The Use of Public Railway Transportation Network for Urban Intermodal Logistics in Congested City Centres

Lino G. Marujo, Edgar E. Blanco, Daniel Oliveira Mota and João Marcelo Leal Gomes Leite

Abstract The Mega-cities around the world are experiencing a rapid growth demanding more and more services and products in urban areas, which are often very dense and congested. The traditional road-based logistics strategies have been inadequate in dealing with large restricted delivery operations. Challenges arise due to legislation that restricts the travel of trucks inside the city centres, or to the increasing number of medium size vehicles in the streets. This paper shows a new method by comparing two options of delivering products in the city centres, one using traditional road-based delivery, and another with a hub-spoke model using the public railway transit system. Data analysis of the city's Master Transportation Plan shows a low level of utilization of the public railway transit system, and through this finding, we analysed the inter-modal freight transportation in such urban areas. To cope with transit time and cost, we developed a model, assessing the sensitivity and opportunities by carrying out analysis in a real case study. There is evidence that the model is sensible for the proposed congestion factor in the transit time as it can be a way to improve the service level of the deliveries inside the city centres, decreasing the number of medium sized trucks needed. The results show that it is possible to use inter-modal transportation when the road-based distribution operations suffer from a certain level of congestion in the haulage and last-mile stage.

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1 Introduction

The Mega-cities[1] around the world are facing a rapid growth in their markets. An increasing number of new customers are demanding more and more services and products in urban areas, mainly in emerging markets, which are often very dense and congested. The process of fulfilling these needs is denominated "City Logistics". One critical component is the urban distribution of products, predominantly road-based, which contributes to traffic congestion and is negatively impacting the sustainability dimensions (environmental and financial).

In urban areas, the logistics operations show specific characteristics differentiating them from general logistics activities (Barceló et al. 2007). For example, the parking process is restricted to a few available areas and time to perform deliveries is shorter than at the city outskirts. The relevance of urban freight transportation can also be shown by the last-mile distribution cost within the freight transportation chain. About 40% of the costs are related to pick-up and delivery operations for the total door-to-door cost (Taniguchi and Thompson 2004).

Nevertheless, the intermodal freight chain in urban contexts is little explored compared to interurban distribution operations. Intermodal networks can be characterized by nodes, representing transfer or transhipment points and links, and the possible routes and flows of goods on a network (Crainic and Kim 2007). Hence, the interrelations between different possible modes of transportation to deliver products to customers, is not well analysed in the urban context.

The general objective of this paper, therefore, is to provide an innovative framework for analysing the intermodal operations inside the high-density city centres using alternative schemes of distribution.

The specific aims of this paper are twofold. Firstly, we set out to analyse the utilization of the public railway system in general and identify the opportunities within its capacity. Secondly, we aimed to establish an intermodal cost and time model urban, intermodal operations that are subject to congestion patterns in the stem haul and last-mile section of the delivery process. Both objectives are based on the data available from the public railway systems and demographics patterns of a Mega-city.

The remainder of the paper is organized as follows. Section one reviews the current literature on intermodal logistic operations. Section two discusses the research motivation, the methodology and presents the developed models. Section three presents the numerical example for the public railway transportation system analysis and the intermodal operation scheme assessment for the entire city. Section four presents the discussions and concludes the paper.

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[1] Cities with more than 10 million inhabitants.

Recently, Behrends (2012) stated a relationship between the urban transport system and intermodal transport strategy using the interface of road-rail modes. The aim was to identify possible strategic actions, taken by the local stakeholders, to improve the competitiveness and environmental benefits of rail freight. While pointing out some policies and actions, no explicit model was provided.

Some cities have adopted policies relating to access restriction schemes for certain types of cargo vehicles when entering city centres. This is an attempt to promote the efficiency of mobility and mitigate traffic jams. In this environment, several challenges are faced by deliverers including lack of space, the protection of activities of the citizens and their social-health dimensions. Cargo vehicles are restricted commonly by the time of day of access, by allowed license plates per weekday, by vehicle size and type of operations (Alessandrini et al. 2012).

Diziain et al. (2013), and Taniguchi and Nemoto (2008) have reported some initiatives about the use of intermodal freight transport in urban areas. These relate to the combination of road and rail freight transportation and road and waterways transportation. These case studies focus on garbage collection and transportation of rubbish to a disposal area in Japan, and crops and chemistry in France. Many challenges were highlighted such as the development of specific equipment, for example, containers, for these operations which required subsidies from the government for the initial investment. The authors have stated that intermodal transport of goods can be an option even on short distances. However, the model needs existing logistics facilities, located in the urban centre, adequate transport mode infrastructure (e.g. railways, waterways, etc.), high level of roads and public policy support. Thinking about how a train can carry people and goods, Kelly and Marinov (2017) suggested various designs for the interior of the metro. The authors concluded that is possible to have interior designs which allows good and people transport.

Marinov et al. (2013) have explored the idea of using the existing urban light rail networks for distributing goods in cities. They argued that an efficient distribution of goods by rail will have significant economic and environmental benefits and also minimize traffic congestion and greenhouse gas emissions, along with traffic-generated noise pollution. But the counter side is that it requires huge amount of investments. They analysed six case studies around Europe and stated whether or not an urban rail freight operation is feasible. Following the same idea, Singhania and Marinov (2017) built a simulation model for analysing the utilization levels of a section of a railway line. The authors evaluate the impacts of inclusion of new freight trains. The results proved the viability to include extra freight trains without prejudice to current passenger train timetables. Dampier and Marinov (2015) cited in their paper one of most important benefits of using metropolitan railways for freight transport is accident reduction, with a lower casualty rate.

Moreover, Janic (2007) developed a model for calculating the combined intermodal and road internal and external costs involved, taking into account the costs of the social and environmental impacts. Therefore, the model was implemented with a regional freight perspective; not in an urban context, not being affected by population density, nor congestion (another example is Hanssen et al. 2012). Motraghi and Marinov (2012) created an event based simulation model using ARENA to evaluate the use of urban rail for freight transport. The model allows users to analyse the actual situation and provide alternatives to improve rail system utilization. They used, as example, the Tyne and Wear Metro system in the North East of England.

A study of intermodal freight networks have shown a considerable contribution to the transportation carbon footprint analysis and possible mitigation strategies (see Craig et al. 2013). Craig et al. (2013) derives an expression from the work of Niérat (1997), with the objective of determining the maximum intermodal operation service area, around an origin or a destination, to establish when to use an intermodal operation or a road-based one.

A more generalized intermodal operation is analysed in the work of Smilowitz and Daganzo (2007), where they formulate a general model for a parcel collection, intermodal long-haul, delivery operations, based on the continuous approximation approach (Daganzo 2005). The model was also implemented on a regional perspective.

Another factor, the presence of congestion and its impacts in the logistics activities, has been studied by authors in the classical area of vehicle routing models, but none of these are tackling intermodal operations. They are considering the "green" factors of this activity, analysing the costs and the restrictions as well as the environmental impacts (see Crainic et al. 2004; van Woensel and Cruz 2009; Browne and Gomez 2011).

Figliozzi (2010) has developed an approach based on numerical experiments with real-world data to understand the impacts of congestion in the reliability of logistics operations. He has also analysed the increasing costs, time and distance borne by the carriers. With this cost and structure analysis, he could categorize the distribution system into three different groups, with many stops, fewer stops but inside a large delivery area, and located farther from the depot. The travel time was the fundamental factor to worsen the impact on congestion.

The structure of the last-mile delivery problem is analysed by Novaes et al. (2000). They presented a model of setting district boundaries for fleet planning, taken into account the capacity of the trucks, the time restrictions and the shape of each region of service delivery. These concepts are also used in this paper.

2 Conceptual Framework

2.1 Problem Statement

According to the data analysed, there exists a lack of utilization in public railway transportation networks. The railway system is usually overloaded during the peak-hours. However, in the middle of the day, between peak-periods, the system is sub-utilized. This capacity could be reverted to transport freight, either in a mixed way with passengers or with dedicated transportation units in a segregated schedule.

The traditional delivery method uses trucks from the distribution center to the client location, in a door-to-door schema. It is called a road-based system. Trucks travel the entire line haul inside the delivery zone, attending the customers. The suggested new method combines truck and railway systems to deliver goods to different parts of the city. It uses an intermodal scheme to perform the operations. It begins in a distribution center, where the first-mile (collection of the goods) is performed by trucks. After a transhipment operation, the product is transported by the public railway system to the next destination, the rail line-haul. Finally, transhipment is made to the last-mile delivery vehicles on smaller vehicles, where the products are delivered to the clients. In this work, we have studied a dataset comprising of a Mega-city population density and transit network to estimate the capacity of a railway transit system for freight. We have developed a model to study cost and time parameters for capacity analysis in an intermodal operation.

2.2 Methodology

Our first step was to analyse the city's Master Transportation Plan data to identify the opportunities and existing gaps in the use of the public railway transportation networks. We focussed on the peak-hour identification and the percentage of usage of the public railway system in general and the light rail system in particular. The rail system as an option, but also any transit system with dedicated lanes (for a complete classification of that, see Vuchic 2007). It is important to identify the most relevant period of usage and the critical rail branch for commuting to the city centre, the occupation of lines and stations, as well as the available capacity that could be used for freight.

The second step was to compare the road-based delivery system with the intermodal system. To make this comparison, it was necessary to evaluate the customer service level and the operational cost of each option. The customer service level was measured as the transit time between the distribution center and the customer destination. The cost and transit time evaluation of both operations, shown in Fig. 1, should comprise overall operation steps, including collecting, handling, transporting and delivering the goods to the clients. Both operations have the same initial point, that is the satellite distribution center on the outskirts of the city (Crainic et al. 2004). An important input for transit time calculation is the traffic jam level between the distribution center and the delivery zone and inside the delivery zone. Both models calculate the transit time and total cost of traffic jam levels as one inputs.

After comparing road-based and intermodal service levels and costs using current data, the model allows for elaborate as-if analysis. It is possible to evaluate the impact of traffic jam level changes and evaluate performance level of each delivery system from this model.

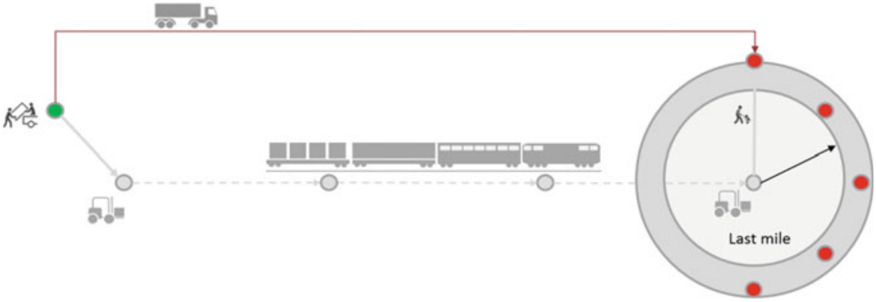

Fig. 1 Intermodal and road-based operations schema, showing the origin of the products and the destination delivery service area, called here as last-mile area. The delivery operation to the service area can be made by truck directly or using an intermodal operation

2.3 *Road-Based Logistic System*

As it was mentioned in the previous section, to evaluate the road-based logistics system required evaluation of customer service levels (measured as total transit time) and total cost. Both models (transit time and cost) are divided in two steps:

1. Line-haul transportation: includes all operations from the distribution center loading until arriving at the beginning of the delivery zone;
2. Last-mile transportation: a set of deliveries to the customers located inside the determined zone, with a volume v_i to attend each customer.

To calculate the transit time and the cost, we used approximate formulas to estimate the vehicle travelled distances and times along the route according Daganzo (2005), Novaes et al. (2000).

2.3.1 Transit Time Model

The Road-based logistic system transit time (T_{RB}) has two components:

1. line-haul transportation transit time until the last-mile zone (T_L);
2. last-mile transit time (T_z),

$$T_{RB} = T_L + T_z, \tag{1}$$

The line-haul transit time (T_L) can be expressed as:

$$T_L = \frac{2.d_{ik}.k_L}{v_L}(1 + \gamma_L) \tag{2}$$

where:

- k_L denotes the dimensionless factor for line-haul distance in Euclidean metric,
- d_{ik} is the distance from origin i to point of entrance into the zone delivery k ($D_L = 2 \cdot d_{ik} \cdot k_L$ denotes the line-haul distance),
- v_L is the free-flow velocity of line-haul transportation,
- γ_L is the traffic jam factor (Sheffi 1985) for the line-haul transportation.

According to Sheffi (1985) the transit time between two points i and k is affected by the traffic jam and can be calculated as:

$$t_{ik} = \frac{d_{ik}}{v_L} = t_{ik}^0\left[1 + \alpha\left(\frac{f_{ik}}{c_{ik}}\right)^{\beta}\right] = t_{ik}^0\left[1 + \gamma_{(.)}\right], \tag{3}$$

where:

- *t_{ik} is the transit time between i and k,*
- *t_{ik}^0 tik is the free flow transit time of the link i, k,*
- *f_{ik} denotes the flow on the link,*
- *c_{ik} is the capacity of the link i, k,*
- *α and β are traffic jams parameters,*
- *γ is the traffic jam factor ($\gamma = \alpha(f_{ik}/c_{ik})^{\beta}$) with $\gamma \in$ [0, 1].*

The last-mile transit time can be determined by:

$$T_z = \left[\frac{2.r_{kj} + \frac{k_z}{\sqrt{\delta}}}{v_z}\frac{W_z}{\beta_i}\right](1 + \gamma_z) = \left[\frac{k_z}{v_z.\sqrt{\delta}} + \delta.A_k.t_s\right](1 + \gamma_z). \tag{4}$$

where:

- r_{kj} is the radios of the delivery zone,
- k_z is the dimensionless factor for the delivery zone distance,
- δ represents the density of customers to be served, when the locations of clients follow a homogeneous 2-dimensional point process (e.g. Poisson). In this paper we assume that the density δ of visiting points over the region is constant. According to Daganzo (2005) and Novaes and Graciolli (1999), the distance of deliveries inside a delivery zone can be approximate by $k_z \cdot \delta^{-0.5}$,
- v_z is the free-flow velocity for the last-mile transportation,
- W_z is the capacity of the vehicle,
- β_i is the average demand per point of delivery,
- A_k represents the area of the zone of delivery k,
- t_s the stop time per deliver,
- γ_z is the traffic jam factor (Sheffi 1985) for the last-mile transportation.

Let n be the number of visits performed in a tour. We assume that the displacement time between two clients within the district of area A (last-mile delivery) suffers under traffic congestion, so $\delta = n/A$. In our work, we were not interested in finding the best sequence of visiting points for each tour in the delivery service for a certain district, constrained by congestion or not (as one can see in Novaes et al. 2009 and others abundant literature as in Pillac et al. 2013).

The maximum number of stops attended per vehicle is $C = \frac{W_z}{\beta_i} = 2.\delta.w.L$, where the w and L are delivery zone dimensions of width and length, respectively.

2.3.2 Cost Model

As the transit time model, the Road-based logistic system cost (C_{RB}) has two components:

1. line-haul transportation transit time until the last-mile zone (C_L);
2. last-mile transit time (C_z),

$$C_{RB} = C_L + C_z, \tag{5}$$

The line-haul cost (C_L) and the last-mile cost (C_z) can be expressed as:

$$C_L = T_L.\frac{c_L^v}{W_L}, \tag{6}$$

$$C_Z = T_Z.\frac{c_Z^v}{W_Z}, \tag{7}$$

where:

- *T_L is the line-haul transit time,*
- *c_L^v represents the variable cost per time in the line-haul transportation,*
- *W_L is the capacity of the vehicle in the line-haul transportation,*
- *T_Z is the last-mile transit time,*
- c_z^v represents the variable cost per time in the last-mile transportation,
- W_z is the capacity of the vehicle in the last-mile transportation.

2.4 Multimodal Logistic System

To calculate both customer service level (measured as total transit time) and total cost, the operation is divided in five steps:

1. First-mile transportation: collecting operation from origin i to the station l,
2. Train loading: handling operation at station l to load the volume to attend the customer zone i in the train,
3. Rail haulage transportation: transport the volume $\sum_i v_i$ from station k to the station l, the beginning of customers' zones,

4. Train unloading: handling operation at customer zone's to unload i volume at station k,
5. Last-mile transportation: a set of deliveries to the customers located inside the deter- mined zone, with a volume v_i to attend each customer.

We will use the same methodology applied in the last session (Daganzo 2005; Novaes et al. 2000).

2.4.1 Transit Time Model

The Intermodal logistic system transit time (T_{IM}) has five components:

1. first-mile transportation transit time (T_{FM}),
2. loading handling time (H_l),
3. rail-haul transportation transit time until the last-mile zone (T_R),
4. unloading handling time (H_u),
5. last-mile transit time (T_z).

$$T_{IM} = T_{FM} + H_l + T_L + H_u + T_z, \tag{8}$$

The first-mile collection operation transit time is calculated as:

$$T_{FM} = \frac{2.d_{il}.k_L}{v_{FM}}.(1 + \gamma_L), \tag{9}$$

where:

- d_{il} denotes the distance between the origin i to transhipment point l,
- k_{FM} denotes the dimensionless factor for first-mile distance in Euclidean metric,
- v_{FM} denotes the free-flow velocity of first-mile,
- γ_{FM} is the traffic jam factor.

The handling time in the loading and unloading transhipment points is:

$$H_l = h_l \cdot L_l, \tag{10}$$

$$H_u = h_u \cdot L_u, \tag{11}$$

where:

- h_l and h_u denote the capacity for loading and unloading handling the quantity of cargo per hour, respectively,
- L_l and L_u is the time consumed for the loading and unloading handling capacity, respectively.

The rail haulage transit time is defined as

$$T_R = \frac{d_{lk}}{v_R} + h_k.L_k, \tag{12}$$

where:

- d_{lk} is the distance from the loading point l until the unloading station k close to the delivery zone,
- $h_{(.)}$ and $L_{(.)}$ follow the same definition of the handling operations (Eqs. 10 and 11),
- v_R is the free-flow velocity of rail haulage transportation.

Based on the work of Pachl and White (2004) the average minimum line headway t_h of the rail-line in study was obtained by:

$$t_h = \sum_{i,j} \frac{t_{h,i,j} n_i n_j}{n^2} \tag{13}$$

where:

- $t_{h,I,j}$ is the minimum line headway adopted for train type j following train type i, for example, express service and regular,
- n_i, n_j are the number of trains for each type,
- n is the total number of trains.

With expression 13, one can determine the total capacity of trains in such branch and with the capacity of each railcar, derive the traction capacity per wagon in kilograms, $W_r = \psi \hat{w} l_r w_r$, once we have the average occupancy of the rail-line, ψ, in terms of passengers per square meters, pass/m^2, the weight profile of the population that uses this branch, $\hat{w}$, and the railcar dimensions l_r, w_r.

Finally, the last-mile transit time approximation function for the intermodal operation is determined in the same way as previously, by:

$$T_z = \left[\frac{2.r_{kj} + \frac{k_z}{\sqrt{\delta}}}{v_z} \times \frac{W_z}{\beta_i} \right] (1 + \gamma_z) \tag{14}$$

Thus, the total cost for intermodal operation (C_{IM}) is given by:

$$C_{IM} = T_{FM} \cdot c_{FM}/W_{FM} + H_l \cdot c_l/W_l + T_R \cdot c_R/W_R + H_u \cdot c_u/W_u + T_z \cdot c_z/W_z \tag{15}$$

where:

- $c_{(.)}$ is the cost per time for each operation: first-mile (FM), loading (l), rail-haul transportation (R), unloading (u) and last-mile (z),
- $W_{(.)}$ is the cost per time for each operation: first-mile (FM), loading (l), rail-haul transportation (R), unloading (u) and last-mile (z).

Table 1 Passengers boarding per branch, per day (adapted from SETRANS 2013b)

Branch	Boarding
Deodoro	256,725
Japeri	115,587
Santa Cruz	81,906
Saracuruna	54,766
Belford Roxo	27,663

3 Numerical Example

3.1 Analysis of the Public Railway System

Rio de Janeiro is a mega city in Brazil. The estimated population including neighbouring municipalities is about 12 million people. The region has more than 4 million vehicles. Rio de Janeiro has a very complex transportation system and suffer with traffic jams due to its geographical characteristics. Rio is a beach town with many mountains, and a poor public transport system.

The analysis of the public railway transportation system of the Rio de Janeiro city started with the tabulation of the Origin-Destination (OD) matrix. This OD matrix is based on 265.000 interviews made in 2012, resulting in about 22.600.000 daily trips.

The analysis of the OD matrix has shown only 24% of the population uses the public transportation system for their morning and evening commute to the central area of the city. Furthermore, only 31% of people use the railway to commute to the city Downtown, which indicates others modes of transportation for commuting (SETRANS 2013a, b).

The modal share evolution shows a 10% decrease in the usage of public transportation and an increase of 15% in the usage of private cars, adding to a 73% growth in the car fleet. Another important analysis is the percentage of total daily trips at each working hour (Fig. 2). For private cars, the peak hour is 7–8 a.m. with 8.00% and the less busy hour is 6–7 a.m. with 6.25% (21.9% less, comparing to peak hour). For public transit, the peak hour is 7–8 a.m., with 8.79% and the less busy is 13–14 with 6.12% (30% less, comparing to peak hour). This result shows a bigger lack of utilization for the public transport.

The profile of the most used branch in Rio de Janeiro City (Deodoro branch—Table 1) shows several opportunities for using the line as freight line, once the peak-periods of passengers are well defined, as shown in Fig. 3. We can see the travel demand to the city, which rises and falls over the course of a day. It characterizes a time-dependent travel demand pattern, and the operating day can be divided into pieces, as the rush periods and the off-peak periods (Fig. 4).

One point to be highlighted is the existing correlation between the low usage of public transportation and the growing usage of private cars in the cities. This, which

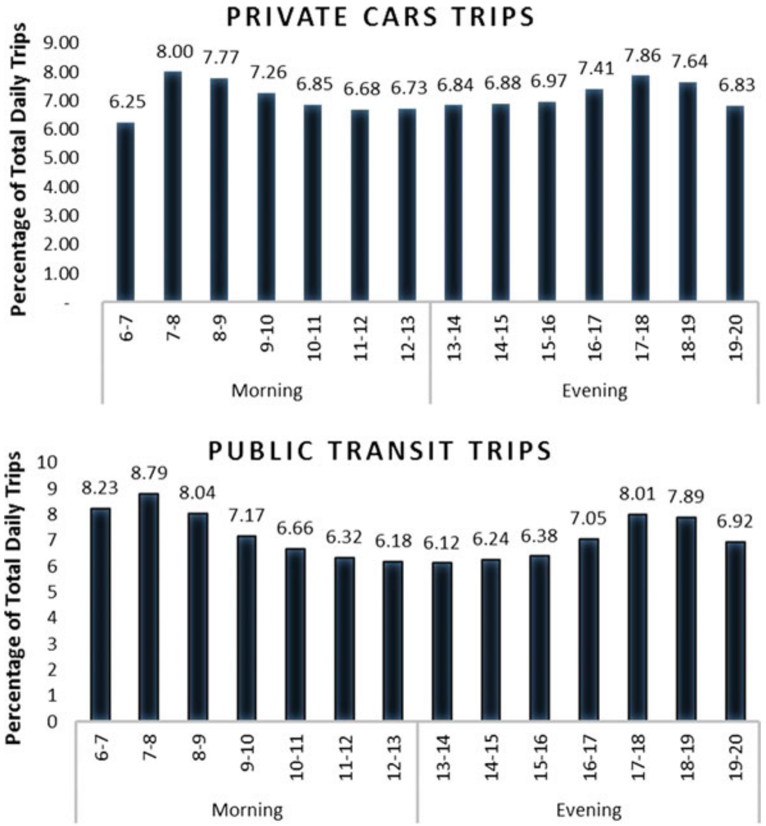

Fig. 2 Percentage of daily trips by hour of the day for private car users and for public transit users. The gap between the maximum and the minimum percentage is more relevant in the public transit trips than the one in the private car trips

leads to an increasing number of traffic-jams and under-utilization of the public transit system, especially out of peak periods.

Therefore, once the public railway system is already implemented and established, these systems could be used for carrying goods from the suburbs to the city in Megacities in a dedicated lane without interference or congestion.

In our analysis, the entire city was divided into 2250 small pieces, called generally as km^2, and for each km^2, the distance to each station was calculated. This produces a graphical structure of the service regions over the entire rail network, oriented by the nearest neighbour logic.

The demand for each km^2 was calculated as a function of the daily trash generation. This generation was related to the concentration of inhabitants in each region to find the estimated demand (COMLURB 2014).

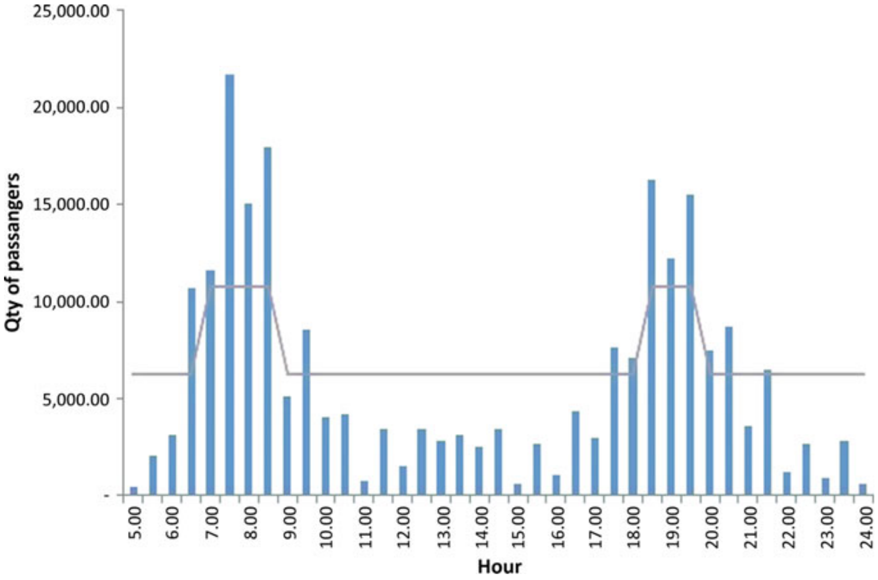

Fig. 3 Usage profile of the Deodoro rail branch, expressed as the quantity of passengers. The straight line represents the capacity of the rail line for a typical day. There are several underutilized periods between the peak ones

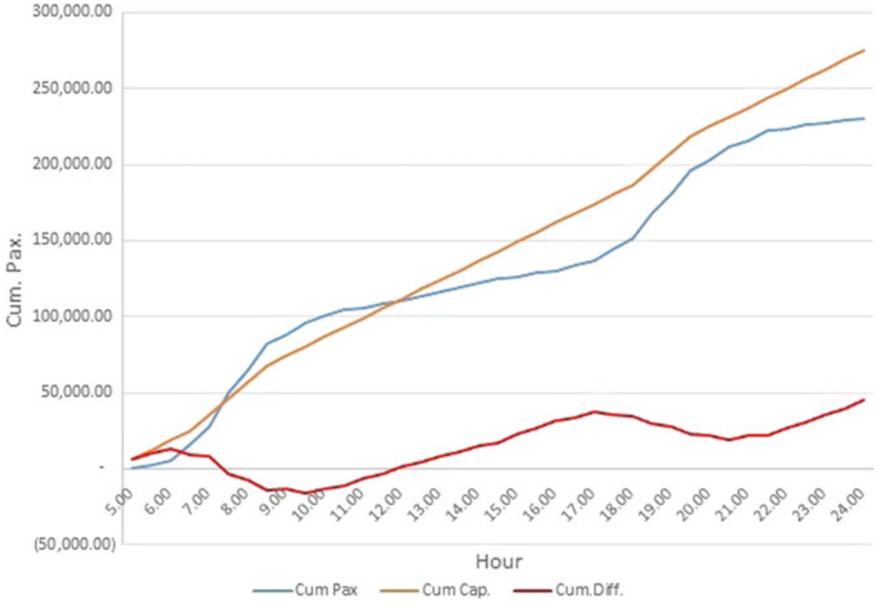

Fig. 4 Cumulative capacity and demand profile of the analysed rail branch per hour. The difference of the capacity and demand is plotted in the curve below

3.2 The Truckload and Intermodal Comparison Results

The comparison between the truckload and intermodal operations strategies can be made based on total costs or transit time benefits. The last-mile is the most congested step of the delivery process, and in our case study, it is located in the Central Business District of the city.

The numerical example analyses the delivery of goods in five dense districts of the centre of city of Rio de Janeiro. The region concentrates about 1200 micro and nano stores and receives more than 70 thousand clients a day in an important commercial area called "SAARA". These districts are the basis of our example, showing the last-mile delivery complexity (Fig. 5).

Within these five closest districts to the destination Central Station, we analysed the five closest stations to each km^2, giving us a basis for the distances, demand, density of stores for the entire rail system.

The rail distance and velocity were taken from the city data and local operators. It is divided into five branches, as in the real planned system. The needed parameters for the models can be found in Table 2.

The parameters A_z, as the area of service zone, N_z, Number of stops per zone and β_i, let be the average demand per stop and W_b, as the capacity of the railcar that was estimated based on the model of railcar and the load factor, come from the city analysis data described in the previous section, and the parameter c_h is a monthly wage based parameter.

The analysis of the trade-off between the direct delivery using trucks and the use of the intermodal configuration (using the railroad system and subject to congestion), identified the intermodal operation is better than the truck-based operation for some regions of the city in terms of total costs.

Fig. 5 Last-mile region characterization of the region called Saara in Rio de Janeiro's downtown (from: maps.google.com)

Table 2 Truckload and Intermodal model parameters and units (based on values provided by Janic (2007) and updated for the 2018 year)

Parameter	Description	Value	Unit
k_L	Dimensionless factor for linehaul distance	1.15	
c_L^v	Cost of linehaul per hour	45.10	\$/hr
c_z^V	Cost of zone delivery per hour	25.72	\$/hr
W_L	Capacity of linehaul vehicle	12,000.00	kg
W_z	Capacity of last mile vehicle	12,000.00	kg
k_z	Dimensionless factor for last mile	1.15	
t_z	Stop time per customer	0.60	hr
c_h	Handling cost per hour at origin station	4.39	\$/hr
c_k	Handling cost per hour at end station	$1.2 \cdot c_h$	\$/hr
h_l	Handling capacity in kg per hour	3000.00	kg/hr
c_r	Cost per railcar per km	0.77	\$/km
ψ	Load factor of railcar per m^2	4.00	pax/m^2
$\bar{w}$	Average weight profile of the		
	Population (IBGE 2013)	67.00	kg/pax

Some critical points arose from the analysis. The handling time at the entrance and destination stations are a function of the coming capacity from the previous transportation mode in that chain. The simulation results have shown that the more controlled these activities are, the more the intermodal system gains advantage.

One first results was the capacity profile per day within the city. It is related to the minimal distance between each km^2 to the nearest station, and so, compared with the estimated demand. It shows the requirement to attend the regions, on a daily basis, is achieved by small vehicles, less than 12 tons (Fig. 6).

There is a specific point of trade-off in terms of cost per ton, as a result of the congestion's influence in the last-mile velocity, as stated by Fig. 7, for the critical branch analysis. This result is due to the dedicated lanes that the rail system has, avoiding the congested infrastructure in part of the delivery.

This can be understood in two fold. Firstly, the total cost per ton is less affected by this factor, which induces to a higher threshold of the velocity, because, in the intermodal operation, more cost to deal with handling the goods are needed. Therefore, for transit time-based analysis, the truck-based operation is more suitable once it can make fewer movements with the cargo.

The analysis of the total transit time, and how it varies with the velocity in the last- mile (most congested part of the delivery), shows that the intermodal schema is worthy in velocities bellow 17 km/h (Fig. 8).

The analysis of the entire system shows that there is a concentration of regions served by each station. Figure 9 shows the heat map for the regions (km^2) served by each station. Some stations serve a 427 km^2 population area.

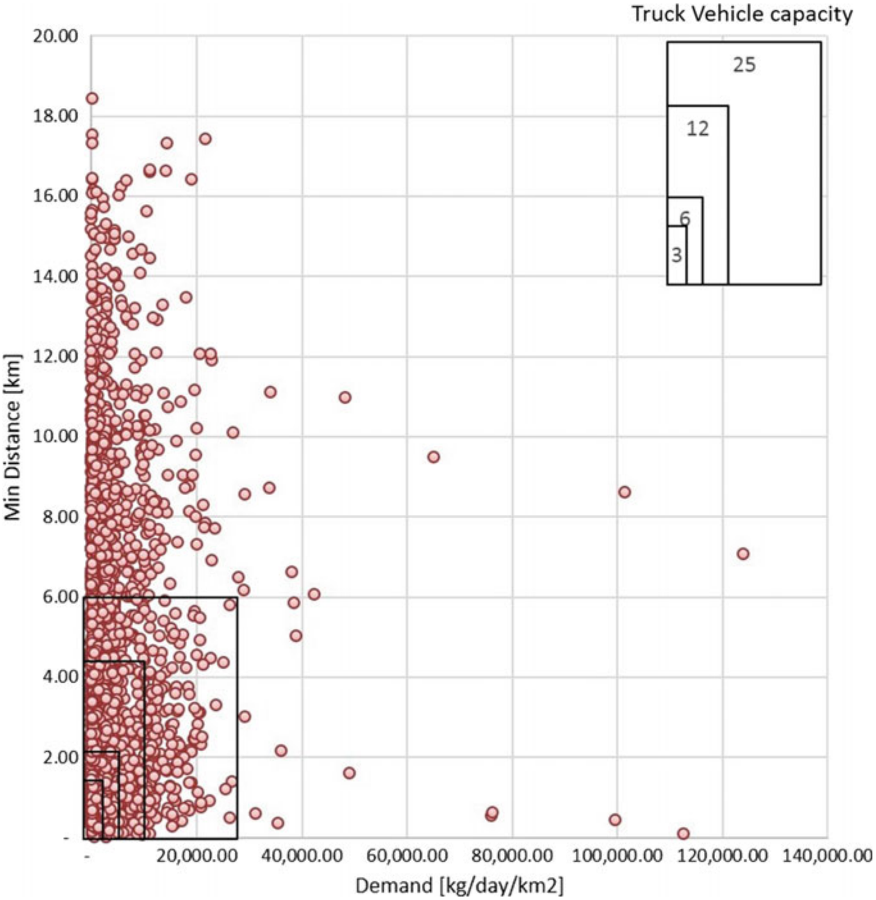

Fig. 6 Analysis of the capacity profile to serve each region in a day by one delivery vehicle

The variation of the congestion factor (γ) produces different sizes of service areas by the intermodal system to serve the city area. Figure 10 shows the service recommendation based in total cost for three different levels of congestion. While with $\gamma = 0\%$ only the west area of the city should use intermodal transport, with $\gamma = 50\%$ only the area close to the city should keep using road-based transportation. Figure 11 makes the same analysis based in transit time. While with $\gamma = 0\%$ only two limited areas should use intermodal transport (green area), with $\gamma = 0\%$ around 50% of the city area should use intermodal transport.

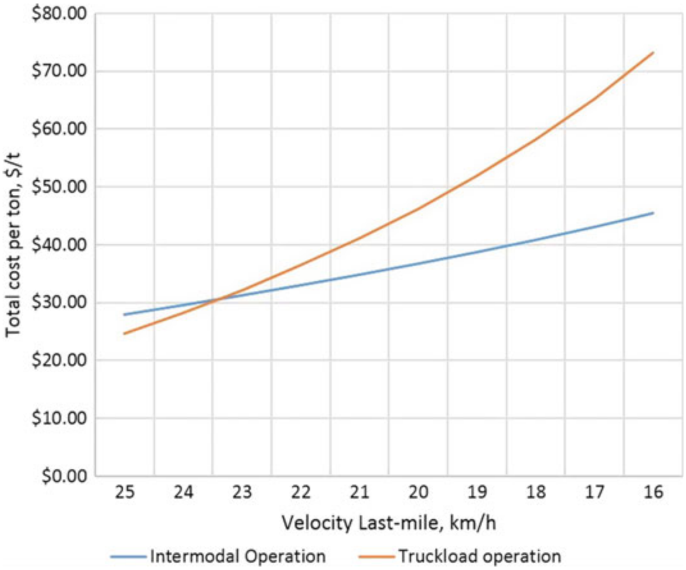

Fig. 7 Sensitivity analysis of the cost per ton delivered and the last-mile velocity affected by congestion. The velocity in the last-mile is affected by γ_L. The point of limit is around 23.5 km/h to intermodal operation becomes worthy

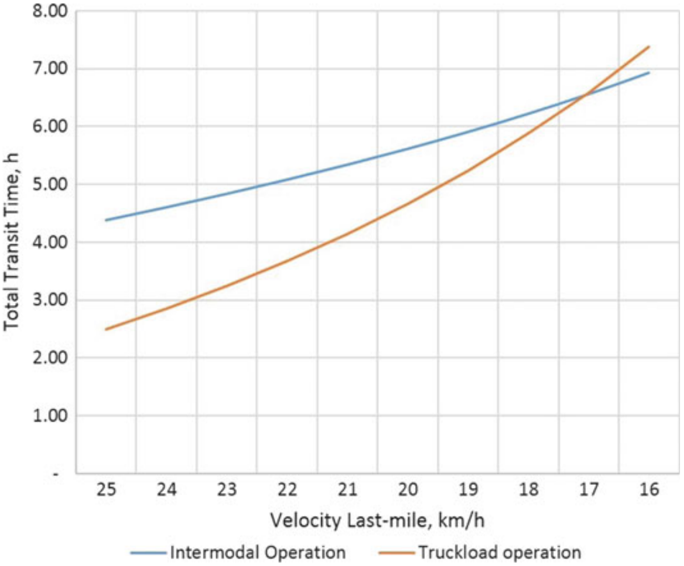

Fig. 8 Sensitivity analysis of the transit time and the last-mile velocity affected by congestion. The limit point to operate with truck-based delivery is about 17.5 km/h

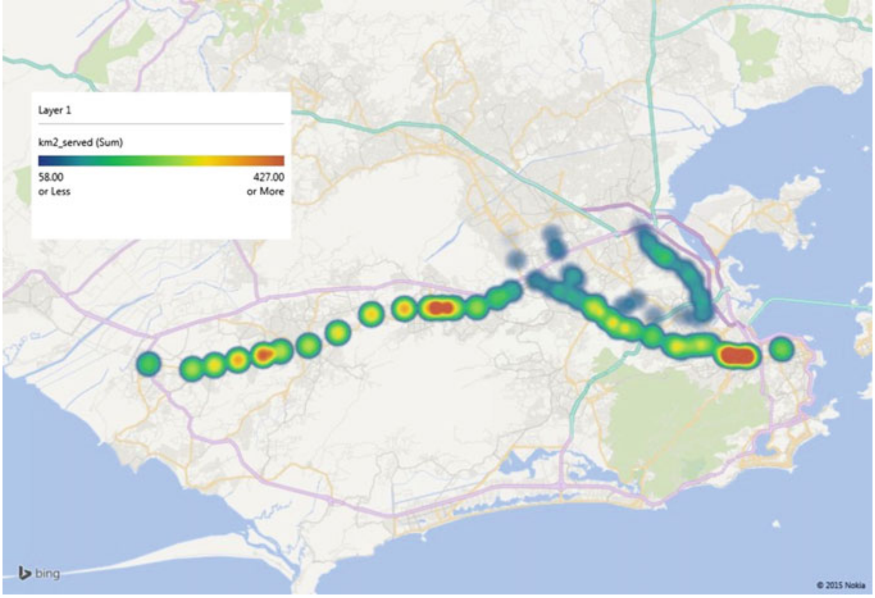

Fig. 9 Heat map for the regions served by each station of the rail system

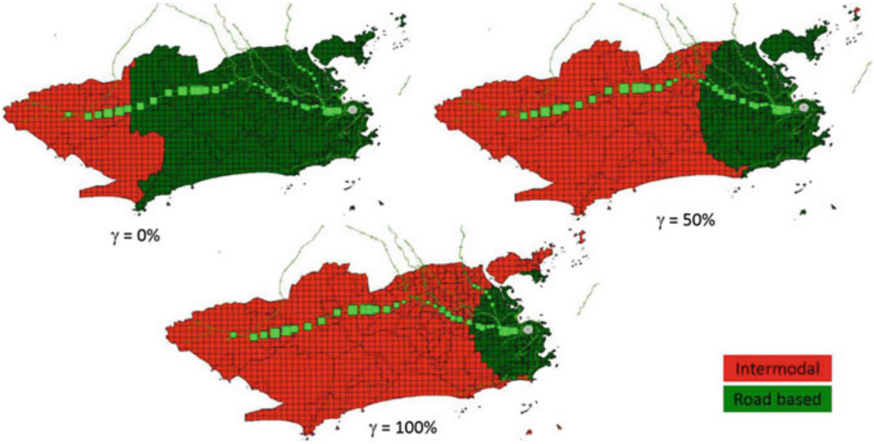

Fig. 10 Service regions variation based on total cost analysis for three level of congestion

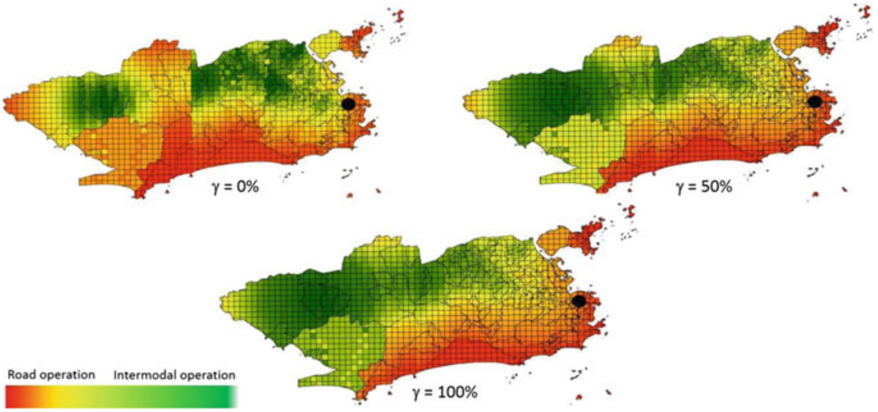

Fig. 11 Service regions variation based on transit time different analysis for three level of congestion

4 Conclusions

The model we developed was able to conduct the trade-off analysis between the use of a road-based system and an intermodal one making the deliveries inside the city centre. The possibility of gains in terms of reducing congestion in the cities' networks are discussed.

The simulation of each station and the surrounding 5 km^2 demonstrates the capacity of the existing rail system to manage the cargo that has a destination in the city centre. The demand served varies across the station as a function of the distance for each region to reach them.

The station profile to attend the demand is a function of the location and population density of the surroundings of each station. Some stations concentrate the demand to serve the km^2's, because they possess a privileged location. One region can be served by more than one station, but its attractiveness decreases in terms of cost, time and probability of congestion.

The system depends on a shared last-mile service system, in order to avoid underutilization of the stations and the fleet, and the generation of undesired pipeline inventory. Future developments can be done to assess other commercial zones and the entire public railway system of a city, simulating the impact generated of the adoption of these strategies, and an analysis of the influence in the system of the different geographical patterns around the world, with their specific transit systems. Also, the inventory levels that can be created in each echelon of the distribution chain should be evaluated and constitutes a future pathway in this research.

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