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Evaluating the potential environmental impacts of a large scale shift to off-hour deliveries

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Abstract

This paper assesses the potential environmental impacts of a large-scale deployment of off-hour deliveries (OHD), focusing on CO₂ and pollutant emissions. We use a methodological framework involving four steps: transport demand estimation, traffic simulation, emissions calculation and emissions environmental social cost calculation. Based on five scenarios, depending on the scale of the shift to OHD, and applied to the case of the Lyon urban area, we find that OHDs lead to a reduction in CO₂ and pollutant emissions. However, their impact is rather small. The maximum reduction in CO₂ emissions is 3.4% for 100% OHD for the whole urban area of Lyon (1.9 million inhabitants and 3,325 km²). Some factors (population size, density, traffic conditions, research methodology, vehicle fleet composition, etc.) limit the comparability of the results obtained from other case studies. One of the reasons for this low environmental impact of OHDs is that the LUA is a small and not very congested metropolitan area. This impact is 5% when we focus on the densest area (core of area with 0.7 million inhabitants on 2.2% of surface area) which is more important than in the least dense area (outskirts of area with 0.6 million inhabitants on 83.6% of surface area) with 2.6%. These results confirm the limited impacts of OHDs in smaller, less congested urban areas. It also reaffirms the need for OHDs to be implemented in the densest parts of metropolitan areas. The maximum decrease in the environmental social cost is 4.25 million euros per year. Furthermore, the analysis reveals that the adoption of OHD makes it possible to achieve gains of 2.5 million hours per year in travel time that augur a productivity gain for all the actors involved in urban goods movement.

Keywords: Off-hour Deliveries, Urban goods movements, Environmental impacts, Large-scale simulation

1. Introduction

Urban areas are highly exposed to pollutant emissions (UN-Habitat, 2015). For example, it is estimated that 40% of the population in the centre of Lyon's Urban Area (LUA), the second French conurbation, are frequently exposed to regulatory threshold exceedances: 69 days at more than 50 $\mu\text{g}/\text{m}^3$ of PM_{10} in 2013 when the maximum should be of 35 days/year (SYTRAL, 2017). Considering the sanitary risks related to environmental pollution, it is urgent to find solutions to decrease these emissions. One available lever is to regulate the transport sector, which has been steadily increasing its share of pollutant emissions in the last several years (European Environment Agency, 2018). Among all urban traffic-related emissions, it is estimated that goods movements are responsible for about 15% of greenhouse gas (GHG) emissions, as well as a large share of pollutant emissions: 40% of nitrogen oxides (NO_x) and 50% of particulate matter (PM) (CERTU, 2013). Therefore, improving the environmental efficiency of Urban Goods Movements (UGM) is an absolute necessity and requires the use of all possible approaches (Holguín-Veras et al., 2016a).

In recent years, there has been a growing awareness among city stakeholders (public and private) of the need to act on UGM in order to reduce the negative effects of transport. But this action should not negatively impact the city's economic vitality. This challenge mobilizes the reflection of researchers and experts in urban logistics around the search for solutions to achieve this.

Off-hour Deliveries (OHD) could be one of those solutions. The principle consists in postponing deliveries to periods when urban traffic is less dense, outside peak passenger traffic periods. The expected effects of the adoption of OHDs, in terms of environmental impacts, stem from the assumption that carrying out a share of goods movements during periods of low

infrastructure demand, and therefore lower congestion, improves urban traffic conditions in general and particularly freight traffic conditions. As goods movements take place under better traffic conditions, several chain effects should be observed: reduction of travel times, reduction of energy consumption, reduction of GHG and pollutant emissions, reduction of accidents, reduction of inconvenient parking, etc (Holguín-Veras et al., 2016a, 2011; Sánchez-Díaz et al., 2017; Verlinde, 2015). On the other hand, this measure may have drawbacks that should be kept in mind. The most cited is the noise from engine, refrigeration units, handling (Douglas, 2011; Verlinde and Macharis, 2016). This can be tackled by using silent vehicles and handling equipment and providing to drivers a special training on silent deliveries (Delaître, 2010; Verlinde, 2015). For example, the Certibruit label guarantees the use of PIEK-certified engines, handling equipment, premises and staff practices for low-noise night deliveries (Sánchez-Díaz et al., 2017). There are also potential reorganization costs for some stakeholders (Holguín-Veras et al., 2011; Silas et al., 2012) as well as social costs (health, social life, and safety) of nightshift work (Verlinde et al., 2010).

Several OHD experiments have been conducted in cities around the world (Bertazzo et al., 2016; Delaître, 2010; Holguín-Veras et al., 2016a; Niches, 2006; STRAIGHTSOL, 2014). These experiments, conducted at different scales, but mostly at small scale, lead to promising results in some of the largest cities in the world. However, they raise the question of whether they can be efficient to reduce emissions in a context of large-scale deployment of OHDs, since general traffic conditions will be affected, especially in the case of a small-sized city (less than 2 million inhabitants). The purpose of this paper is to answer the following question: in this context, does postponing a large share of goods movements during the off-hours (OH) leads to a significant reduction of freight-related emissions? Answering this question would help to better

guide the decision-making of all the actors involved in UGM, since such a postponement would lead economic and organizational changes that would have a cost for all of them.

A scenario-based simulation relating to the LUA is used to accurately evaluate the potential of OHDs to reduce emissions generated by UGM. It contributes to extend the short body of literature on the impacts of OHDs deployment at large scale. The choice of the LUA as a case study has a two-fold interest. First, the metropolis of Lyon is committed to improving ambient air quality by acting on freight transport in particular. Its Urban Mobility Plan 2017-2030 envisages the study of several types of initiatives in order to evaluate the conditions for successful new temporal or spatial cohabitation such as experiments in zones with the potential for "late evening" and "early morning" silent deliveries (SYTRAL, 2017). Assessing the potential impacts of OHDs on this perimeter would be helpful in decision-making. Secondly, the availability of data at the LUA scale is facilitated by the fact that the tools used have been calibrated at this scale.

The paper is organized as follows. After a brief review of the literature on OHDs experiments, we describe the methodology. Then the results are presented and discussed before the conclusion.

2. Literature review

Little research has accurately evaluated the environmental performance of OHDs (Holguín-Veras et al., 2016a), and even less so on a citywide scale. This is partly due to the difficulty of collecting data at this scale. However, there is an abundant literature on the impacts of small-scale OHDs (Sánchez-Díaz et al., 2017). Here we use *small-scale* to refer to the part of freight movements concerned by the study and not to the size of the city in which the study is

conducted. The results of the small-scale experiments are, in some cases, used to estimate the performance that could be achieved by deploying OHDs on a larger scale.

Holguín-Veras et al. (2011) estimate the potential impacts of a wide adoption of OHDs (7 PM to 6 AM) in New York (NYC). The study is based on a pilot experiment conducted with 33 establishments (transporters, receivers and vendors) over a one-month period in Manhattan. Vehicles' routes are tracked using a GPS system. The results of the experiment show a significant increase in speeds between depots and first customers when switching from regular hours (RH) to OH (+71%). They go from 19 km/h during the peak hours of the day (6-9 am) to 32.5 km/h between 7 pm and 6 am. The gain is even more important between two delivery points (+166.7%, from 4.8 km/h to 12.8 km/h). Based on these promising results, a simulation of the wide adoption of OHDs across Manhattan was conducted. It estimates that a 10% shift in transport from RH to OH reduces travel time by more than 6% during daytime hours. When the increase in travel time during OH is considered, this figure drops to 4% (Holguín-Veras et al., 2012). Based on these results, Holguín-Veras et al. (2014) estimate that a 20.9% carry-over of NYC traffic in OH would result in annual environmental gains of 202.2 tons (t) of CO, 11.8 t of NO_x, and 69.9 kg of PM₁₀.

These results from extrapolating the performance achieved in the Manhattan pilot experiment are well below those obtained for the same city in the study conducted by Holguín-Veras et al. (2016a). Using data from the test and implementation phases of two 2009 OHD projects, all carried out in NYC, the authors estimate that a 10% shift from RH to OH would allow an annual reduction of: 8.9 million t of CO₂, 25,273.5 t of CO, 3,616.3 t of NO_x and 591 t of PM₁₀. This very large gap with the previous studies carried out in Manhattan could be explained by the assumptions used in the second study. The latter is part of a major study of

three cities: NYC, Bogotá and Sao Paulo. 38 routes (including 6 in NYC, 15 in Bogota and 17 in Sao Paulo) were monitored using GPS systems for two to four weeks at RH and OH. Based on the characteristics of the fleet of vehicles used, the transfer of goods flows to OH achieve reductions of 13%, 64% and 48% in emissions per km travelled for Bogotá, NYC and Sao Paulo respectively. These average reductions are used to move from the scale of the routes followed to the scale of cities. On this basis, the annual pollutant emission reductions for the city of Sao Paulo are 2.9 million t of CO₂, 9,015 t of CO, 1,197 t of NO_x and 221 t of PM₁₀. For Bogotá, they are 1.7 million t of CO₂, 4,762 t of CO, 671 t of NO_x and 114 t of PM₁₀ (Holguín-Veras et al., 2016a). The experiments were carried out in highly congested areas of the case studies leading to high-speed variations when switching from RH to OH. The environmental impacts of OHDs would tend to be greater in areas with high levels of congestion.

Mommens et al. (2018) propose an assessment of the potential impacts of the adoption of OHD by all supermarkets in the Walloon region (Belgium). Although the study is intended to be large-scale, the impact analysis is not comprehensive. Indeed, changes in the quantities of pollutants are estimated in relation to the supermarket sector alone. This does not make it possible to assess the effectiveness of such a measure on the performance of the entire UGM at the regional level. This could have been done if the effects of the adoption of OHDs by supermarkets on traffic conditions throughout the region had been estimated. This last point seems to be one of the difficulties to be overcome in the transition from small to large scale.

Iyer et al. (2011) estimate, using a macroscopic and mesoscopic model, the impacts that OHDs could have on traffic conditions in NYC. Both models show that with an increase in the percentage of OHD, traffic conditions tend to improve during regular hours and deteriorate during off-hours. However, the gains to be made from the improvement of traffic conditions in

regular hours are greater than the losses generated by their deterioration in off-hours. OHDs would therefore benefit for traffic conditions and consequently decrease pollutant emissions, since these two elements are linked.

The beneficial trend of OHDs in terms of improving overall travel time over the whole day is also observed by Ukkusuri et al. (2016) through their macroscopic and mesoscopic models used in the NYC case. Sathaye et al. (2010) investigate the evolution of pollutants concentration over the course of the day in the case of a postponement of share of traffic flow on off-hours. To do this, they built OHD scenarios in two cities in California. They estimate that OHDs would lead to an increase in the average concentration of pollutants over the entire 24 hours. However, according to them, OHDs would be an effective measure when peak-hours speeds are very low.

This brief review shows, using micro or meso data, that large-scale OHDs most often produce a positive environmental impact, but this varies in magnitude from one case to another. This paper proposes an assessment of the magnitude of this impact using simulation methodology directly at the macroscopic scale.

3. Methods

This section includes the methodological framework description and the main characteristics of the study area through the presentation of data.

3.1 Description of the methodological framework

The assessment of the potential impact of OHDs is based on a four-step methodology illustrated by **Fig. 1**.

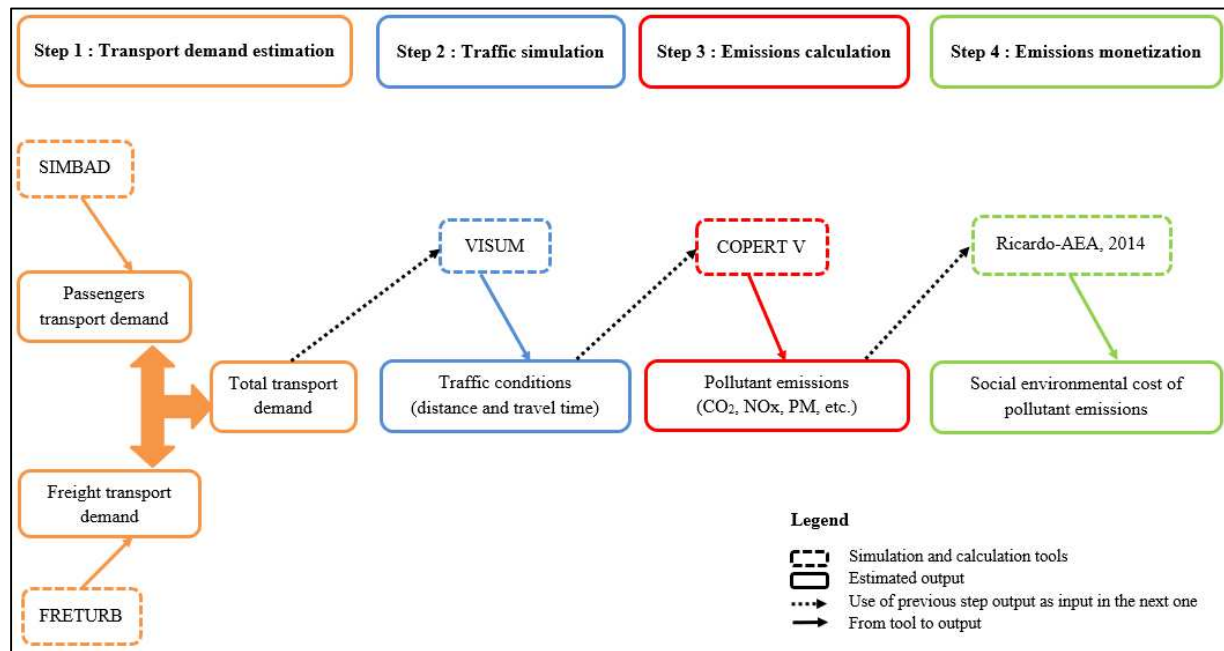


Fig. 1. Methodological framework
Source : authors' elaboration

3.1.1. Step 1 Transport demand estimation

Our case study is the LUA within its 1999 limits (see **Fig. 2**). It is divided in 777 IRIS (the smallest geo-statistical unit in France) which are the origin and destination areas of passenger and freight flows in the context of our analysis. In order to generate origin-destination (OD) matrices representing the total transport demand of the LUA, we use two tools developed by the Transport Urban Planning Economics Laboratory (LAET): SIMBAD and FRETURB. They respectively provide OD matrices for passenger and freight movements. The OD matrix of the total traffic is obtained by aggregating these two OD matrices. It is not our aim to explain in detail the methodology of the two tools: readers can refer to the papers mentioned below to have more information.

SIMBAD (Nicolas et al., 2009) is a Land Use and Transport Interaction (LUTI) model calibrated on the LUA and whose household and establishment location choices are built on the URBANSIM model (Waddell, 2002). The passenger transport model used is based on four-step modelling. The application of the model to the data from the Lyon household mobility survey (EMD 2015) makes it possible to obtain the OD matrix of motorized trips expressed in private cars (PC) and according to the periods of the day.

Goods flows are obtained through the FRETURB model (Routhier and Toilier, 2007). It allows to quantify and characterize freight flows of a given urban area (Toilier et al., 2018) on the basis of two main inputs: an establishment file and a zoning file. By running the model within our study area, we obtain, for each OD pair, the flow distribution by period of day and for three types of vehicles: light goods vehicles (LGVs), rigid or articulated heavy goods vehicles (HGVs). A private car equivalency (PCE) is introduced in order to aggregate the two matrices obtained. It is 1.5 PCE for 1 LGV, 2 PCE for 1 rigid HGV and 2.5 PCE for articulated HGV, which is consistent with PCE values usually observed in the literature (Webster and Elefteriadou, 1999).

3.1.2. Step 2 Traffic simulation

The simulation of traffic conditions is performed using the VISUM software. It is calibrated for simulations of hourly road network load. The transport demand obtained in *step 1* is a daily demand. It is therefore necessary to derive the demand by hour or by homogeneous periods of the day. In order to reduce computation time, we choose four homogeneous periods based on 2015 EMD Lyon data. The morning peak period (HPAM) between 7 and 9 am, and the afternoon peak period (HPPM) from 5 to 7 pm. Off-hours are separated between day off-hours

(HCJ) from 9 am to 5 pm and 7 pm to 9 pm, and night off-hours (Night) from 9 pm to 7 am. In this paper, for the simulation, we refer to Night (9pm-7am) when we mention Off-hours.

For each of the four specified periods, VISUM assigns the demand on the network, which determines the traffic conditions and speeds (travelled distance / travel time) for each OD. It is therefore not an instantaneous speed but an average speed. Nevertheless, it can be used to measure changes in traffic conditions, since it reports on possible delays on the same OD from one period to another (Yannis et al., 2006). Of course, these average speeds do not capture traffic dynamics (acceleration and deceleration) as accurately as the instantaneous speeds that would be obtained with GPS track data, for example (Gonzalez-Feliu et al., 2013; Holguín-Veras et al., 2016a; Laranjeiro et al., 2019). However, instantaneous speed data are not available for all traffic in the Lyon urban area.

Scenario generation can be done in several ways. It may be based, where appropriate, on a preliminary statement indicating the consent of the actors to adopt OHDs (Holguín-Veras et al., 2008, 2007). Another way may be to characterize flows in order to identify the types of flows most likely to be deferred and the percentage of flows that could be affected (Verlinde, 2015). Our aim is to estimate the maximum potential of OHDs to reduce emissions throughout the LUA. Thus, we deliberately choose carry-over rates ranging from 0% to 100% of deliveries, all sectors combined. On the basis of a reference scenario “*Scen ref*” which describes the current situation, five scenarios are built in order to capture the effect of postponing deliveries from day to night :

- Scen 20%: 20% of deliveries carried out during the daytime are postponed to the *Night*.

- Scen 50%: 50% of deliveries carried out during the daytime are postponed to the *Night*.
- Scen 80%: 80% of deliveries carried out during the daytime are postponed to the *Night*.
- Scen 100%: of deliveries carried out during the daytime are postponed to the *Night*.
- Scen 0%: All deliveries are carried out during the daytime, between 7 am and 9 pm. It represents a situation without off-hour deliveries. This allows to know what would happen if no deliveries were carried out at Night.
- Scen Ref: it describes the current situation with 66% of trips take place in HCJ, 17.6% in HPAM, 7.3% in HPPM and 8.9% in Night. More details on this situation are available in the section 3.2.

We therefore assume that all flows can be subject to OHDs and exclude the issues of stakeholder consent and acceptability of the measure from the scope of the study. This way of formulating our scenarios has the advantage of measuring the potential extent to which OHDs could be effective in terms of reducing the environmental pollution generated by UGM. Readers should keep in mind that above a certain threshold, the percentage of OHDs becomes unrealistic, but we simulate it anyway to estimate the environmental performance. Indeed, there are some flows that are well-suited OHDs and others that are slightly less (e.g. pharmaceuticals) or not at all (e.g. medical wastes). For example, in the case of NYC, an OHD project is estimated to be able to switch between 20% to 40% of the deliveries in the retail and accommodation and food sectors to the off-hours.(Holguín-Veras et al., 2016b). The estimates produced for New York City indicate that the optimal amount of staffed off-hour deliveries is between 14% and 21% and more than 40% for unassisted off-hour deliveries (Holguín-Veras, 2011). We also reason all

other things being equal. This means that regarding the demand for passenger transport, we assume that it remains constant. Therefore, there is no induced demand or modal shift from public transport to private cars as a result of reduced freight traffic during peak hours. For goods movements, it is assumed that OHD scenarios do not impact either the quantities to be delivered or the size of tours. This hypothesis makes it possible to know what the potential gains are at constant delivery quantities. Of course, OHDs are expected to save time, since the flows will operate under better traffic conditions, and therefore at higher speeds. Since VISUM is a deterministic simulation model, we simulate each scenario once instead of averaging the results of several simulations for each scenario.

3.1.3. Step 3 Emissions calculation

We calculate GHG and pollutant emissions based on COPERT V emission standards (Ntziachristos et al., 2009) for goods transport vehicles. This model, developed by the European Environment Agency, is used in most EU countries. COPERT V is a macro-scale vehicle emission model built around the average-speed approach (Ntziachristos et al., 2009). To calculate total exhaust emissions, COPERT V distinguishes hot emissions and cold-start emissions, taking into account the effect of driving behavior and climatic conditions (European Environment Agency, 2019). By using data from the bench test made in EU countries, COPERT V provides emission factor functions for most vehicle technologies in the European stock (Ntziachristos et al., 2009). . Our estimation considers a typical fleet of trucks and vans based on the 2012 French National Fleet Surveys, and the Copcete tool (Coulombel et al., 2018). Our typical fleet is 100% diesel for rigid or articulated HGVs, 99% diesel and 1% petrol for LGVs (see **Table A.1**). The COPERT V model allows the calculation of several types of emissions but

for brevity reasons, we will only focus on CO₂, CO, PM, NO_x and volatile organic compounds (VOC).

3.1.4. Step 4 Emissions monetization

Pollutant emissions are translated into monetary terms from the most recent European guideline on external transport costs (Van Essen et al., 2019). The use of these standards allows the calculation of the environmental cost associated with the UGM, as well as its variation following the implementation of a measure such as OHD. This guideline provides costs for each type of pollutant and GHG emissions according to the areas in which they are emitted: urban, peri-urban and rural. The differentiation of these areas is based on population density. We apply these costs to all the routes carried out between the different OD. The detail on these costs are provided in **Table A.2**.

3.2 Data

The LUA has 1.9 million inhabitants and more than 1.2 million jobs over an area of 3,325 km² i.e. an average density of 576 inhabitants and 381 jobs per km² (see **Table 1**). Even if Lyon is the second biggest conurbation in France, the LUA can be classified as a small metropolitan area compared to the large metropolitan areas found throughout the world.

Table 1

Characteristic data of Lyon urban area (2018)

Source: authors' calculations from FRETURB and SIMBAD, IGN, SIRENE (Insee)

	LUA	C1	C2	C3	C4
Inhabitants (1,000)	1,916.1	704.2	351.6	249.9	610.4
		36.8%	18.3%	13.0%	31.9%
Area (km ²)	3,325	73.3	129.7	253.5	2,868.5
		2.2%	3.9%	7.6%	86.3%

Inhabitant/km ²	576.3	9,612.2	2,711.6	985.8	212.8
Jobs (1,000)	1,267.1	562.3	207.4	182.0	315.5
		44.4%	16.4%	14.4%	24.9%
Jobs/km ²	381.1	7,674.9	1,599.2	717.9	110
Establishments (1,000)	275.7	117.3	41.9	36.7	79.7
		42.5%	15.2%	13.3%	28.9%
Jobs/Establishment	4.6	4.8	4.9	5.0	4.0

Note: Percentage data represent the proportional share of each area in the whole LUA

The population data are from the database of the French national institute of statistics and economic studies (INSEE) for the year 2018. To obtain data on establishments and jobs, we use a geo-coded SIRENE dataset (the National System of Identification and Register of Companies and their Establishments), the repertory of French economic establishments produced by INSEE for the year 2018. Assuming that OHDs can have different impacts from one area to another, depending on their population density, we divided the LUA into four rings (C1 to C4) according to the IRIS population densities around the city centre of Lyon (see **Fig. 2**).

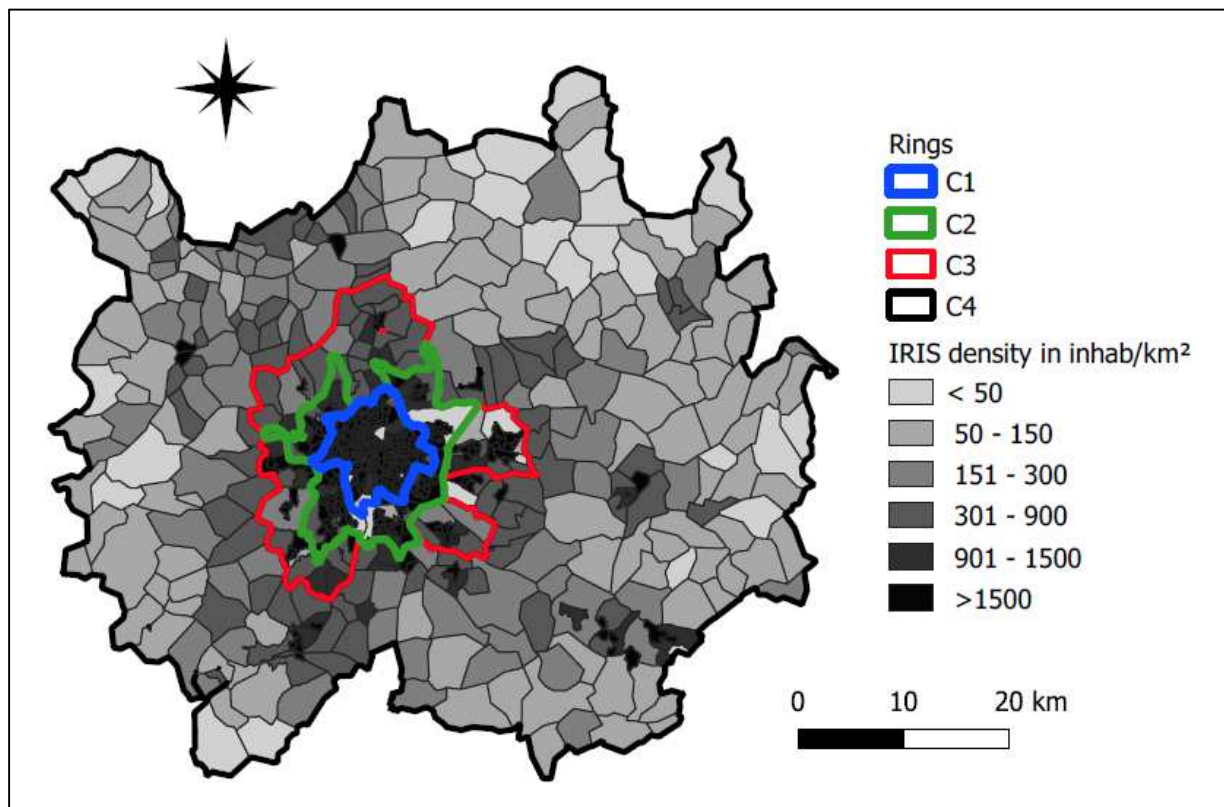


Fig. 2. Lyon Urban Area in its 1999 limits

Source: authors' elaboration from IGN

Thus, the densest area (ring C1) concentrates 36.8% of the population, 44.4% of jobs and 42.5% of establishments on only 2.2% of the surface area of the LUA (see **Table 1**). The least dense area (ring C4) concentrates 31.9% of the population, 24.9% of jobs and 28.9% of establishments. These shares are explained by the fact that this area represents 83.6% of the LUA surface. The size of establishments (ratio jobs/establishment) increases as one moves away from the centre, except in ring C4 (see **Table 1**). Activities located on the outskirts of the cities are those that require more space and are labor-intensive (wholesale, logistics and industry), while services activities are more located in downtown.

Simulations from SIMBAD and FRETURB provide the traffic data (passengers and goods) reported in **Table 2**. 719,271 PC trips per day are generated in the LUA, of which 31.7% within the C1 ring. This figure rises to just over 1.1 million trips per day when considering the total number of trips (passengers and goods) in PCEs. In terms of freight traffic, there are 119,910 for LGVs, 74,980 for rigid HGVs and 24,685 for articulated HGVs. We note the large share of LGVs in dense areas (C1 and C2) while rigid and articulated HGVs are used more often in the C4 ring..

Table 2

Daily distribution of trips by ring and vehicle type (1,000)

Source : authors' calculation from FRETURB for freight vehicle and SIMBAD for PC

	LUA	C1	C2	C3	C4
PC	719,271	227,869 31.7%	112,396 15.6%	96,216 13.4%	282,791 39.3%
LGV	119,910	45,759 38.2%	17,647 14.7%	16,127 13.4%	40,378 33.7%
Rigid HGV	74,980	25,115 33.5%	10,933 14.6%	11,050 14.7%	27,882 37.2%
Articulated HGV	24,685	6365	3897	4220	10,203

		25.8%	15.8%	17.1%	41.3%
Total (PCE)	1,110,808	362,648	170,475	153,056	424,630
		32.6%	15.3%	13.8%	38.2%

Note: Percentage data represent the proportional share of each area in the whole LUA; For each ring (C1 to C4), the figures refer to internal, incoming, outgoing and transit trips

C4 has a larger portion of the freight trips (36.2% in PCE) even more than the densest area (34.4% in PCE). When looking at the total traffic these figures are respectively of 38.2% et 32.6% (see **Table 2**). This is partly explained by the strong presence of wholesale, logistics and industrial activities in the area. Such activities generate multiple vehicle movements to and from the area. Indeed, the wholesale, logistics and industrial activities generate inbound traffic of raw materials and finished products in large quantities and very regularly, but also outbound traffic to the city of Lyon and neighboring cities. In addition to this, there is the traffic generated by the product needs of the 32% of the LUA's population who live in the C4

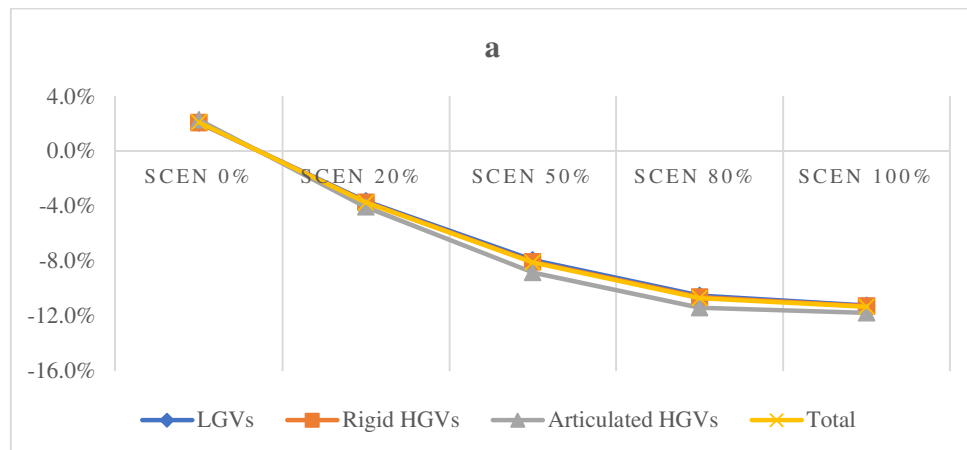
The analysis of vehicle use by OD shows that LGVs and rigid HGVs are widely used for short trips while articulated HGVs are used more for long trips (see **Table A.3**). Indeed, for trips starting from the C1 ring and carried out with LGVs, 59% are intra-C1, and only 16% go to the C4. Conversely, for articulated HGVs, 25% of these trips are intra-C1 and 50% go to C4 ring.

If we look at the periods of day during which these trips take place, we note on the LUA that 58.3% of trips take place in HCJ, 18.5% in HPAM, 14.9% in HPPM and 8.3% in Night. When we look specifically at freight transport, these figures are 66%, 17.6%, 7.3% and 8.9% respectively.

4. Results

4.1. Distances and travel times evolution

Fig. 3a shows a decrease in the total travel time at the LUA scale of 11.3% for the 100% OHD scenario, representing a maximum absolute gain of 2.5 million hours per year (see **Table A.4**). The minimum time saving is obtained with 20% OHD and amounts to 827,106 hours per year, or 3.7% less than the reference scenario. We notice that the larger the size of the vehicle, the greater the reduction in time (see **Table A.4**). The relative evolution of these gains, from one OHD scenario to another, is more important in C1 (14.6% gain with 100% OHD) than in C4 (8.5% gain with 100% OHD). The time saved is undoubtedly an economic gain for carriers, since it can represent fewer working hours or be used to increase the number of points affected in each vehicle tour. The value of these hours of work gained is another argument in favor of OHDs.



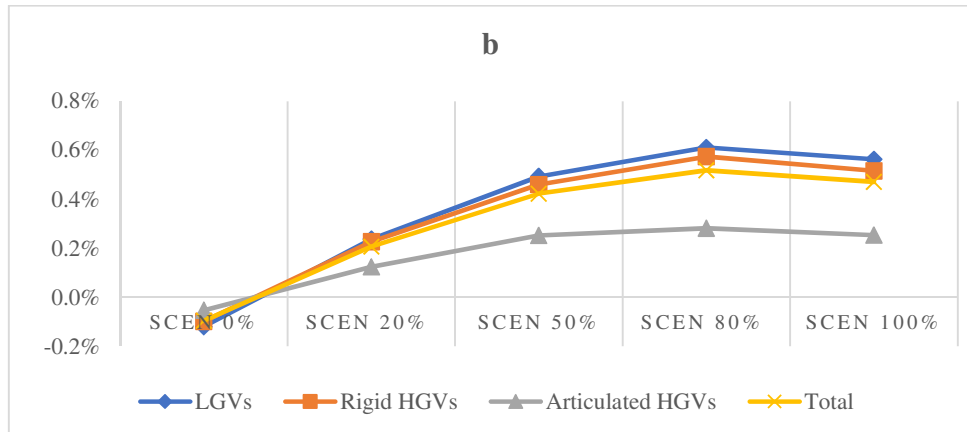


Fig. 3. Variation from the reference scenario of : travel time (a) in hour and distance traveled (b) in Vehicle kilometers (VKMs); Source: authors' calculation from VISUM

We observe a growth in distances travelled as the percentage of OHDs increases (see **Fig. 3 b**). However, this growth remains very low (0.5% for 100% OHD) and can be considered as insignificant. This is explained by the slight changes in the routes chosen by the vehicles as their tours are optimized according to the traffic conditions. The major roads are prioritized (main roads and highways) in the routes used in the model as in the real world. The city of Lyon is accessible from all sides without great obstacles that would reduce traffic flow and require major detours. Thus, traffic conditions are comparable at all entrances to the city during peak and off-peak hours. This characteristic of the city limits the number of bypasses to access the city. Thus, between off-peak and peak hours, the sum of the distances traveled remains more or less the same (see **Table A.5**), but there is a reduction in travel time due to the better traffic conditions at night compared to daytime. Mommens et al. (2018) also found that OHDs do not have a significant impact on distances travelled in the case of Brussels. In contrast, in the case of New York City, Holguín-Veras et al. (2018) assume that the distance traveled by drivers who take OHD routes is 10% shorter than the distance in the daytime delivery routes, because drivers are able to take the shortest path to their destinations during the off-hours. This assumption has an

influence on the impact of OHDs because, in addition to having better traffic conditions at night, the distances travelled are shorter. This tends to further reduce emissions, all other things being equal.

4.2. Freight traffic emissions in the whole LUA

In order to calculate the annual quantities of emissions, we considered five working days per week, for a total of 260 days per year. Thus, in the current situation (Scen Ref) the LUA UGM generates 382,778 t of CO₂, 195 t of CO, 2,462 t of NO_x, 8 t of PM and 20 t of VOC per year (see **Table 3**). OHDs lead to a reduction in pollutant emissions as the percentage of postponed flows increases.

CO₂ emissions decrease by 1.1%, then by 2.5% and 3.4% respectively when the percentage of goods flows reported in OHD increases to 20%, then 50% and 100%. On the other hand, if the flows now carried out at night (8.9% of the total flow) were carried over to daylight hours (Scen 0%), emissions would increase by 0.6% for CO₂, 0.8% for NO_x and 1.1% for PM. These results show that there is no threshold effect in relation to the gains in pollutant emissions that would be achieved by increasing the percentage of OHDs. As this percentage increases, so do the environmental gains, but less than proportionally. The maximum gains are obtained when 100% OHD is reached. These gains are partly explained by the relative improvement in traffic conditions as the percentage of OHD increases. Indeed, there is an increase in the average speed of 1.9% during the morning peak period when we have 20% OHD. This increase is 4.8% for 50% OHD and 9.6% for 100% OHD. At the same time, there is a decrease in the average speed during the night period due to the increase in traffic. However, this decrease does not have a significant negative impact on environmental gains. The daytime flows that are postponed to

night were already occurring at lower average speeds than those reached at night, despite the decrease observed following OHDs.

Table 3

Emissions (tons/year) and average speed (km/h) in the whole LUA

Source: authors' calculations

	Scen 0%	Scen Ref	Scen 20%	Scen 50%	Scen 80%	Scen 100%
CO ₂ (tons/year)	385,246	382,778	378,468	373,360	370,384	369,584
	0.6%		-1.1%	-2.5%	-3.2%	-3.4%
CO (tons/year)	197	195	191	186	183	183
	1.2%		-2%	-4.4%	-5.8%	-6.1%
NO _x (tons/year)	2,481	2,462	2,428	2,388	2,364	2,358
	0.8%		-1.4%	-3%	-4. %	-4.2%
PM (tons/year)	9	8	8	8	8	8
	1.1%		-2%	-4.3%	-5.6%	-5.9%
VOC (tons/year)	20	20	19	19	18	18
	1.4%		-2.6%	-5.6%	-7.3%	-7.6%
HCI Speed (km/h)	41.7	42	42.5	43.2	43.9	44.3
	-0.6%		1.2%	3%	4.5%	5.5%
HPAM Speed (km/h)	35.5	35.9	36.6	37.6	38.6	39.3
	-1%		1.9%	4.8%	7.6%	9.6%
HPPM Speed (km/h)	37.7	37.9	38.2	38.6	39	39.3
	-0.4%		0.8%	1.9%	3%	3.8%
Night Speed (km/h)	46.8	46.8	46.7	46.5	46.1	45.7
	0.0%		-0.1%	-0.6%	-1.5%	-2.4%

Note: Percentage data represent variations from the reference scenario (Scen Ref)

4.3. Freight traffic emissions: densest area vs. least dense area

A great advantage of our simulation approach is that it allows us to isolate a portion of the study area and see the impact of OHD deployment on that portion alone. In order to assess the disparities in the results obtained at various scales, we chose to focus on traffic-related CO₂ and pollutant emissions in the densest and least dense areas (C1 and C4). C1 corresponds to the core of the urban area and C4 to the outskirts. In each ring, we consider the emissions generated by internal, incoming, outgoing and transit traffic.

Table 4
Emissions (tons/year) and average speed (km/h) in C1
Source: authors' calculations

	Scen 0%	Scen Ref	Scen 20%	Scen 50%	Scen 80%	Scen 100%
CO ₂ (tons/year)	79,534	78,828	77,560	76,093	75,169	74,884
	0.9%		-1.6%	-3.5%	-4.6%	-5%
CO (tons/year)	40	39	38	37	36	36
	1.5%		-2.7%	-5.8%	-7.6%	-8.2%
NO _x (tons/year)	554	548	538	526	518	516
	1%		-1.9%	-4.1%	-5.4%	-5.8%
PM (tons/year)	2	2	2	2	2	2
	1.5%		-2.7%	-5.8%	-7.8%	-8.3%
VOC (tons/year)	4	4	4	4	4	4
	1.8%		-3.3%	-7.1%	-9.4%	-10%
HCJ speed (km/h)	24.1	24.3	24.7	25.2	25.6	25.9
	-0.7%		1.4%	3.5%	5.4%	6.5%
HPAM speed (km/h)	18.9	19.2	19.8	20.7	21.5	22.1
	-1.6%		3.1%	7.8%	12.4%	15.5%
HPPM speed(km/h)	20.8	20.9	21.2	21.5	21.9	22.1
	-0.6%		1.1%	2.9%	4.6%	5.8%
Night speed (km/h)	28.4	28.4	28.3	28.1	27.7	27.5
	0.1%		-0.3%	-1%	-2.2%	-3.2%

Note: Percentage data represent variations from the reference scenario (Scen Ref)

Table 4 shows, as expected, that traffic conditions are the least favorable in C1, given the high population and employment density. Under current conditions, the average speed is 24 km/h in

HCJ (42% less than in LUA), 19.2 km/h in HPAM (47% less than in LUA), 20.9 km/h in HPPM (45% less than in LUA) and 28.4 km/ in Night (39% less than in LUA). Within this ring, in the current situation, we have as emissions 78,828 t of CO₂ (20.6% of LUA emissions), 39 t of CO (20.3% of LUA emissions), 548 t of NO_x (22.3% of LUA emissions), 2 t of PM (21.4% of LUA emissions), 4 t of VOC (or 21.1% of LUA emissions). By looking at the evolution of the quantities of CO₂ and pollutants emitted with OHDs, we can see that at the first ring scale, any increase in the percentage of OHD leads to a relatively larger decrease in CO₂ and pollutant emissions than at the LUA scale. At this scale, similarly to the LUA scale, the maximum reduction in emissions is also achieved when 100% of deliveries are carried out in OH, i.e. 5% for CO₂, 8.2% for CO, 5.8% for NO_x, 8.3% for PM and 10% for VOC. These levels of decline are partly explained by the relatively larger variations in speed at this scale than at the LUA scale.

For all four periods, in C4, we note that the average speeds are relatively higher than those observed for the LUA, and even higher than for C1 (see **Table 5**). In the reference scenario, traffic generates 185,506 t of CO₂ (or 48.5% of LUA emissions), 94 t of CO (or 48.1% of LUA emissions), 1,164 t of NO_x (or 47.3% of LUA emissions), 4 t of CO₂ (or 47.6% of LUA emissions) and 9 t of VOC (or 47.3% of LUA emissions). The results show a low sensitivity of the quantities of CO₂ and pollutants emitted into this ring as the percentage of OHDs increases. Indeed, by transferring 100% of the flows to the OH period, the reduction in CO₂ emissions is only 2.6%, that of CO 4.8%, that of NO_x 3.2%, that of PM 4.5% and that of VOC 6%. As this area is peripheral, these results were partly predictable since traffic conditions are already good. They are therefore slightly sensitive to deliveries postponing, as shown by the increase of only 3.1% and 1.2% respectively in HPAM and HPPM speeds for the 100% OHD scenario. The

peripheral location of this area and low population densities lead to long delivery routes. In addition to this, as mentioned above, there is a greater presence of articulated vehicles. These elements partly explain the relatively high share of C4 in total emissions.

Table 5
Emissions (tons/year) and average speed (km/h) in C4
Source: Authors' calculations

	Scen 0%	Scen Ref	Scen 20%	Scen 50%	Scen 80%	Scen 100%
CO ₂ (tons/year)	186,432	185,506	183,896	182,006	180,987	180,737
	0.5%		-0.9%	-1.9%	-2.4%	-2.6%
CO (tons/year)	94	94	92	90	89	89
	0.9%		-1.6%	-3.6%	-4.6%	-4.8%
NO _x (tons/year)	1,172	1,164	1,152	1,137	1,129	1,127
	0.6%		-1.1%	-2.3%	-3%	-3.2%
PM (tons/year)	4	4	4	4	4	4
	0.9%		-1.5%	-3.3%	-4.3%	-4.5%
VOC (tons/year)	9	9	9	9	9	9
	1.2%		-2.1%	-4.5%	-5.8%	-6%
HCJ speed (km/h)	52.0	52.2	52.5	53.0	53.5	53.8
	-0.3%		0.6%	1.7%	2.6%	3.1%
HPAM speed (km/h)	49.0	49.1	49.4	49.9	50.3	50.6
	-0.3%		0.7%	1.6%	2.4%	3.1%
HPPM speed (km/h)	50.0	50.0	50.1	50.3	50.5	50.6
	-0.1%		0.2%	0.5%	0.9%	1.2%
Night speed (km/h)	55.4	55.4	55.4	55.2	54.8	54.6
	0.0%		-0.1%	-0.3%	-1%	-1.5%

Note: Percentage data represent variations from the reference scenario (Scen Ref)

4.4. Environmental social cost

The environmental social cost for the entire LUA is calculated based on the average density of the four rings. Thus, the first and second rings are considered as "urban area", the third

ring as "peri-urban" and the fourth ring as "rural" within the meaning of the reference frame (Van Essen et al., 2019). Since the PM calculated from the COPERT V standards does not distinguish between PM₁₀ and PM_{2.5}, we use the considerations of Airparif (2016) according to which 65% of the PM is composed of PM_{2.5}. Only CO₂ emissions and the following pollutants NO_x, PM_{2.5}, PM₁₀, and VOC are considered in this calculation. In the reference scenario, the annual cost generated by freight transport in the LUA is around € 106.45 million.

Table 6
Environmental social cost of CO₂ and pollutant emissions (€ million /year)
Source: authors' calculations

	Scen 0%	Scen Ref	Scen 20%	Scen 50%	Scen 80%	Scen 100%
Cost by component						
CO ₂	38.52	38.28	37.85	37.34	37.04	36.96
NO _x	67.50	66.97	66.04	64.95	64.30	64.13
PM _{2.5}	1.17	1.16	1.13	1.10	1.08	1.07
PM ₁₀	0.02	0.02	0.02	0.02	0.02	0.02
VOC	0.03	0.03	0.03	0.03	0.03	0.03
Total cost by area						
LUA	107.24	106.45	105.06	103.43	102.47	102.20
	0.7%		-1.3%	-2.8%	-3.7%	-4.0%
C1	23.52	23.28	22.86	22.38	22.07	21.98
	1.0%		-1.8%	-3.9%	-5.2%	-5.6%
C2	15.35	15.22	14.99	14.71	14.54	14.49
	0.9%		-1.5%	-3.3%	-4.5%	-4.7%
C3	17.61	17.47	17.24	16.96	16.80	16.76
	0.8%		-1.3%	-3.0%	-3.9%	-4.1%
C4	50.76	50.48	49.97	49.38	49.06	48.98
	0.6%		-1.0%	-2.2%	-2.8%	-3.0%

Note: Percentage data represent variations from the reference scenario (Scen Ref)

CO₂ accounts for 36% of this cost, followed by NO_x, which accounts for 63%. PM_{2.5}, PM₁₀ and VOCs represent the remaining 1% (see **Table 6**). The annual cost of € 102.2 million of the 100% OHD scenario represents the minimum of the cost that can be achieved with OHDs on the LUA. This corresponds to a maximum gain of €4.25 million per year, a decrease of 4% compared to

the reference scenario. The scenario *0% OHD* leads to an increase in the environmental social cost of 0.7%. **Table 6** shows that C4 is responsible for the highest share of the total cost, with 50.48 million euros, or 48% of the total cost. It is followed by C1, C3 and C2 respectively, with 22%, 16% and 14% of the total cost. The most significant variations in cost according to the percentage of OHD are recorded in C1. They decrease as we move further away from the centre of LUA.

5. Discussion

The results show that OHDs have a positive environmental impact in the case of LUA, although this is much lower than those obtained in some pilot experiments. Indeed, with a maximum reduction of 3.4% in CO₂ emissions, this is a far cry from the gains achieved of 13%, 64% and 48% per km travelled for Bogotá, NYC and Sao Paulo respectively (Holguín-Veras et al., 2016a). However, some factors limit the comparability of the results obtained from one case study to another. These include the characteristics of the cities studied (e.g. population size, traffic conditions, density, etc.), the research methodology and the vehicle fleet involved.

Regarding the city's characteristics, in Holguín-Veras et al. (2016a) the case studies are NYC, São Paulo and Bogotá, all large metropolitan areas, and respectively the third, fourth and sixth most congested cities in the world. This high congestion implies significant differences between peak and off-peak traffic conditions. This is not the case for LUA which is a small and not very congested metropolitan area. As shown in the data in **Table 3**: the lowest average speed is observed in HPAM and is 36 km/h for the reference scenario, while for the scenario 100% OHD, the average speed at night is 46 km/h. This 10 km/h gap is not enough to drastically reduce fuel consumption and emissions. In addition, the hypercentre of the LUA is probably

different from the American-style city with its wide avenues. Indeed, there is a strong presence of 30 km/h zones in the city of Lyon. This tends to limit the speed gaps between day and night, as shown in **Table 3**. The variation in total travel time gives an idea of the level of improvement in traffic conditions that can be achieved with OHDs. While 10% of OHD in NYC reduces total travel time by 4% over a day (Holguín-Veras et al., 2012), only 3.7% of this time is reduced with 20% OHD on the LUA (see **Fig. 3a**). The number of inhabitants and density have an impact on the efficiency of OHDs. Holguín-Veras et al. (2016a) estimate that a population of at least 2 million inhabitants in a city is needed for OHDs to be a practical solution. They add that OHDs could still be feasible in a city of less than 2 million inhabitants if it experiences high levels of congestion. LUA does not meet these conditions, as it has less than 2 million inhabitants and is not very congested, which may therefore explain the low environmental impact of OHDs. Our results confirm the effect of density on the impact of OHDs. Indeed, in C1 which concentrates 37% of the population on 2.2% of the surface area of the LUA, the impact of OHDs is much greater (-5% of CO₂ for 100% of OHD) than in C4 which concentrates 32% of the population on 86% of the surface area (-2.6 of CO₂ for 100% OHD). In addition, traffic conditions are not as good in the densest areas (in C1 the speed is 19 km/h in HPAM and 21 km/h in HPPM) as they are in the least dense areas (in C4 the speed is 49 km/h in HPAM and 50 km/h in HPPM). Hence, OHDs are more relevant in larger, dense and congested urban areas.

The methodological aspects that may explain the differences in results are related to the method of capturing traffic conditions. While we use data from aggregate model, Holguín-Veras et al (2016a) use GPS data. The advantage of GPS data is that they better capture traffic dynamics (acceleration and deceleration) and more accurately track the routes of every vehicle. Since emission calculation models are very sensitive to these factors, the GPS data approach

allows a better estimate of emissions. However, the drawback of using GPS data is that it is difficult or even impossible to obtain them for all the traffic in a city. This constrains the studies to be based on a limited number of vehicle routes. Aggregate model, since it provides average speeds, therefore has the disadvantage of capturing less traffic dynamics. This could lead to an underestimation of emissions and their variation from one scenario to another. However, it is important to remember that the emissions model COPERT V is built around the average-speed approach, so that it can estimate emissions from average speeds with a minimum of bias (Ntziachristos et al., 2009). The advantage of an aggregate model is that it allows to take into account a diversity of situations such as simulating the traffic generated by deliveries/pick-ups of all the establishments of the LUA. The choice between these two methodological approaches is therefore a trade-off between a fine method that allows to get very accurate estimations but over a limited number of routes, and an aggregate method that takes into account a wide range of situations but captures less accurately the traffic dynamics.

An additional factor that could explain the difference in results is the composition of the vehicle fleet from one case study to another. Considering that emission factors are highly sensitive to the vehicle in terms of emission standards or weight categories (Coulombel et 2018). It is then obvious that the total emissions from freight transport depends on the characteristics (size, age, type of fuel, etc.) of the vehicle fleet used. These characteristics are not the same from one country to another. Since we do not have enough information to allow a comparison between our vehicle fleet and the fleets in the other case studies, we cannot say more about how much of any difference in the results can be explained by the influence of the vehicle fleets. Emission factors are a central element in emission calculations. Thus, the emission model used is also a factor that influences the results obtained. Indeed, by comparing two emission models (CMEM

and MOVES), Zhang and Ioannou (2016) find that they have different characteristics that can affect the evaluation results.

All in all, these are all parameters that limit the comparison of our results with those of the other case studies. On the one hand, this overview of the factors influencing the effectiveness of OHDs nevertheless makes it possible to affirm that the environmental impacts of OHDs will be low in LUA, given its small size and low level of congestion. Their impact would be greater if one concentrated only on its most congested area (C1), i.e. the core of the LUA. On the other hand, it has raised some limitations to our paper. The first is the use of aggregate models for estimating traffic conditions. As mentioned above, the aggregate model does not capture accurately the traffic dynamics on which emissions are highly dependent. This could lead to bias in our results by underestimating emissions. The second limitation is related to the vehicle fleet used. Due to the lack of recent data at city level, we use the fleet from the 2012 French National Fleet Surveys. The composition of the fleet according to the distribution in Euro standard is no longer the same today because of the renewal that takes place over time. This can influence the total emissions generated by the fleet and the results from one scenario to another.

One objective pursued by the metropolis of Lyon in its Urban Mobility Plan for 2030 is the reduction of VKMs and emissions (SYTRAL, 2017). By putting our results in perspective with these objectives, we could think that OHDs, as a solution, will not help much to achieve them. Indeed, even if OHDs do not lead to a significant increase in VKMs, they do not induce their reduction. Two of our hypotheses could explain this fact: the assumption of a constant fleet and constant quantities of goods to be delivered. The first excludes the possibility of replacing small vehicles with larger ones at different times. The second one excludes the possibility of increasing the vehicle load factor, whereas this would allow more points to be delivered with the

same vehicle. Since travel time is one of the constraints that limits the size of tours, these hypotheses impede the capitalization of time savings achieved with OHDs. The more time is saved, and assuming that this time saved on the trip is not lost at delivery points, the more it will be possible to deliver additional points in a tour. This is possible because vehicle load factor tends to increase with OHDs (Holguín-Veras et al., 2011) since it leaves a fairly large margin in reference scenario. Since the VKMs travelled impact the quantity of pollutant emissions, our results may therefore have underestimated the rate of emission reductions that could be achieved.

6. Conclusion

This paper assesses the potential environmental impacts of large-scale implementation of OHDs, focusing on CO₂ and pollutant emissions from UGM in Lyon urban area. The methodological framework developed is composed by four steps: transport demand estimation, traffic simulation, emissions calculation and emissions environmental social cost calculation.

The results show that the environmental impact of OHDs is positive and increases with the percentage of OHD. When this percentage varies from 20 to 100%, the reduction in emissions goes from 1.1 to 3.4% for CO₂, 2 to 6.1% for CO, 1.4 to 4.2% for NO_x, 2 to 5.9% for PM and 2.6 to 7.6% for VOC. This corresponds to a maximum reduction in the annual environmental social cost generated by the UGM of €4.25 million. Spatial analysis of the results shows that OHDs have a greater relative impact in the densest areas. It should be noted, however, that the environmental impacts of the OHDs recorded in this case study are low. Readers should keep in mind that this corresponds to an “unrealistic” shift of deliveries to off hours. Furthermore, these gains are much lower than what the literature attributes as the potential for OHDs to reduce the environmental impacts of UGM. Thus, we postulate that OHDs

deployed at large-scale could have a positive but low environmental impact in small metropolitan area which are not very congested, such as the LUA. Knowing that Lyon is a medium-sized metropolitan area by European standards and the 26th largest urban area in Europe (United Nation, 2017), the question arises as to the environmental relevance of OHDs in most European cities. However, this result does not detract, on the contrary, from the relevance of implementing OHDs in LUA. Indeed, in the battle for climate emergency, each ton of CO₂ and pollutants saved by adopting a sustainable urban logistics measure is already in itself a positive step towards improving the sustainability of urban freight transportation. Compared to the results of other measures, such as the low emission zone in London, where several studies found no clear evidence of a reduction in either pollutant (NO_x, PM) that could be attributed to it (CITYLAB, 2015; Holman et al., 2015), these OHDs performances in the case of the LUA are a big step in the right direction. As we know that emissions reduction could be improved by, for example, using larger vehicles for night deliveries, OHDs remain a relevant option for reducing the environmental impact of urban freight transport. This reduction in impact could be amplified if OHDs were combined with another measure such as electric vehicles.

In addition, the analysis reveals that the adoption of OHDs makes it possible to save travel time. Indeed, we could save 2.5 million hours of travel time per year with 100% OHD. This represents a decrease of about 11% in travel time compared to the current situation. These time savings augur a productivity gain for carriers and UGM operators in general. They could represent less working time or be used to extend the size of rounds if the vehicle load factor allows it. They could also allow for the use of heavier and / or longer vehicles. However, these gains must be weighed against the additional costs relating to silent vehicles and handling equipment, staff costs or investment in a delivery locker that the switch to OHD would entail.

This opens study prospects through the simulation of the reorganization of tours with bigger vehicles and the calculation of net productivity gains.

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Appendix A

Table A.1

Vehicle fleet distribution (2012, in % of distances traveled)

Source : Copcete et « Enquête Parc Auto – IFSTTAR ». From Coulombel et al. (2018)

	PC			LGV		HGV
	Petrol	Diesel	Others	Petrol	Diesel	Diesel
Euro 0	1.9%	1.3%	-	0.2%	2.1%	0.2%
Euro I	2.6%	3.1%	-	0.1%	3.6%	0.6%
Euro II	5.4%	6.3%	-	0.2%	7.0%	7.9%
Euro III	4.4%	19.9%	-	0.2%	23.5%	23.6%
Euro IV	7.7%	28.1%	-	0.2%	38.7%	33.6%
Euro V	3.7%	15.1%	-	0.1%	24.1%	34.1%
Total	25.7%	73.8%	0.5%	1.0%	99.0%	100.0%

Table A.2

External costs of emissions

Source: Van Essen et al.(2019)

	Rural area	Peri-urban area	Urban area
CO ₂ (€/ton)	100	100	100
NO _x (€/ton)	16,200	27,200	27,200
PM _{2.5} (€/ton)	87,000	131,000	407,000
PM ₁₀ (€/ton)	5,900	5,900	5,900
VOC (€/ton)	1,500	1,500	1,500

Note: “Rural area” corresponds to areas with less than 300 inh./km² as population density ; “Peri-urban area” corresponds to areas with population density ranging from 300 inh./km² to 1500 inh./km²; Urban corresponds to areas with more than 1500 inh./km².

Table A.3

OD matrices for freight vehicle and private car trips

Source : authors' calculation from FRETURB for freight vehicle and SIMBAD for PC

Vehicle	Origin	Destination			
		C1	C2	C3	C4
PC	C1	135391	42690	19230	17460
		63.0%	19.9%	9.0%	8.1%
	C2	43698	48951	21688	19382
		32.7%	36.6%	16.2%	14.5%
	C3	19989	22170	36675	29595
		18.4%	20.4%	33.8%	27.3%
	C4	22797	21747	29310	188499
		8.7%	8.3%	11.2%	71.8%
LGV	C1	27589	6915	4750	7408
		59.1%	14.8%	10.2%	15.9%
	C2	6915	5610	3024	3681
		36.0%	29.2%	15.7%	19.1%
	C3	4750	3024	4318	6149
		26.0%	16.6%	23.7%	33.7%
	C4	7408	3681	6149	18540
		20.7%	10.3%	17.2%	51.8%
Rigid HGV	C1	14602	3840	2863	4585
		56.4%	14.8%	11.1%	17.7%
	C2	3840	3577	2028	2455
		32.3%	30.1%	17.0%	20.6%
	C3	2863	2028	3353	4280
		22.9%	16.2%	26.8%	34.2%
	C4	4585	2455	4280	13345
		18.6%	10.0%	17.4%	54.1%
Articulated HGV	C1	2059	885	1224	4145
		24.8%	10.6%	14.7%	49.9%
	C2	885	707	537	1473
		24.6%	19.6%	14.9%	40.9%
	C3	1224	537	495	1223
		35.2%	15.4%	14.2%	35.1%
	C4	4145	1473	1223	2451
		44.6%	15.8%	13.2%	26.4%

Note: Percentage data represent the share of each OD in the total trips starting from the same origin.

The traffic external to the LUA perimeter is taken into account in the modeling in the following way: all incoming external flows originate from C4 and all outgoing external flows are destined for C4.

Table A.4

Travel time in hour per year (1,000)

Source: authors' calculations from VISUM

		LUA	C1	C2	C3	C4
Scen 0%	LGV	11,586.6	3,303.2	1,728.4	1,762.3	4,792.7
	Rigid HGV	7,326.1	1,871.6	1,051.1	1,177.1	3,226.2
	Articulated HGV	3,695.4	724.5	555.2	682.8	1,732.9
	Total	22,608.1	5,899.4	3,334.7	3,622.2	9,751.7
Scen Réf	LGV	11,353.8	3,217.4	1,688.9	1,725.9	4,721.5
	Rigid HGV	7,177.0	1,823.2	1,027.2	1,151.9	3,174.6
	Articulated HGV	3,612.8	706.0	541.1	666.8	1,699.0
	Total	22,143.6	5,746.6	3,257.3	3,544.6	9,595.1
Scen 20%	LGV	10,940.1	3,065.4	1,618.7	1,661.5	4,594.5
	Rigid HGV	6,910.6	1,736.8	984.5	1,107.2	3,082.1
	Articulated HGV	3,465.8	673.0	515.9	638.3	1,638.6
	Total	21,316.5	5,475.2	3,119.1	3,406.9	9,315.2
Scen 50%	LGV	10,455.1	2,888.3	1,535.6	1,585.4	4,445.8
	Rigid HGV	6,598.9	1,636.3	934.1	1,054.3	2,974.2
	Articulated HGV	3,294.2	634.6	486.3	604.8	1,568.5
	Total	20,348.2	5,159.2	2,956.0	3,244.5	8,988.5
Scen 80%	LGV	10,162.2	2,777.9	1,483.7	1,540.0	4,360.6
	Rigid HGV	6,415.2	1,574.2	903.0	1,023.6	2,914.4
	Articulated HGV	3,201.4	612.5	469.4	586.8	1,532.7
	Total	19,778.8	4,964.6	2,856.1	3,150.4	8,807.6
Scen 100%	LGV	10,079.6	2,743.0	1,467.9	1,528.6	4,340.1
	Rigid HGV	6,367.9	1,555.2	894.1	1,016.8	2,901.7
	Articulated HGV	3,187.5	607.8	466.2	584.3	1,529.2
	Total	19,635.0	4,906.1	2,828.2	3,129.7	8,771.0

Table A.5

Distances traveled in VKM per year (1,000)

Source: authors' calculations from VISUM

		LUA	C1	C2	C3	C4
Scen 0%	LGV	2,491.0	544.7	344.6	386.9	1,214.8
	Rigid HGV	2,133.4	422.6	281.5	345.5	1,083.8
	Articulated HGV	1,493.5	249.5	213.7	278.4	752.0
	Total	6,117.9	1,216.7	839.8	1,010.8	3,050.6
Scen Réf	LGV	2,493.9	545.3	345.3	387.6	1,215.7
	Rigid HGV	2,135.5	422.9	282.1	346.1	1,084.4
	Articulated HGV	1,494.3	249.6	213.8	278.6	752.4
	Total	6,123.7	1,217.8	841.2	1,012.3	3,052.4
Scen 20%	LGV	2,499.9	546.3	346.8	389.2	1,217.6
	Rigid HGV	2,140.3	423.6	283.2	347.5	1,086.1
	Articulated HGV	1,496.2	249.7	214.3	279.1	753.0
	Total	6,136.4	1,219.6	844.3	1,015.8	3,056.8
Scen 50%	LGV	2,506.3	547.5	348.2	390.8	1,219.7
	Rigid HGV	2,145.3	424.4	284.2	348.8	1,087.9
	Articulated HGV	1,498.1	250.0	214.7	279.5	753.8
	Total	6,149.6	1,222.0	847.2	1,019.1	3,061.4
Scen 80%	LGV	2,509.2	547.9	348.9	391.7	1,220.6
	Rigid HGV	2,147.8	424.6	284.8	349.5	1,088.9
	Articulated HGV	1,498.5	250.0	214.8	279.6	754.1
	Total	6,155.5	1,222.5	848.4	1,020.9	3,063.6
Scen 100%	LGV	2,508.0	547.6	349.0	391.5	1,219.9
	Rigid HGV	2,146.5	424.3	284.8	349.2	1,088.2
	Articulated HGV	1,498.1	249.8	214.8	279.6	753.8
	Total	6,152.6	1,221.7	848.7	1,020.3	3,061.9

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