An Environmental Approach to Optimize Urban Freight Transport Systems

Juan P. Romero, Juan Benavente, Jose L. Moura, Angel Ibeas and Borja Alonso

Abstract This chapter proposes an optimization-simulation model for planning and managing an urban freight transport system, which has to serve one or more points of the network that receive and/or generate a great volume of cargo, using trucks. This type of transport has special characteristics and generates significant impacts: increased traffic congestion, due to the presence of large vehicles which take up much space and are very slow; and air pollution caused by the extra traffic volume and the extra congestion. Therefore, the purpose of the model is to minimize these negative effects on the environment and on the users of the local road network. To achieve this goal, the authors propose and solve an optimization problem to minimize the total system cost (operating costs of the suppliers, costs supported by private vehicle users and public transport users, operating costs of the public transport, etc.). The proposed optimization problem is a bi-level mathematical programming model, where the upper level defines the total cost of the system, and the lower level defines the behaviour of private and public users, assuming that each of them chooses the route that minimizes his total journey cost. Then, this model is applied to the real case in the city of Santander (Northern Spain) obtaining a series of interesting conclusions from the corresponding sensitivity analysis.

J. P. Romero · J. Benavente · J. L. Moura (✉) · A. Ibeas · B. Alonso
G.I.S.T. Group of Research in Transport Systems, University of Cantabria, Cantabria, Spain
e-mail: mourajl@unican.es

J. P. Romero
e-mail: romerojunquerajp@gmail.com

J. Benavente
e-mail: juan_benavente_ponce@yahoo.es

A. Ibeas
e-mail: ibeasa@unican.es

B. Alonso
e-mail: alonsobo@unican.es

J. F. de Sousa and R. Rossi (eds.), *Computer-based Modelling and Optimization in Transportation*, Advances in Intelligent Systems and Computing 262,
DOI: 10.1007/978-3-319-04630-3_10, © Springer International Publishing Switzerland 2014

Keywords Urban freight · Optimization · Environment

1 Introduction

On the subject of urban freight transport, the situation in which one or more points of the network require large amounts of supplies, and/or generate a significant volume of waste material, usually construction and demolition debris, has not been sufficiently considered in the literature. Due to the characteristics of the vehicles used to move the cargo, and how traffic flow is affected by their presence, this type of transport has a significant impact on the urban environment: increased traffic congestion; more air pollution; and, due to longer journey times, a raise in private transport costs.

This problem can be approached as a typical supply chain problem; where materials need to be delivered, in predetermined quantities, to a point, following a schedule. There are many studies where supply chain modeling and simulation have been applied to predict the behavior and optimize the design of many kinds of industry. One example is [1], who modeled and designed the supply chain structure for a food company. With the same aim in mind, other types of tools and techniques have been developed to study urban goods movement in supply chains: simulation techniques to study production, accounting and distribution policies, as in the work of [2]; the Goodtrip model by Boerkamps and Binsbergen [3]; microscopic-level models for mode choice and vehicle routing, as in the work of [4], who use adaptive stated preferences for designing a freight mode choice model; and the freight routing model of time-definite delivery by Lin [5].

As previously stated, none of the references above mention the particular case of transporting large amounts of cargo to or from one or more points of an urban transport network, a subject which has hardly been studied; although some work does exist, such as [6], who designed an integrated model that combines concrete production scheduling with its transport by trucks. Their objective was to minimize the operator costs only, thus social and environmental impacts were not taken into account.

Most of the studies that examine social and environmental impacts have mainly concentrated on the development of rules, regulations, measurement and legislation in order to minimize the impact of goods transport in urban areas. The work of [7] stands out in this field, discussing measures taken and the effects they produced in large European cities; and identifying three characteristics of the urban mobility of goods: the movement of goods is not affected by the internal structure of the city; urban policies regarding freight mobility are inefficient; and the provision of adequate logistic services is growing slower than the need for them in urban areas. From a social point of view, the work of [8] proposes a model for the movement of containers using trucks with time constraints at origins and destinations, guaranteeing that the drivers will not work more than a certain number of hours per shift.

Therefore, this chapter presents a model to optimize freight transport to and/or from one point of the urban network, based on the minimization of the overall costs of the system. Apart from quantifying the costs associated with transport planning, the proposed model considers the emission of pollutants throughout the study area.

This section has presented the Introduction and State of the Art. In Sect. 2, we describe our methodology; Sect. 3 provides specific details of the case study; and finally our main conclusions are shown in Sect. 4.

2 Methodology

We present a model to optimize the planning and management of a system that uses large vehicles (trucks) to supply and/or retrieve great amounts of supplies/waste materials from one point of an urban network. This model considers a number of potential routes, and determines the optimal way to distribute truck trips among them from an economic, social, and environmental point of view. To achieve this goal, a network with car, bus, and truck modes has been modelled and then calibrated; using the modal split and the trip assignment to the network steps to implement the interactions between modes. Therefore, any variation in the characteristics of the freight transport system affects both car and bus modes, as it can lead to modal shifts and changes in the routes chosen by drivers, or lines selected by bus users.

The optimization model is based on the minimization of the total system cost, which is a social cost function composed of car and bus user costs, and bus and truck operating costs [9–11]. Bi-level mathematical programming has been applied to find the best alternative: the urban network model on the lower level returns the data (flows, access times, waiting times, travel times, etc.) needed by the upper level to calculate the total system cost.

$\text{Social Cost} = \text{C}u + \text{C}op$

$$
\begin{aligned}
Cu_{\text{T}} &= Cu_{\text{C}} + Cu_{\text{B}} \\
&\quad Cu_{\text{C}} = \varphi_{Viaje,\text{C}} \cdot T_{Viaje,\text{C}} \\
&\quad Cu_{\text{B}} = \varphi_{Acc,\text{B}} \cdot T_{Acc,\text{B}} + \varphi_{Egr,\text{B}} \cdot T_{Egr,\text{B}} \\
&\qquad\qquad + \varphi_{Esp,\text{B}} \cdot T_{Esp,\text{B}} + \varphi_{Travel,\text{B}} \cdot T_{Travel,\text{B}} + \varphi_{Tra,\text{B}} \cdot T_{Tra,\text{B}}
\end{aligned}
\tag{1}
$$

where:

Cu_{T}	Total users cost
Cu_{C}	Car users cost
Cu_{B}	Bus users cost
$T_{Travel,\,C}$	Car travel time
$\varphi_{Travel,\,C}$	Car travel time worth
$T_{Acc,\,B}$	Bus access time

$\varphi_{Acc,B}$	Bus access time worth
$T_{Egr,B}$	Bus egress time
$\varphi_{Egr,B}$	Bus egress time worth
$T_{Esp,B}$	Bus waiting time
$\varphi_{Esp,B}$	Bus waiting time worth
$T_{Travel,B}$	Bus travel time
$\varphi_{Travel,B}$	Bus travel time worth
$T_{Tra,B}$	Bus transfer time
$\varphi_{Tra,B}$	Bus transfer time worth.

Operating costs are calculated using the following formulation:

$$\begin{aligned} Cop_T &= Cop_B + Cop_{Tr} \\ Cop_B &= CR + CP + CF \\ CR &= \varphi_{CR} \cdot Total\,Km. \\ CP &= \varphi_{CP} \cdot Person\,hours \\ CF &= \varphi_{CF} \cdot N^{\circ}Buses \\ Cop_{Tr} &= \sum_i T_i \cdot f_i \cdot C_u \\ T &= T_{outward} + T_{return} + T_{loading} + T_{unloading} \end{aligned} \tag{2}$$

where:

Cop_{T}	Total operating costs
Cop_{B}	Bus operating cost
Cop_{Tr}	Truck operating cost.

Bus operating costs (Cop_{B}) is made up of three factors: Cost proportional to travelled distance (*CR*), personnel costs (*CP*), and fixed costs (*CF*).

Total cost due to the distance travelled by the buses is equal to:

$$CR = \varphi_{CR} \cdot \; Total \;\; Km. \tag{3}$$

where:

φ_{CR}	Unit cost per kilometer covered by bus

$$Total \;\; Km. = \sum_i L_i \cdot f_i$$

where:

L_i	Length of route i
f_i	Frequency of route i.

Employee costs are calculated considering only the personnel who are really working on the buses:

$$CP = \varphi_{CP} \cdot Person\ hours \tag{4}$$

where:

φ_{CP}	The hourly employee cost (€ per hour)

$$Man - Hours = \sum_i \frac{tc_i}{h_i}$$

where:

tc_i	Time of a round trip (min)
h_i	Headway on route i (min).

Fixed costs are calculated with the following formula that only considers the buses that are really circulating:

$$CF = \varphi_{CF} \cdot N^{\circ} buses \tag{5}$$

where:

φ_{CF}	Fixed cost per hour of bus (€ per hour)

$$N^{\circ} buses = \sum_i \frac{tc_i}{h_i}$$

where:

tc_i	Time of a round trip (min)
h_i	Headway on route i (min).

Truck operating cost (Cop_{Tr}) is estimated as:

$$\begin{gathered} Cop_{Tr} = \sum_i T_i \cdot f_i \cdot C_u \\ T = T_{outward} + T_{return} + T_{loading} + T_{unloading} \end{gathered} \tag{6}$$

where:

$T_{outward}$	Truck outward time
T_{return}	Truck return time
$T_{loading}$	Truck loading time
$T_{unloading}$	Truck unloading time
C_u	Cost per hour of truck use
f_i	Truck flow.

To gauge the environmental impact of the different alternatives, the emissions of 5 types of pollutants have been calculated (CO, NOx, NMVOC, CH_4 and PM). Each transport mode's fuel consumption depends on the total distances travelled

Table 1 Vehicle's consumption rates (litres/Km) and vehicle's emission rates (g of pollutant/Kg of fuel)

	Emissions (g of pollutant / Kg of fuel)					Consumption (l/Km)		
	CO	NOx	NMVOC	CH_4	PM	Congested	Uncongested	Kg/l
Gasoline cars	75.99	10.89	13.44	1.19	0.03	0.08	0.06	0.680
Diesel cars	3.77	11.12	0.61	0.07	0.80	0.07	0.05	0.850
Buses	6.62	32.67	0.99	0.24	0.81	0.34	0.26	0.850
Trucks	9.82	34.84	3.06	0.38	1.34	0.34	0.26	0.850

by vehicles of that mode through congested and uncongested roads [12, 13]. Then, the emissions produced by these consumptions can be estimated [14].

Table 1 shows the different fuel consumption rates for the different kinds of vehicles in our model, depending on if the road is congested or not, and each kind of vehicle's emission rates (g of pollutant/Kg of fuel):

To solve the optimization problem, due to the size of the case study in relation to the number of variables, an exhaustive search algorithm will be applied. It will return all possible solutions, allowing us to analyze how the system behaves.

3 Case of Study

The methodology described above is applied to a real case: the city of Santander (Spain). It is a medium-sized city, with approximately 180,000 inhabitants, located on the north coast of the Iberian Peninsula.

A large construction project in the southeast of Santander will require a flow of 20 trucks per hour. The size and speed of these trucks create a substantial negative impact, increasing air pollution and traffic congestion.

The three alternatives to supply materials to the construction site are shown in Fig. 1. R1 route passes for the most part through a 2-lane urban road, except in the section closest to the construction site, where it goes through a tunnel of 800 m with a single lane in each direction. The route R2 has a initial leg in common with route R1, passing in its final stage to a single lane road in each direction, going around housing areas instead of through the tunnel to get to the construction. Finally, Route R3, even though runs through 2-lane and 3-lane urban roads in each direction, passes through areas of the city with high traffic density.

Applying the methodology previously described, we determine the social cost (user and operating costs), and pollutant emissions of all the different ways to distribute 20 trucks between the three routes.

Also, we perform a sensitivity analysis, studying how different values of the maximum speed for the trucks (20, 15, and 10 km/h) affect social cost and emissions in the city of Santander. The results are shown in Fig. 2.

Moreover, we represent the social cost of all simulated cases, ordering these from lowest to highest social cost. See Fig. 3.

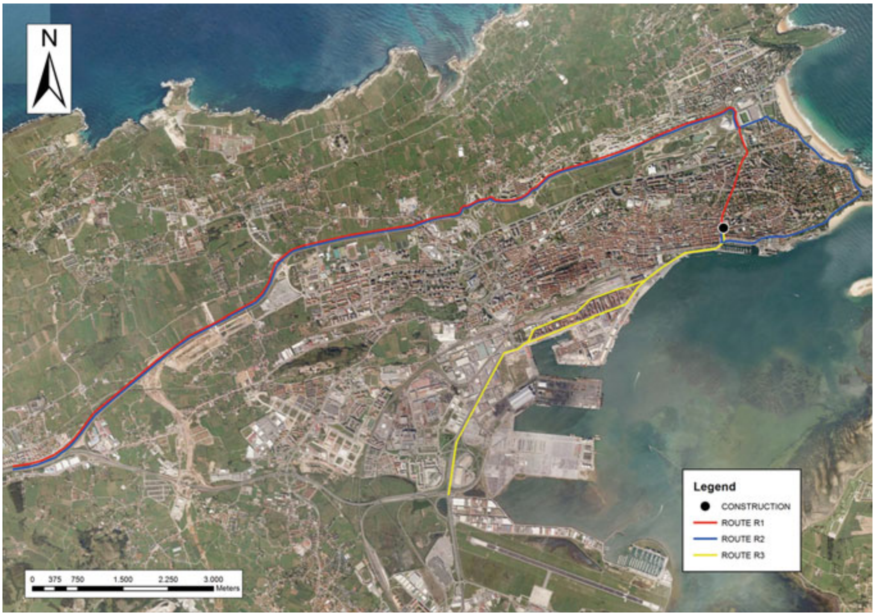

Fig. 1 Considered routes

Analyzing Figs. 2 and 3, it can be seen that, as expected, the lower the truck speed becomes, the further to the right the center of mass of each cloud of points is located; because slower trucks increase the negative influence of the construction project in the urban system. Furthermore, lower truck speeds have the consequence of a wider range of possible social costs (the points are arranged closer to a straight line): from 470 units in the case of a truck speed of 20 km/h, to 670 units in the case of a truck speed of 15 km/h, and finally 1161 units in the case of a truck speed of 10 km/h.

It can also be seen in Fig. 2 that slower trucks means that the cloud of points will resemble a straight line more closely.

Regarding emissions, their overall value hardly changes at all, because we are working with mean fuel consumption rates, instead of considering fuel consumption as function that depends on the vehicle's speed. It would be necessary a detailed analysis at this point. See Table 2.

Regardless of the chosen truck speed, we can minimize the social cost, the emissions, or choose an intermediate solution. Thus, if we want to minimize the social cost, will have to move along the Ox axis ($\alpha = 0°$) until the perpendicular from our position touches the curve shown in black in Fig. 4 (Pareto boundary). In the same way, if we want to minimize emissions, we will travel along the Oy axis ($\alpha = 90°$). If the planner wants an intermediate optimal solution, he should use: $\alpha \mid 0° < \alpha < 90°$. As an example, we represent in Fig. 4 the Pareto optimal for $\alpha = 45°$.

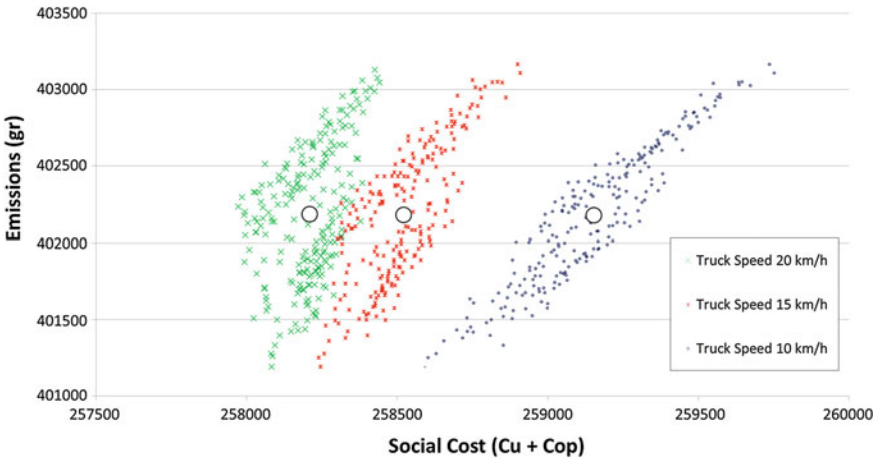

Fig. 2 Social cost versus emissions

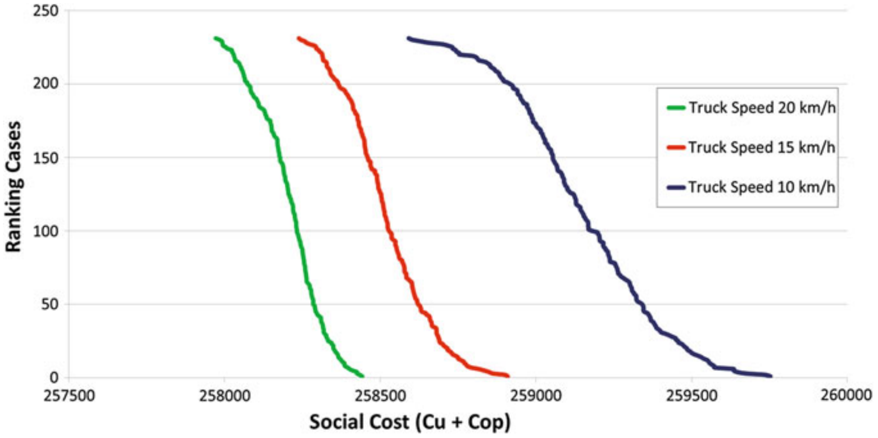

Fig. 3 Social cost versus ranking cases for different truck speeds

Table 2 Social cost and emissions values

Truck speed	Social cost			Emissions
	20	15	10	
Maximum	258442	258909	259753	403166
Minimum	257972	258239	258592	401190
Centre of mass	258209	258521	259153	402181

This way we can obtain many different solutions, according to the truck speed, and the chosen objective: social cost minimization, emission minimization, or a combination of both.

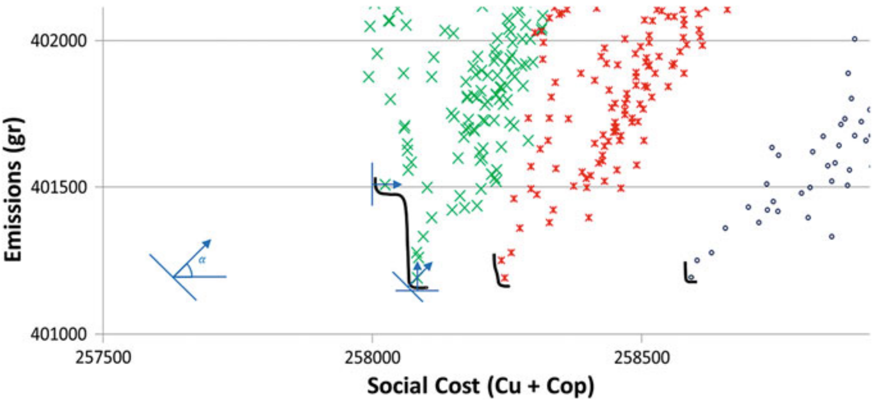

Fig. 4 Detail of social cost versus emissions

4 Conclusions

This chapter proposes a model to distribute truck trips along different routes in an urban environment, in a way that makes possible to analyze the emissions and the cost of the alternatives. In this way, we can propose policies to minimize the negative consequences, from a completely environmental, purely social, or intermediate point of view.

Due to the special characteristics of the case study, we opted for an exhaustive search algorithm, which yielded plentiful data, which was examined and used to perform a sensitivity analysis to determine how variations in the speed of the trucks influence the model's output.

Considering a family of solutions as the points that represent, for a certain value of the speed of the trucks, the social cost and emissions consequence of all possible ways to distribute the 20 trucks between the three routes; we observe that, as expected, the social cost of the center of mass of a family of solutions increases as the speed of the trucks decreases. For instance, if we compare the centers of masses of the families corresponding to truck speeds of 20 and 15 km/h, the latter's social cost is 0.12 % times greater. Analogously, studying 20 and 10 km/h families reveals a 0.37 % increase in the social cost of the center of mass. Also, the greater a family of solutions' truck speed, the wider its range of social cost values: 20 km/h family has a social cost range of values 42 % greater than the 15 km/h family; and 147 % greater than the 10 km/h family. It is also worth mentioning that as truck speed decreases, a family of solutions' outline becomes less steep, longer, and thinner.

References

1. Reiner, G., Traka, T.: Customized supply chain design: problems and alternatives for a production company in the food industry. Int. J. Prod. Econ. **89**(2), 217–229 (2004)
2. Siprelle, A.J., Parsons, D.J., Clark, R.J.: Benefits of using a supply chain simulation tool to study inventory allocation. In: Proceedings of the 2003 Winter Simulation Conference (2003)
3. Boerkamps, J., Binsbergen, A.V.: GoodTrip a new approach for modelling and evaluation of urban goods distribution. In: Proceedings 1st International Conference on City Logistics: City Logistics, Australia (1999)
4. Shinghal, N., Fowkes, T.: Freight mode choice and adaptive stated preferences. Transp. Res. Part E Logist. Transp. Rev. **38**(5), 367–378 (2002)
5. Lin, C.: The freight routing problem of time-definitive freight delivery common carriers. Transp. Res. Part B Methodol. **35**(6), 525–547 (2001)
6. Shangyao, Y., Weishen, L., Maonan, C.: Production scheduling and truck dispatching of ready mixed concrete. Transp. Res. Part E **44**, 164–179 (2008)
7. Dablanc, L.: Goods transport in large European cities: difficult to organize, difficult to modernize. Transp. Res. Part A **41**, 280–285 (2007)
8. Jula, H., Dessouky, M., Ioannou, P., Chassiakos, A.: Container movement by trucks in metropolitan networks: modelling and optimization. Transp. Res. Part E **41**, 235–259 (2005)
9. Moura, J.L., Ibeas, A., dell'Olio, L.: Optimization-simulation model for planning supply transport to large infrastructure public works located in congested urban areas. Netw. Spat. Econ. **10**(4), 487–507 (2008)
10. Romero, J.P., Moura, J.L., Ibeas, A., Benavente, J.: Car-bicycle combined model for planning bicycle sharing systems. Transp. Res. Board. 91st Annual Meeting No. 12-3062 (2012a)
11. Romero, J.P., Ibeas, A., Moura, J.L., Benavente, J., Alonso, A.: A simulation-optimization approach to design efficient systems of bike sharing. Procedia—Soc. Behav. Sci. **54**, 646–655 (2012b)
12. IDAE: Guía para la estimación del Combustible en las Flotas de Transporte por Carretera (2006)
13. IDAE: Guía de Vehículos Turismo de venta en España, con indicación de consumos y emisiones de CO_2 (2013)
14. Ntziachristos, L.: 1.A.3.b. Road Transport TFEIP endorsed draft. Emision Inventory Guidebook (2009)