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City logistics policy evaluation with system dynamics

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Abstract

In City Logistics (CL) contexts, public stakeholders' goal is often to implement policies aimed at reducing the negative externalities generated by freight transportation activities, while at the same time maintain and foster the efficiency of the CL system without hindering the profitability of private operators. This task can become quite arduous because of the complexity of CL systems, which are composed by multiple actors with different objectives and driving factors. In this context, we argue that existing literature should explore more deeply the effects of public policies on operation and economic variables that shape the CL context. To this end, we propose a System Dynamics (SD) model that identifies the interconnections between those variables and helps assess the effects of public policies on the system.

Keywords: City Logistics, System Dynamics, Modelling, Feedback Loop, Policy Evaluation

1. Introduction

Increasing demand for goods in urban areas has turned into a surge in freight traffic, with negative consequences on traffic congestion and pollution. These trends have led researchers, practitioners and public administrations to shift their efforts toward solving these problems and City Logistics (CL) has emerged as a concept for coordinating all stakeholders into optimizing urban freight activities and reducing the negative impacts of urban freight distribution on the citizens. In fact, public stakeholders are called to implement policies aimed at reducing the level of pollution and traffic congestion and other negative effects generated by freight transportation activities, but also to foster the efficiency of CL systems (Marciani and Cossu, 2014). Efficiency is in fact the major goal of private freight transport operators, and is directed towards the improvement of logistic services, maximizing revenue, and reducing costs.

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Several initiatives in CL have been devised and implemented over recent years. However, the results achieved by these initiatives in terms of efficiency and environmental benefits are not always realised and were abandoned after the experimental phases. One of the most common reasons for failure is the lack of profitability for private operators. For instance, some of these CL initiatives could be financially viable only if subsidized (Van Rooijen et al., 2017).

Ex-ante evaluation of CL outcomes is thus one of the major research streams in this field, and requires a consideration of a wide set of issues relating to the problems that CL projects aim to solve (Thompson, 2014). A subset of *ex-ante* evaluation methods for CL is represented by modelling techniques. However, we argue that the existing literature falls short in addressing the multi-faceted complexities of CL contexts, and thus research should aim at identifying and quantifying the relationships between operation and economic variables that shape the CL context, in order to assess the effects of public policies on the CL system.

To this end, we propose a System Dynamics (SD) model. SD methodology (Sterman, 2000) is used given its proven ability to represent and simulate the behaviour of complex systems that involve several factors and stakeholders, such as governments, companies, citizens, and carriers, with different objectives (Koç et al., 2016). So far, very few SD approaches to CL modelling have been proposed. For instance, Thaller et al. (2016) included freight demand from the population, freight transport demand, road mileage and fuel consumption, transport lead time and costs as the main model components. Their model however does not set out to test the effects of CL policies on the system.

The objective of this paper is therefore to build a model able to grasp the complexities inherent to CL policy making by making evident its connections to operational and economic variables driving not only their success but also the overall efficiency and profits of private operators.

The paper is structured as follows. First, a literature review on CL policy evaluation through modelling is presented, together with existing efforts in transport policy evaluation with System Dynamics. Then, a section on SD methodology is presented. The Model development section is the core of the paper and presents the main feedback loops, stocks and flows of the model, highlighting the loops taking place between the policies. Finally, some conclusions are drawn on the value of this approach, exploring its potential use and its limitations.

2. Literature review

2.1. CL Policy evaluation through modelling

Among the methods used to assess the feasibility of CL projects, modelling techniques can be used to perform ex-ante evaluation of the potential outcomes of the introduction of CL private and public policies (Muñuzuri et al., 2012). Models investigate different scenarios and aim to model the behaviour of the system considering social, economic and sustainability aspects (Comi et al., 2011). Most of these models take into account the freight flows and aim to optimize them to achieve both operational efficiency and a reduction in emissions (Taniguchi and Tamagawa, 2005). Such models describe the city topology and traffic regulations, in addition to representing logistics chains and the main vehicles used.

However, the complexity of the system might be overseen in traditional urban freight flows models. In fact, CL systems are complex systems where a multitude of stakeholders pursue different objectives (Anand et al., 2012). Hence, the implementation of successful CL projects requires in-depth analysis of the potential success factors and the dynamics of the complex interrelations among stakeholders (Benjelloun and Crainic, 2008). The most significant conflict arises between private operators, such as retailers and transport operators, and public administrations. In fact, while public administrations implement policies to cope with the negative externalities of urban freight distribution activities; transport operators are challenged with bearing the additional costs derived from such public regulations. Moreover, it is becoming more and more difficult for them to charge their final customers with such additional costs because of a wider convergence and increasing competition among global delivery operators (Ducret, 2014). Therefore, public policies implemented by local authorities might negatively affect city logistic systems in terms of cost and efficiency.

2.2. Transport and Logistics Policy evaluation with System Dynamics

Scholars use System Dynamics modelling to explore self-reinforcing loops interacting within a mobility system in order to achieve a better understanding of why certain policies are met with considerable resistance by the actors of the system. Some authors have focused on traffic congestion and on the consequential problem of polluting emissions. Armah et al., (2010) developed a casual loop diagram for the city of Accra, to investigate congestion factors and their mutual relationships, along with associated levels of emissions. Vafa-Arani et al., (2014) simulated the behaviour of the parameters influencing pollution levels in Teheran and assessed the effectiveness of several environmental policies. Among the policies investigated, the most effective ones are technological improvement of vehicles and fuels and construction of public transportation infrastructure. Several SD models have been developed specifically with the aim of evaluating CO_2 mitigating policies and strategies. Some models consider intercity private transport as their focus of study (Egilmez and Tatari, 2012; Han and Hayashi, 2008). In particular, Egilmez and Tatari, (2012) focused on American highways and tested different policy scenarios aimed at reducing CO_2 emission levels. Three policy-making strategies were investigated and found to be effective when combined together: increasing fuel efficiency, subsidizing the use of public transportation, and stimulating the adoption of electric vehicles. Strategic choices of private stakeholders were also examined through SD models. Stepp et al., (2009) qualitatively estimated the effectiveness of incentives for the use of alternative fuels vehicles by considering a timespan equal to the average vehicle lifetime. Besides the strategic decisions of manufacturers, the model also includes consumers' preferences, industry dynamics, and the environmental impacts during the life cycle of a vehicle.

Finally, System Dynamics can be adopted to describe to represent logistics chains and the main vehicles used according to a city's peculiar characteristics. Thaller, Clausen and Kampmann (2016) proposed groundwork for introducing system dynamics as a tool to model freight transportation in urban areas. The main model components are freight demand from the population, freight transport demand, road mileage and fuel consumption, and finally transport lead-time and costs. To the best of our knowledge, this is the most comprehensive SD model for CL systems developed so far.

3. System dynamics methodology

SD methodology was originally developed by Forrester, (1961) to study the evolution over time of complex systems composed by numerous and heterogeneous variables and nonlinear connections between them. According to Sterman, (2000), there are three main elements of a SD model: Causal Loop Diagrams, Stock and Flow Diagrams, and the equations that represent the relationships between variables. The Causal Loop Diagram (CLD) is a qualitative and graphical representation of the variables of the model. We can identify two types of loops linking those variables: negative (balancing) and positive (reinforcing) ones. In particular, reinforcing loops connect variables that are positively linked, wherein for each increase in one variable, the growth generated in the linked variables originates in turn an additional increase in the first variable. The opposite obviously holds for balancing loops. Stock are cumulated quantities given by the difference between the inflow and the outflow of a process (i.e. Flows). Finally, "the equations of a SD model can be either algebraic or differential in nature, they are independent from one another, and are functions of the state of the system in the previous time steps" (Cagliano et al., 2015).

4. Model development

The model structure and feedback loops are derived from pertinent CL literature. Balancing loops are developed to link selected public and private policies on the operational and economic factors that drive the global outputs of city logistics systems, in terms of road occupancy, fuel emissions and profits. The oscillating effects on the global outputs are calculated by means of stock and flow diagrams, and drive the adoption of selected policies, and thus feedback loops embedded in the system (Fig. 1).

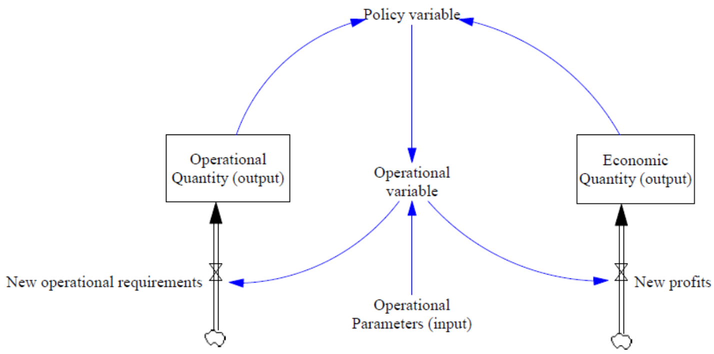

Fig. 1. Macrostructure of the CL SD Model.

Each policy is modelled via a parameter that can be fine-tuned according to the magnitude of the policy implemented, whose unit of measure varies depending on the object and aim of the policy. The model is built using the Vensim™ software (Eberlein and Peterson, 1992). Due to space constraints we do not include the mathematical formulations of the model, which are however available on request.

The first policy concerns the reduction of traffic congestion by means of improving road capacity. In Sterman (2000), the pressure to reduce traffic congestion leads to an effort by public authorities to increase the capacity of the road network, which reduces the average travel time. Such a variable is compared with a desired level set by the authorities, and the variance between the two variables generates the pressure to increase the capacity. A stock and flow diagram is used to represent new construction or improvements to the road network. A typical approach to measure traffic congestion involves a comparison between congested traffic conditions and some reference level using indicators such as travel or journey time (Toledo, 2011). The relationship between road capacity and travel time is better explained via the travel time function of the Bureau of Public Roads (Transportation Research Board, 2010). Traffic flow can be measured as the multiplication of the daily kilometres travelled by each vehicle and the total number of vehicles in the system (Armah et al., 2010). Both the SD model of Sterman (2000) and the analytical formulation of the BPR do not include the combined effect of other modes of transport (e.g. public transport). For CL purposes, we can overcome these issues because we do not include different modes of transport but rather we distinguish between freight and passenger transport, and thus assume a fixed volume of passenger transport since it is outside the boundary of the model presented here.

The second policy is related to the consolidation and coordination of loads, whereby the number of delivery locations is reduced by means of consolidation at the reception point (e.g. parcel lockers) or at the source of the urban goods delivery (e.g. urban consolidation centre) (Figure 2). During the daily activities of a commercial van driver, there are several idle times that hamper the productivity of last-mile delivery, for instance the time lost looking for parking (Arvidsson and Pazirandeh, 2017). Hence, the stops the driver can make depends on fixed variables such as working-day hours and distance from the distribution centres, and variables such as idle time for parking selection, which in turn depends on traffic congestion and parking availability. The length of the delivery tour in terms of time is the output of the number of stops taking into account the time per stop, including delays. In order to reduce the time per stop, we include a third policy representing the effort by municipalities to optimize the usage of curb-side loading bays through optimal location or ICT-enabled services that monitor their real-time usage.

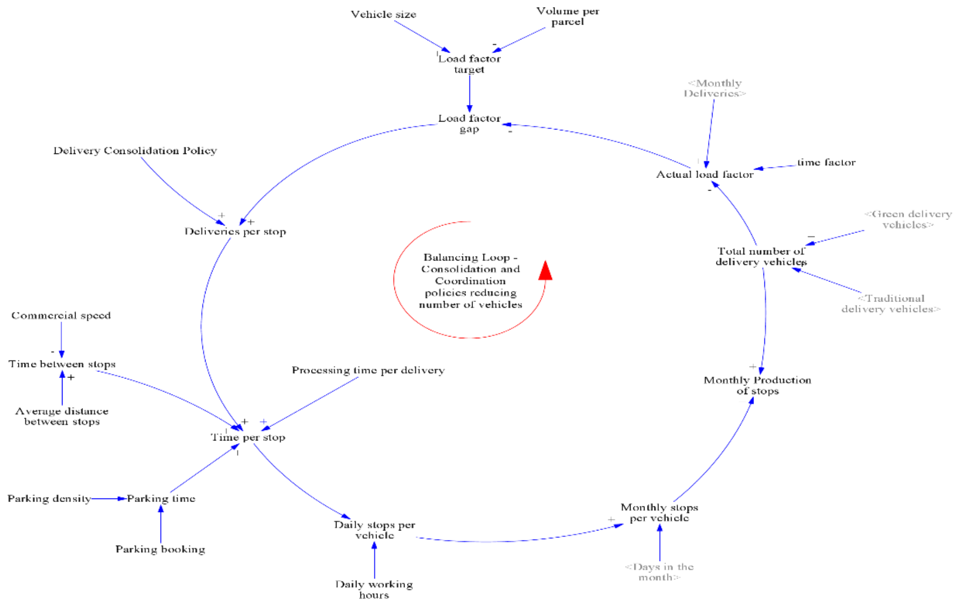

Fig. 2. Consolidation loop.

The next policy (Figure 3) aims to decrease the level of emissions by fostering incentives for sustainable means of transportation such as electric vehicles. CO_2 emissions are usually calculated from fuel consumption. The report of DEFRA – Department for Environment Food and Rural Affairs (2012) calculates that deliveries with diesel vans have a total greenhouse gas emissions, expressed in kilograms CO_2 equivalent per year, equal to 3.1672 times the fuel use in litres. Ntziachristos and Samara (2000) calculate a very similar value of 3.1376 for this ratio. Alternative fuels can reduce emissions in addition to fuel consumption, which is dependent on the load factor. Arvidsson (2013) takes into account the load factor in a mathematical model of urban fuel consumption. Figure 3 shows the balancing loop regarding the policies for reducing CO_2 emissions.

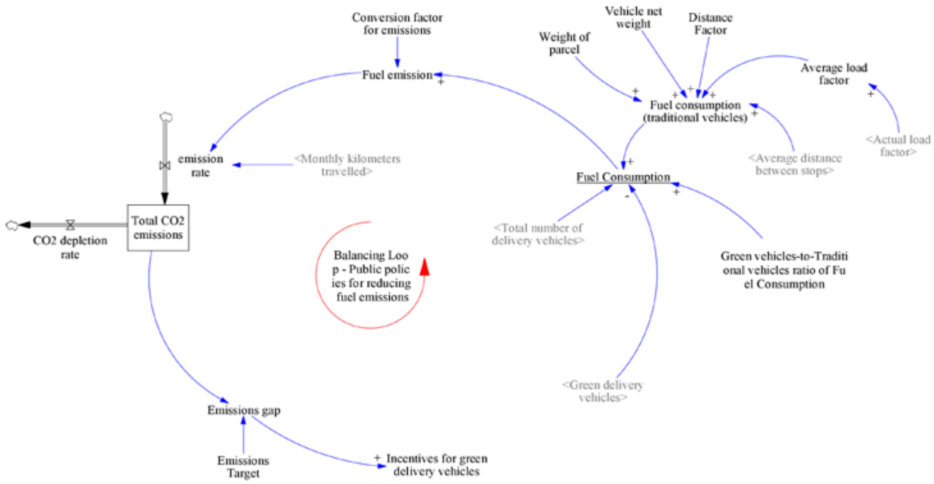

Fig. 3. Public policies for reducing emissions

The loops previously identified show the potential outcomes of public policies on the operational outputs of city logistics. These outputs are in turn a driving factor behind the economic quantities relevant for a company when acquiring new vehicles and achieving profitability, which are modelled as a private investment loop (fifth policy). Each month the model calculates the overall operating costs and uses stock and flow diagrams to accumulate profits and revenue. In order to compute the operating cost we use a kilometric cost. The number of kilometres travelled each day by each vehicle is estimated via the formulation expressed in Gonzalez-Feliu et al., (2012).

4.1. Feedback loops between policies

The consolidation sub-part of the model calculates the production of stops, which dictates the requirements of vehicles needed to fulfil all the delivery requests. New demand of deliveries enters the system and is fulfilled through the availability of stops. Unfulfilled demand ensues when the availability of stops cannot cope with the existing demand, and thus new vehicles are needed. The demand for new vehicles is then coupled with the availability of funding for new vehicles, which in turn depend on the overall profits accrued by private delivery companies. Hence, the flow of new vehicles entering the system is affected by both parking and consolidation policies, via the number of stops performed by each vehicle, and the overall costs depending on the number of stops as well as on fuel consumption. Given that the reduction of emissions revolves around the adoption of green delivery vehicles, we differentiate the flow of green vehicles and traditional vehicles. The model's structure is built so that funding is used first on green vehicles, provided that their price is lower than the price of acquiring a traditional vehicle. Incentives can be introduced to lower the price of green delivery vehicles. Then, traditional vehicles are only bought if their price is lower or demand is not met through green vehicles. Demand and supply balance each other out, as new vehicles entering the system increase the production of stops, which in turn reduces the unfulfilled demand.

The introduction of green vehicles generates a reinforcing loop with a positive effect on the level of investment. When funding is used for purchasing new green vehicles, fuel consumption and costs decrease as well. The increased profits then brings additional investment. This means that a policy setup with the objective of enforcing a reduction of emissions could generate positive spillover effects on private investments on the same kind of vehicle.

5. Model simulation

The robustness of the model has been tested under extreme conditions by setting the major parameters at minimum and maximum values of their range, to test for non-consistent behaviours. The consistency of the model is proven under such conditions, and differential equations are always calculated by the internal engine of the software.

The simulation is focused on highlighting the effect of CO_2 emissions on the decisions to adopt either green or traditional vehicles. To model this decision we include the following variable (equation 1):

$$Buy\ Green\ Vehicles? = \ IF\ THEN\ ELSE(Purchase\ cost\ of\ green\ delivery\ vehicles \\ < Purchase\ cost\ of\ traditional\ delivery\ vehicles, 1, 0) \tag{1}$$

Where incentives by the public administration moderate the purchase cost of green delivery vehicles. Such incentives are modelled as a dependent variable based on the CO_2 emissions gap (equations 2 and 3):

$$CO2\ emissions\ gap = \ Total\ CO2\ emissions/Emissions\ Target \tag{2}$$
$$Incentives\ for\ green\ delivery\ vehicles = \alpha \times CO2\ emissions\ gap \tag{3}$$

Where α is a deterministic parameter set by the modeller. This parameter can be fine tuned according to the objective of the local authority.

The parameters and formulation with respect to the simulations are shown in Table 1. Such parameters have been retrieved from pertinent literature and calibrated for the robustness of the model. The full table of parameters can be provided upon request. We simulate over a time span of 100 months, equal to 8.3 years.

Table 1 Parameters of the base case simulation

Parameter	Value	Unit of measure
Monthly deliveries	1,000,000	Parcels /month
Initial number of traditional vehicles	5,000	Vehicles
Market cost of traditional vehicles	50,000	€
Market cost of green vehicles	90,000	€

The simulation results show that as the CO_2 emissions rise, the incentives for green vehicle increase as well, up to the point that green vehicles become attractive to purchase. Until the existing fleet can meet the demand, there are no fluctuations in the number of green vehicles. However, the system has a spike for vehicles needed when the existing fleet cannot cope anymore with the demand of deliveries. Then, as green vehicles are more attractive they absorb the spike in the demand, starting a transition from traditional vehicles to green vehicles (Figure 4).

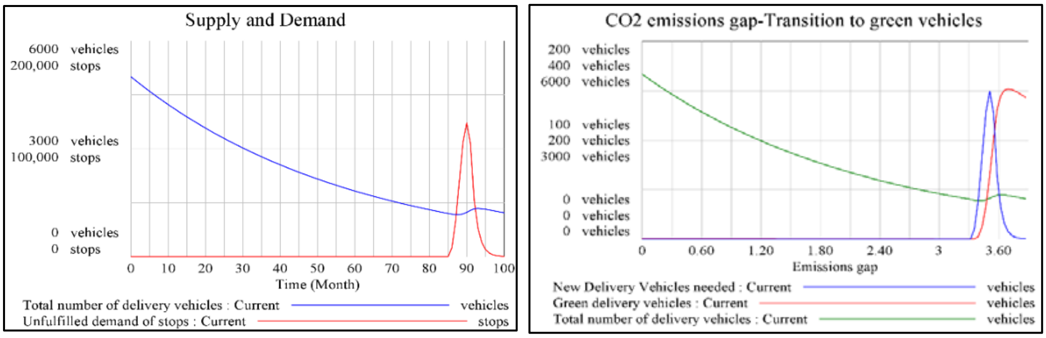

Fig. 4. Supply and Demand and transition to green vehicles

6. Applications

Besides the example provided in the previous section concerning public incentives to foster the transition to green vehicles, the SD model can be used to test various policy scenarios with regard to a variety of existing and future real case scenarios, such as improving the availability of loading bays, increasing the capacity of the road network or fostering goods consolidation. For instance, measures related to the availability of loading bays could be tested by changing the parameter "Parking Density", which is measured in terms of reduction of time spent for each stop, and in turn reduces the parking time. As for the capacity of the road network, local administrations could reduce the time delay that exists within the road capacity loop and determine the quickness of road capacity adjustments to the desired level of capacity. Finally, the effect of consolidation is measured by manipulating the parameter, "Delivery Consolidation Policy". The deployment of a wide network of parcel networks could for instance substantially increase the average number of deliveries per stop. A second policy scenario that might reach a similar effect is represented by a local authority imposing that each newly built dwelling arrange a micro-consolidation point for all deliveries.

7. Conclusion

The proposed SD model provides for a holistic and aggregated view on the effects of public and private policies in a CL system, which are responsible for the global outputs of the system itself in terms of economic gains and losses as well as environmental sustainability. Such view enables the modeller to draw useful insights on the topic at issue that might be otherwise overlooked. The model is used to simulate a base case scenario in order to identify the effect of the emissions gap on the transition to green vehicles. Results show that under certain circumstances, namely incentives to purchase green vehicles, it is possible to leverage off the supply and demand gap to foster the introduction of new green vehicles. This model has some limitations. For instance, the adoption of green delivery vehicles is limited to an average vehicle, whereas multiple vehicles have been introduced in recent years. Moreover, their adoption is simply guided by the purchase price and therefore does not include other aspects such as carrying capacity and availability of charging stations. Further research will be addressed at solving the above mentioned limitation as well as developing case scenarios and performing sensitivity analyses to understand the main levers that drive efficiency and reduce the externalities.

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