeling of CO2 emissions is relevant for decision making. For the purpose of this paper, we will use NTM method at this higher aggregation level.

With respect to delivery tour lengths, Daganzo [13] proposed an analytical strategy to determine good traveling salesman tours and estimate their lengths in zones of irregular shapes. Daganzo and Newell [14] analyzed the costs involved in distributing items from a warehouse or depot to randomly scattered customers on a daily basis, and derived expressions to determine tour lengths based on density of stops and their average distance to the depot when the location of the delivery points cannot be determined. Motivated by the fact that in most real problems, the road network is a rough combination of Euclidean, rectangular, or ring-radial metric, Galvão et al. [15] applied a multiplicatively weighted Voronoi diagram formulation to finding a near optimal partition of the served region into delivery zones or districts. The Voronoi diagram approach aims to smooth district contours. The method was applied to solve the parcel delivery problem that had been previously analyzed by Novaes and Graciolli [16] [17]. The resulting district contours are smoother and closer to configuration contours encountered in practical situations. The resulting region partition led to a more balanced time/capacity utilization (load factors) across the districts. These approximation methods form the basis for our trip length estimations.

3 Estimating CO2 emissions in the ZMRC

3.1 Assumptions on Traveled Distances and Customers Demands

A delivery vehicle must visit a certain number of customers in its delivery route, according to the demand and to its load capacity. For the same company, it is assumed that all customers’ orders have the same basic characteristics, i.e., items delivered belong to the same category and drop sizes are comparable during the entire route, i.e., they do not differ significantly among deliveries and thus can be used to determine how many vehicles are required to service an area, as detailed in the following subsection. All the deliveries are assumed to be made by driving the vehicle to the customers to be serviced. The vehicle starts its route from the company’s depot/distribution center and travels to the delivery area. After servicing all the customers, the vehicle must return to the depot/distribution center. These two legs of the round trip are assumed to be of same length, named here as line haul distance \(d_l\), see Figure 1. The average distance between two consecutive customers \(d_e\) is a function of a density parameter, described in the model as customers per block. We estimate \(d_e\) using the formulation proposed by Daganzo [13] [14] developed an approximate formula for expected tour length in zones of irregular shape that is a function of the area density levels. Assuming \(N\) points uniformly and independently scattered on a region of area \(A\) Daganzo (1984) shows that the expected tour length \(L\) is given by:

\[ L \approx \phi(\delta^2)\sqrt{NA} \] (1)
Figure 1: Traveled distances for a delivery vehicle route

Where:
\( \phi \): tour length factor, given as a function of the shape/density constant \( \delta l^2 \); 
\( \delta \): density of points; 
\( l \): smaller side of a rectangular-shape zone where points are located 
\( N \): number of points located in a connected region of a plane, considered here as the total number of visited customers; 
\( A \): area of the plane where the \( N \) points are located, i.e., the delivery area.

The author shows that for zones with \( \delta l^2 \geq 12 \), the tour length factor \( \phi \) should be equal to 0.9:
\[
L \approx 0.9 \sqrt{NA}
\]  
(2)

Using a density parameter of customers/block and considering a block a surface of 100 m x 100 m, the average distance between two consecutive customers \( (d_c) \), is given by Expression 3:
\[
d_c = \frac{0.9 * 100 \sqrt{\delta}}{\delta}
\]  
(3)

where:
\( d_c \): average distance between two consecutive customers [m]; 
\( \delta \): density of customers [customers/block].

Thus, the total traveled distance by a delivery vehicle \( (D) \), can be then obtained by Expression 4:
\[
d = 2 \cdot d_l + n \cdot d_c
\]  
(4)

where:
\( D \): total traveled distance by the delivery vehicle; 
\( d_l \): line haul distance; 
\( d_c \): the average distance between two consecutive customers; 
\( n \): number of customers visited by the vehicle on the delivery route.

The CO2 emissions are then estimated using the NTM methodology. For a vehicle type \( v \), travelling on a road of type \( r \), CO2 emissions \( (E_{CO2(v,r)}) \) depends on three main parameters, as in:
\[
E_{CO2(v,r)} = EF_{(f)} \cdot FC_{(v,r)} \cdot D_{(v,r)}
\]  
(5)

Where:
\( EF_{(f)} \): emission factor of CO2 [g/L], for fleet's fuel type \( f \); 
\( FC_{(v,r)} \): fuel consumption rate [l/km] of fleet's vehicle type \( v \), driving on a road type \( r \); 
\( D_{(v,r)} \) the distance traveled [km] by vehicle type \( v \) on a road type \( r \).

In summary, using Expression 4 to estimate the total traveled distance of the delivery vehicle and considering a homogenous vehicle fleet and a single type of road, the total emissions \( (E_{CO2(v)}) \) for an entire daily delivery operations of a company is given by:
\[
E_{CO2(v)} = EF_{(f)} \cdot FC_{(v,r)} \cdot (2 \cdot V \cdot d_l + N \cdot d_c)
\]  
(6)
where:

- \( V \): total number of delivery vehicles required;
- \( d_l \): line haul distance (road type \( r \));
- \( d_c \): the average distance between two consecutive customers (road type \( r \)).

The daily number of customers varies significantly by different products and companies. Thus, the total number of serviced customers (\( N \)) is a function of the density parameter and the delivery area (\( A \)):

\[
N = 100 \cdot \delta \cdot A
\]

(7)

where:

- \( A \): delivery area \([\text{km}^2]\).

### 3.4 Delivery Vehicles Assumptions

Two type of vehicles are compared for the analysis: VUC and a standard truck named TOCO. As mentioned before, a VUC is a small vehicle specially designed to meet São Paulo's regulations, including a smaller payload. It is the only type of delivery vehicle allowed to circulate within the ZMRC of São Paulo during daytime. TOCO is a larger vehicle commonly used in urban freight in Brazil.

When a policy restricts the maximum size or weight of delivery vehicles, it restricts the load capacity of these vehicles and, therefore, the number of customers they can visit on a single route. Thus, if \( N \) is the total numbers of customers to be visited in a daily delivery operation (required by Expression 7), the number of required vehicles (\( V \)) is:

\[
V = \left\lceil \frac{\sum_{c=1}^{N} s_c}{W} \right\rceil \cdot V \left[ V \right] = \min \left\{ n \in \mathbb{Z}^+ \mid n \geq V \right\}
\]

(8)

Where:

- \( s_c \): drop size of customer \( c \) (assumed to be the same for all customers);
- \( W \): maximum load capacity of the vehicle, in ton or m\(^3\), whichever is more binding.

### 4 Model parameters

#### 4.1 Vehicle Parameters

Table 1 presents the assumed values for the parameters of the two vehicle types used for the quantitative analysis. As dimensions and load capacities vary, a standard VUC and a standard TOCO are adopted. The standard VUC and TOCO are represented by models ACCELO 815/31 and ATEGO 1419/48 by Mercedes Benz. Fuel consumptions and emission factors are based on the GHG Protocol Brazilian Program: for VUC and TOCO they are based, respectively, on the average fuel consumption for a light truck (TGW between 3.5 and 10 tons) and a medium truck (TGW between 10 and 15 tons). The CO\(_2\) emission factor, in turn, depends only on the type of fuel used by the vehicle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VUC</th>
<th>TOCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average external dimensions (length x width x height) [m]</td>
<td>6.134 x 2.176 x 2.48</td>
<td>8.175 x 2.486 x 2.713</td>
</tr>
<tr>
<td>Total gross weight (TGW) [t]</td>
<td>11</td>
<td>14.3</td>
</tr>
<tr>
<td>Average load capacity [t]</td>
<td>4.93</td>
<td>9.59</td>
</tr>
<tr>
<td>Fuel</td>
<td>Diesel</td>
<td>Diesel</td>
</tr>
<tr>
<td>Fuel consumption [l/km]</td>
<td>0.131</td>
<td>0.180</td>
</tr>
<tr>
<td>CO(_2) emission factor [kg/l]</td>
<td>2.67</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Source: Mercedes Benz and GHG Protocol Brazilian Program (2013)
4.2 Delivery Parameters

Table 2 lists the parameters required to estimate the total number of vehicles for a daily delivery operation. They are based on several observations, detailed field surveys and route shadowings performed in the city of São Paulo in 2012 and 2013.

Delivery time parameters \(a\) and \(b\) are based on average values from data collected. We consider the same type of road for the entire delivery route as São Paulo is mainly composed of urban streets and the traveled distances on not-urban roads observed are irrelevant. The adopted value for vehicle's speed is of 50 km/h, considering the historical average speeds for the morning period (Map data ©2013 Google, MapLink) and the speed limit of 60 km/h for most of São Paulo’s urban roads.

The delivery area is 968 km², which is the urban area of the city of São Paulo (Embrapa, 2013). This does not negate the insights of the analysis, once it only influences the proportions of the delivery operation. In other words, for a given density of customers per block, the number of customers is proportional to the extent of delivery area, as it is the number of vehicles required and their total travelled distance.

The last three parameters of Table 2, company's line haul distance, customer density and customers' drop size are the changing parameters for the base scenario of analysis, as explained in the following section.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adopted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery time, fixed [min]</td>
<td>(a)</td>
</tr>
<tr>
<td>Delivery time, variable [min/kg]</td>
<td>(b)</td>
</tr>
<tr>
<td>Vehicle speed [km/h]</td>
<td>(v)</td>
</tr>
<tr>
<td>Delivery area [km²]</td>
<td>(A)</td>
</tr>
<tr>
<td>Line haul distance [km]</td>
<td>(d_i)</td>
</tr>
<tr>
<td>Customer density [customers/block]</td>
<td>(\delta)</td>
</tr>
<tr>
<td>Drop size [kg]</td>
<td>(s_r)</td>
</tr>
</tbody>
</table>

5 Scenarios and results

We aim to examine scenarios with the perspective of different companies urban delivery systems. A company's urban delivery operation is composed of three basic components: (i) distribution center (DC) location, (ii) delivery area and (iii) type of good delivered. In this sense, the base scenario for a "Vehicle Size/Weight Restriction" policy is based on three parameters, company's line haul distance, customer density and customers' drop size, which are strict related to these basic components.

For each scenario analyzed, CO2 emissions from the two types of vehicles (VUC and TOCO) have been computed using the parameters shown in Tables 1 and 2. From the base scenario others are originated in which drop size is replaced for others parameters such as fuel consumption, and the lowest CO2 emission type of vehicle for the whole fleet is chosen as a function of line haul distance and customer density. Each curve is called indifference curve, and represents the points where CO2 emissions are the same for VUC and TOCO, i.e., below or above the indifference curve, one of them is the less pollutant choice.

In addition, the analysis also takes into consideration two different types of delivery-profiles, based on the density of customers from two companies making deliveries in São Paulo: a beverage company and a small grocery retailer. These companies are represented in the following charts as a point representing their density and line haul distance. The beverage company delivers to more than 3,500 customers per day, which corresponds to a density of about 0.037 customers/block, and has its distribution center located inside the city limits, only three kilometers far from city center. The grocery retailer company attends approximately 100 stores per day, resulting in a density of about 0.0011 customers/block, and its distribution center is located 21 kilometers far from city center.

The "Vehicle's size/weight restriction" policy is strict related to vehicle's load capacity, which is the only determinant parameter for the total number of vehicles required for a daily delivery operation. Thus, considering the same number of customers and drop size, and no other restriction (such as driver’s working hours or customer’s receiving hours), more small vehicles are needed than bigger ones.
5.1 Base Scenario

The base scenario examines the effects of different drop sizes on vehicle's choice. As shown in Figure 2, TOCO outperforms VUC when the number of customers decreases due to larger drop sizes. On the other hand, VUC is more suitable for areas with smaller density of customers and shorter line haul distances as well. Still, as drop size increases, TOCO would be the best option, if the policy that restricts the traffic of larger vehicles was not effective. For reference, actual values for two types of industries are depicted in Figure 2a. Figure 2b shows a bigger scale for density values, but does not add much to the discussion. Following figures will not show this full density scale.

*Figure 2a: Indifference curves: base scenario - "vehicle's size/weight restriction" policy*

*Figure 2b: Indifference curves: base scenario - "vehicle's size/weight restriction" policy*
5.2 VUC's Capacity Scenario

"VUC's capacity" scenario analyzes the effects of different load capacities for VUCs on vehicle's choice. Each indifference curve denotes a specific capacity with respect to the adopted average VUC weight capacity of 4.93 t. In this case, the average drop size is fixed and equal to 300 kg (Figure 3). Load capacity does influence vehicle choice. Smaller capacity vehicles would be preferred for smaller customer density, as well as for shorter distances. As these parameters increase, the advantage of higher capacity vehicles also increase. For even larger VUC capacities (higher than 6.8 ton) VUC is always the best choice, since its lower fuel consumption counterbalances the additional number of vehicles, resulting in a lower total emission when compared to TOCO. Thus, vehicles slightly larger than a VUC could be a good alternative in terms of reducing air pollution and the total number of delivery vehicles on streets.

Figure 3: Indifference curves: VUC's capacity scenario

Figure 4: Indifference curves: VUC's fuel consumption scenario
5.3 VUC's Fuel Consumption Scenario

"VUC's fuel consumption" scenario examines the effects of different VUC's fuel consumption values on vehicle's choice (Figure 4) considering a fixed value for drop size (300 kg). The range of values for VUC's fuel consumption is based on standards developed by EPA and the National Highway Traffic Safety Administration (NHTSA) for future vehicles. One can note that as VUC becomes greener (due to decreased fuel consumption rate), it becomes a better choice than TOCO for most combinations.

6 Final Remarks

Larger trucks (TOCO) have showed to be the best choice in terms of CO2 emissions in most cases. Given its larger capacity, a smaller number of vehicles can service more customers in a single route and, once VUC and TOCO use the same type of fuel, lower CO2 emissions are expected from TOCO. Also, by considering different VUC capacities and fuel consumption rates it is possible to conclude that, in order to allow the traffic of slightly larger vehicles than VUC, or to incentive the use of greener large vehicles could be good alternatives in terms of reducing the air pollution and the total number of vehicles. Thus, this policy of "Vehicle Size/Weight Restriction" does not look appropriate from an emissions standpoint. For future works, we intend to consider the effect of current truck restriction time windows, as well as actual average truck speeds obtained in the night deliveries pilot project in São Paulo. The effects of parking availability for different truck sizes (VUC’s perform better in this case) will be also evaluated.

Acknowledgments

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References