# A new look at the environmental assessment of logistics sprawl Part 1

# The Environmental Impact of Urban Road Freight: A Modeling Exercise for the Paris Region

**Project Number: 17-4.1j**
**Year: 2017**

## FINAL REPORT

**August, 2017**

## Principal Investigator

**Martin Koning**

## Researchers

**Nicolas Coulombel, Laetitia Dablanc, Mathieu Gardrat**

**CITYLAB D2.1 Deliverable version 2017**

**MetroFreight Center of Excellence**
**IFSTTAR Cité Descartes**
**14-20 Bd Newton – 77447 – Marne la Vallée Cedex 2 – France**

*Metrofreight Research Report 4.1j*

*CITYLAB D2.1 Deliverable version 2017*

# A new look at the environmental assessment of logistics sprawl Part 1: The Environmental Impact of Urban Road Freight: A Modeling Exercise for the Paris Region[1]

*August 18, 2017*


Nicolas Coulombel (ENPC - IFSTTAR/AME/LVMT)
Laetitia Dablanc (East Paris University - IFSTTAR/AME/LVMT/SPLOTT)
Mathieu Gardrat (Lyon 2 Lumières University - LAET - Grand Lyon)
Martin Koning (East Paris University - IFSTTAR/AME/SPLOTT)



## Abstract

Whereas public deciders often lack detailed information on the volume and on the spatial shape of trips linked to urban road freight (URF), Light and Heavy Goods Vehicles are accused of contributing to a substantial share of the environmental nuisances in cities. By coupling three modeling exercises, this article estimates the amount of carbon dioxide ($CO_2$), nitrogen oxide (NOx) and fine particulate matter ($PM_{10}$) emitted by URF in the Paris region. Using the Freturb model, we first show that each firm emits and/or receives an average of 6.3 freight operations per week, thus generating around 890,000 freight trips per day. Crossing this information with OD matrix for private cars trips, we then implement a traffic assignment model which gives equilibrium traffic flows, compositions, and speeds at the road link level. In a third step, these traffic data are used to estimate pollutant emissions thanks to the Copcete calculator: URF is responsible for 20-30% of $CO_2$, NOx and $PM_{10}$ emitted by road traffic in the Paris region, whilst accounting for 8% of the total traveled distances. These aggregate results hide major spatial differences: the higher the population density within a zone, the more intensively used the roads therein, the lower the traffic speed, and the larger the environmental nuisances from URF. We additionally propose a simplified indicator of individuals' exposure and we estimate the social costs of local pollutants from road traffic in the Paris region. The monetary valuation of environmental damages linked to the mobility of households amounts to 0.55% of the regional GDP. The corresponding ratio for URF is 0.39%.



**Keywords:** urban freight, pollutant emissions, generation coefficients, traffic assignment model, social costs, Paris region.

**JEL codes:**



[1] This research will be completed with a "Part 2" in 2018. We acknowledge Adeline Heitz and Adrien Beziat for the help with socioeconomic data and some of the maps. This research benefited from useful comments by Michel André and we would like to thank Vincent Demeules (CEREMA) for providing access to the Copcete calculator (V4). This article is part of the CityLab and Metrofreight research programs.

## 1. Introduction

Urban freight today presents a paradox. On the one hand, picking-up and delivering the right volume of goods to the right places at the right time is a crucial activity for the dynamism of urban areas, from the viewpoint of both firms and households (OECD, 2003; Dablanc, 2009; Macharis and Melo, 2011; Cui et al., 2015). On the other hand, freight operators face various economic and technological constrains (Cullinane and Toy, 2000; Holguin-Veras, 2002; Comi et al. 2012) which lead them to opt for motorized vehicles in most cases. As a consequence, urban road freight (URF in what follows) is accused of contributing to a substantial share of the environmental nuisances in cities (OECD, 2003; Cui et al., 2015; CIVITAS, 2015; Russo and Comi, 2016) and public deciders enact various policies aimed at making URF more sustainable (e.g. urban consolidation centers, road pricing, low emission zones; Macharis and Melo, 2011; Demir et al., 2014; Cui et al., 2015; Russo and Comi, 2016).

Data collection efforts on URF have been engaged over the last decade (Allen et al., 2010; Figliozzi et al., 2007; Holguin-Veras and Jaller, 2014). However, a more detailed knowledge is still missing. As opposed to private car (PC) trips - for which information from households mobility surveys (and increasingly from the technology and big data sources) is available-, authorities are rarely aware of the specific distances traveled by LGVs (Light Goods Vehicles) and HGVs (Heavy Goods Vehicles) within their jurisdictions (Dablanc, 2009; EC, 2013; CIVITAS, 2015). Several reasons can explain this. One is related to the commercial nature of URF, which implies information privacy in most countries. Also, roads are sometimes equipped with captors reporting traffic data, but these are generally restricted to a small share of the network and they cannot distinguish LGVs from PCs. Third, the organizational features of URF complicate its observation because of the diversity of the transport operations (e.g. direct or round trips). Put differently, assessing precisely the environmental impacts of URF remains a major challenge, for both public deciders and the research community.

This article aims to question the gap between common beliefs about the environmental impact of URF and its specific empirical measurement. For that purpose, we use and combine a succession of three modeling exercises used to estimate carbon dioxide ($CO_2$), nitrogen oxide (NOx) and fine particulate matter ($PM_{10}$) emitted by URF in the Paris region[2] (2012).

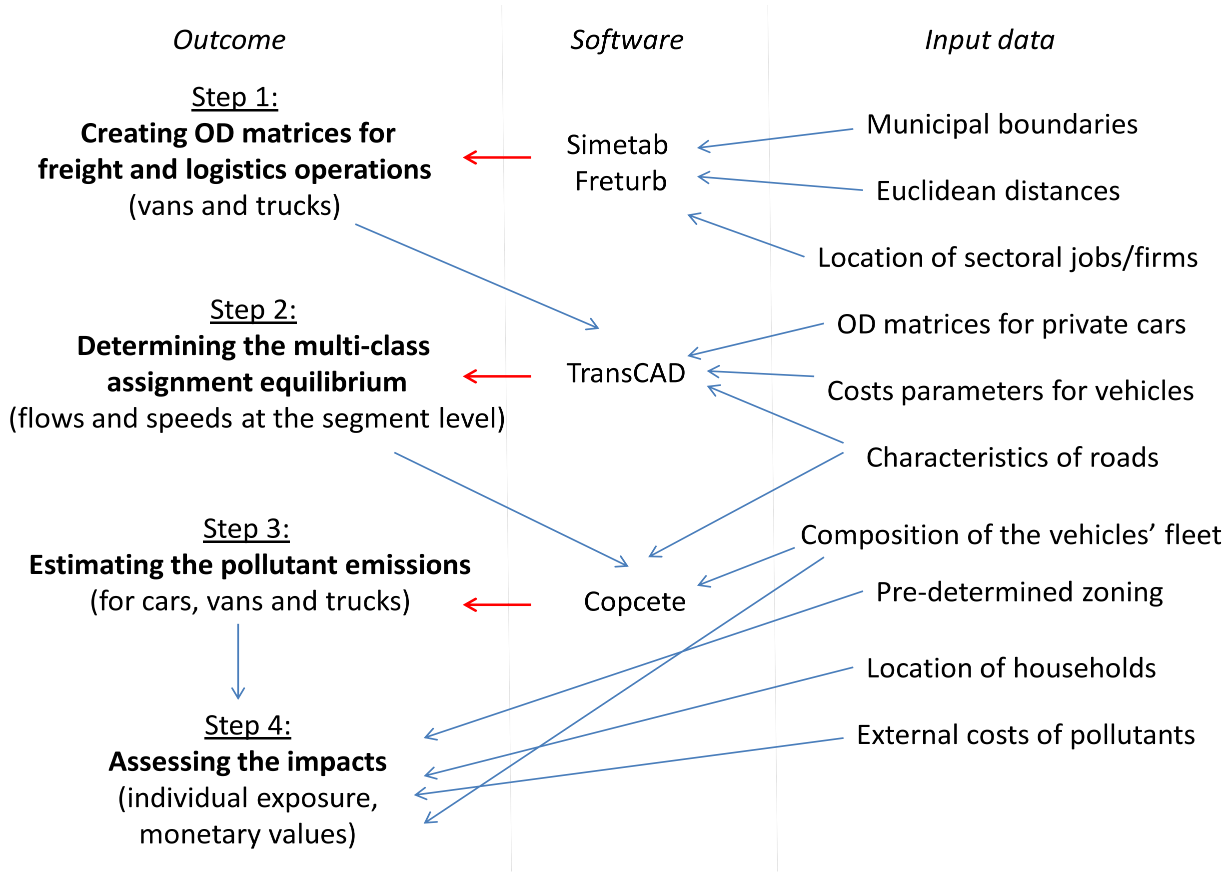
Figure 1 illustrates the four stages of our analysis. The first one relates to URF basic data. We take advantage of the Simetab-Freturb software's (Routhier and Toilier, 2007; Gardrat et al., 2014) to estimate "generation coefficients" (number of weekly deliveries and pick-ups to establishments) of firms[3] in the Paris region and to construct Origin-Destination (OD) matrices for URF. The second stage is based on the TransCAD software and computes the traffic assignment equilibrium (Ortuzar and Willumsen, 2011) for different time periods using a multi-class framework (Dafermos, 1972; Moridpour et al., 2015). OD matrices for both URF and PCs are combined with transport costs parameters and capacities of the road network to have information on traffic flows, compositions and speeds at the road link level. Based on these data, we derive pollutant emissions using the Copcete calculator (Demeules and Larose, 2012). After selecting the technological composition of the vehicle

[2] The Paris region, called "*Ile-de-France*", is larger in size than the statistical metropolitan area of Paris, but is a good proxy for it, and one for which general data is more easily available.

[3] By firm we mean any establishment engaged in an activity, including public administrations, small and large businesses, etc. This does not include private households (B2C e-commerce flows, therefore, are not included in the data).

fleet and the infrastructures' characteristics, Copcete estimates emissions due to road traffic for each link and for each vehicle class. Lastly, this whole information can be crossed with spatialized socioeconomic data and external costs of pollutants to assess the environmental impacts of URF. Apart from $CO_2$, which contributes to global warming and the impacts of which are worldwide (Tol, 2009), NOx and $PM_{10}$ indeed generate various diseases to the exposed (local) populations (Kampa and Castanas, 2008; Ricardo-AEA, 2014; WHO, 2016).

**Figure 1 – Analysis architecture**




Sources: authors' elaboration.

We do not propose any policy scenario aimed at reducing the emissions caused by URF in the Paris region (as done by Kickhofer and Kern, 2015; or by Aditjandra et al., 2016 for Munich and Newcastle respectively; see the reviews of policy options by Demir et al., 2015; or by Russo and Comi, 2016). Nevertheless, this study provides the following contributions to the literature:

As compared with past research that combined traffic and emissions models (see the review by Shorshani et al., 2015 ; and specific case studies by Xia and Shao, 2005; Tirumalachetty et al., 2013 ; Patil, 2016), the emphasis is put here on URF. The Freturb software (Routhier and Toilier, 2007) that we use can provide estimates on goods movement for a variety of activities, firm sizes and types of locations, thus reflecting the spatial heterogeneity of urban freight behaviors. Moreover, OD matrices proposed for HGVs and LGVs are for the entire Paris region, and not restricted to a single economic site (as in Aditjandra et al., 2016). In addition, these data take into account the main specificities of URF, such as the type of routes taken by freight vehicles (direct or round trips) or the characteristics of the transport provider (whether it is an own-account operation or an operation for a third party for example), which was not the case in Kanarogou and Buliung (2008). As a consequence, our estimates of pollutant emissions are based on a precise description of URF, in terms of both the spatial coverage and the organizational features of commercial transport.

Second, the Copcete calculator that we use estimates pollutants for a wide range of traffic speeds, at the road link level. Given the non-linear (generally U-shaped) relationship between emissions and vehicle velocity (Ntziachristos and Samaras, 2000; André and Hammarstrom, 2000), our empirical analysis is likely to gain in precision. Even if past research have already mobilized such emission models (Shorshani et al., 2015), we systematically describe our results in a spatial perspective. By doing so, we can match and map the huge variations in vehicle speeds observed across different places with the corresponding traffic volumes and mixes, pollutant emissions and number of people potentially impacted.

Last but not least, we estimate the social “bill” due to emissions of HGVs and of LGVs for a major urban area. Accounting for 18% of the French population and for 30% of the national GDP in 2012, the Paris region is one of the wealthiest areas in Europe, but also one of the most heavily congested (Inrix, 2014).[4] Concerns related to air pollution are nowadays of major interest to elected officials (IdF, 2016) and to the population (EC, 2016). As a consequence, it seems relevant to put monetary figures in front of these fears and to precise the magnitude of social losses caused by URF.

The rest of this article proceeds as follows. Section 2 describes the main features of the three models presented on Figure 1. Socioeconomic data and results from both the goods’ movement generation and the traffic assignment models are then presented in Section 3. Section 4 is focused on the environmental analysis. We thus estimate emissions of $CO_2$, NOx and $PM_{10}$ from road transport in general[5] and from URF in particular, before proposing a simplified indicator of exposure to local pollutants. We also estimate the corresponding social costs incurred to the Paris region. Section 5 calls for further research.

## 2. Modeling framework

### *2.1. Generating OD matrices for URF*

Freturb is a multipurpose model designed for urban freight analysis (see Routhier and Toilier, 2007). In this research, it is used to generate OD matrices for URF in the Paris region.

Freight surveys collected in France during the 1990’s (Patier and Routhier, 2008) have made explicit that the number of weekly movements ($\square_{\square}$) generated by one economic establishment[6] (e) is explained by its sectoral activity (a), its number of employees (o), and the nature of its premises (*p*). The total number of movements $\square_{\square}$ in the zone z is:

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[4] Around 60% of kilometers of delays registered in France are located in IdF (URF, 2013), where motorists spent in 2013 an average of 55.1 hours per year in traffic jams, only behind London and Stuttgart (INRIX, 2014).

[5] We ignore road traffic (and pollutant emissions) from public buses, motorized two-wheelers and cabs.

[6] A firm is a legal entity that may be made of several establishments (i.e. locations). We use both terms interchangeably.

$$\square_{\square} = \sum_{\square \in \square} \square_{\square}(\square, \square, \square) \qquad (1).$$

The combination of these variables gives a typology of establishments, comprising 116 different classes noted $\square$ and each represented by a unique triplet $\square(\square, \square, \square)$.

Goods movements can also be broken down according to their transport characteristics: the vehicle class *k* (LGVs, rigid or articulated HGVs), the management mode *m* (third party logistics, own account transport shipper or consignee) and the type of routes *r* (direct or round trips):

$$\square_{\square} = \sum_{\square,\square,\square,\square} \square_{\square,\square} \times f_{\square,\square,\square}\,(2) \qquad (2),$$

where $f_{\square,\square,\square}$ is the frequency of characteristics $(\square, \square, \square)$ among establishments of class ε and $\square_{\square,\square}$ the number of movements generated by establishments in zone *z.*

By knowing the volume of goods' movements in each zone and their categorization, Freturb then estimates the total number of trips in a zone z ($\square_{\square}$) as:

$$\square_{\square} = \square\square_{\square} + \square\square_{\square} + \square_{\square} \qquad (3),$$

where $\square\square_{\square}$ refers to the direct trips, $\square\square_{\square}$ to the starting and ending trips of one delivery round and $\square_{\square}$ to the connecting trips of delivery rounds. The distance of each trip type is determined through geographical variables (distance to the center of each zone, density of activity) and the characteristics $(\square, \square, \square)$ of the establishments' category ε.

Last, Freturb applies one typology of trips, defined by their vehicle class, their type, their management mode and their routes' length. According to this 25 class categorization, the beginning of each τ-type trip which touches the zone $\square_{\square}$ matches the movement of τ-type trips generated in $\square_{\square}$. The resulting distribution matrix for each vehicle class k is:

$$\square_{\square\square} = \sum_{\square} [\square_{\square\square}(\square)] \qquad (4).$$

The French SIRENE dataset is the best input data to estimate the generation and the distribution of URF trips with Freturb. It provides information on the characteristics $(\square, \square, \square)$ of the establishments at the municipality level. Our dataset on the Paris region provides information regarding firms' activities (a) and sizes (o), but not about the establishments' premises (p). Fortunately, it remains possible to feed Freturb with more basic local data thanks to Simetab (Gardrat et al., 2014).

Simetab relies on a typology of urban spaces determined through the analyses of different SIRENE files and other local data, in different French metropolitan areas (Lyon, Bordeaux, Paris…) and for various years (Gardrat et al., 2014). Each type of urban space is assumed to be associated with a given distribution of the characteristics $(\square, \square, \square)$. Using statistical classification methods, Simetab first defines urban categories (highly residential, lower density area, high tertiary activity, commercial...) heterogeneous in their economic structures. "Multiple discriminant analyses" are then applied to allocate each zone observed in the dataset to one of these types. By comparing the economic structure of the zones to their typological counterparts, Simetad finally "matches" each firm observed in the dataset with a category $\square(\square, \square, \square)$, thus insuring the operability of Freturb.

*2.2. Finding the multi-class traffic equilibrium*

Traffic conditions in the Paris region are estimated using a static multi-class traffic assignment model (Dafermos, 1972). All calculations are performed with the TransCAD software.

Assignment models simulate the route choice behavior of users on a transport network. Originally designed to determine the traffic on particular roads for a given time period (typically the morning or evening peaks), they can also be used to derive the "shortest path" between any OD pair, and the corresponding travel time, distance and speed (Coulombel and Leurent, 2013).

Road congestion plays a key role in traffic assignment models (Ortuzar and Willumsen, 2011). As more individuals use the same road, it becomes congested and travel time increases. This phenomenon is often represented by a volume-delay function (VDF). The most widespread VDF – used here – comes from the American Bureau of Public Roads (BPR; see TRB, 2010):

$$\square\square = \square\square_{\square} \times \left(1 + \alpha \times \left(\frac{\square}{\square}\right)^{\square}\right) \qquad (5),$$

where $\square\square$ is the travel time on a given link, $\square\square_{\square}$ the free-flow travel time (a function of the maximal-legal speed), $\square$ the traffic flow and $\square$ the link theoretical capacity (a function of the number and the width of lanes). The parameters $\alpha$ and $\square$ $(> 0)$ describe the deviation of $\square\square$ from $\square\square_{\square}$ when the "flow-to-capacity ratio" $(\square/\square)$ grows.

As congestion starts to build up, some drivers turn to alternative routes, thus increasing the traffic flow and decreasing the travel speed therein. This phenomenon develops until a traffic equilibrium – called "Wardrop's equilibrium" – is reached (Small and Verhoef, 2007; Ortuzar and Willumsen, 2011). At the equilibrium, for any given OD pair, the "generalized cost" of travel of all alternative paths are equalized (the cost of unused paths being greater than this minimum cost), i.e. drivers do not have any incentive to change their routes. The generalized cost of travel associated to a path *p* is here:

$$\square\square_{\square}^{\square} = \square\square\square^{\square} \times \square\square_{\square} + \square^{\square} \times \square_{\square} \qquad (6),$$

where the variables $\square\square_{\square}$ and $\square_{\square}$ denote the travel time and the length of path *p* respectively, $\square\square\square^{\square}$ the value of travel time savings of class *k* users and $\square^{\square}$ the monetary kilometric cost (fuel, insurance, depreciation….).

The route choice of drivers consequently involves a trade-off between travel time and distance (thus monetary costs) (Small and Verhoef, 2007; Coulombel and Leurent, 2013). Accordingly, the path(s) with the minimum generalized cost would generally be neither the fastest nor the shortest, but rather a compromise between the two.

Our model comprises four user classes *k*: PCs, LGVs, rigid and articulated HGVs. Whereas the first class regroups all trips (commuting, leisure …) made by PC, the last three classes are exclusively associated to URF. Each class is associated with different values of travel time and kilometric costs, so that route choices may differ from one class to another, for a given OD. It is worth noting that all vehicle classes travel on a given link at the same speed once reached the Wardrop's equilibrium.  Moreover, each type of vehicle does not weigh the same in the VDF function:

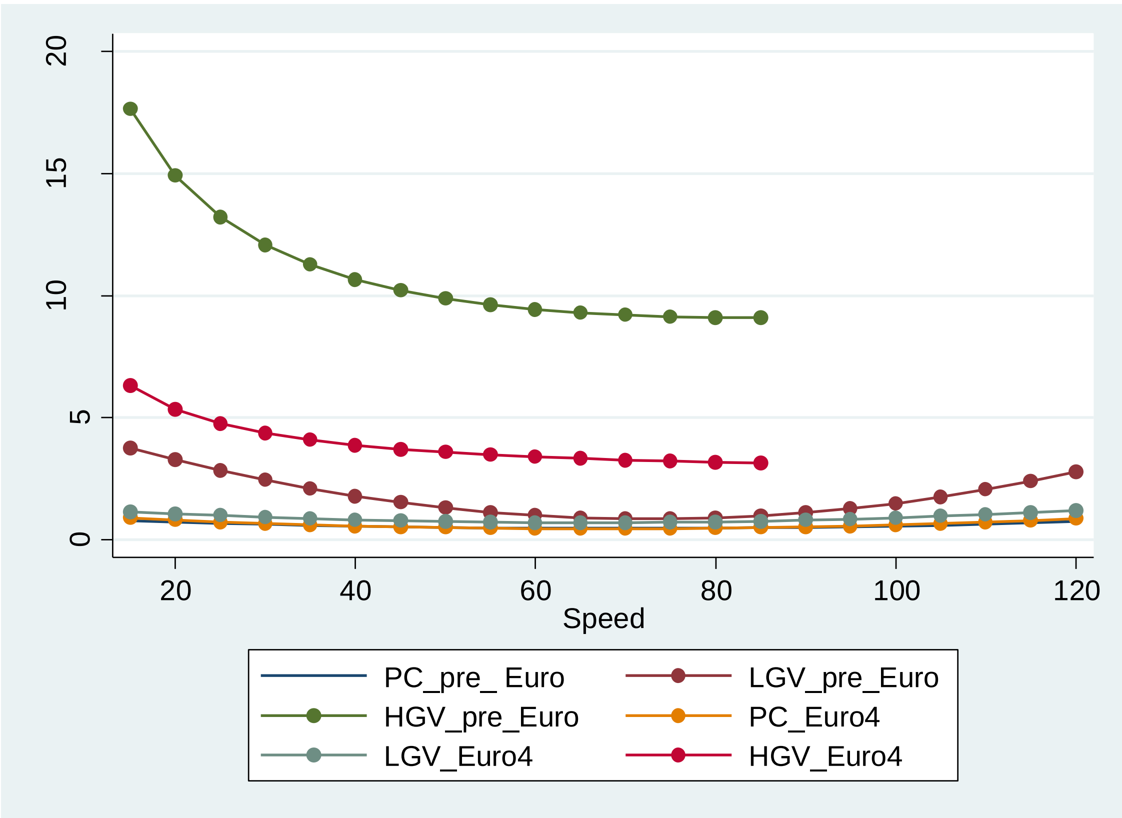
$$□ = \sum_{□} □□□_{□} \times □_{□} \qquad (7).$$

The various flows of class k vehicles $□_{□}$ are converted into a passenger car equivalent (PCE) metric. The $□□□_{□}$ factor describes the amount of road space occupied by one vehicle of class k as compared to one PC, thus accounting for the different congestion impacts of different vehicles classes (Webster and Elefteriadou, 1999; TRB, 2010; Kanaroglou and Buliung, 2008).

### *2.3. Estimating pollutant emissions*

Copcete (Demeules and Larose, 2012) is based on the COPERT IV methodology (Ntziachristos et al., 2009; Shorshani et al., 2015). It compiles emission factors for various driving cycles (representative in terms of speeds, load rates, slopes of the roads) and various vehicles (in terms of classes, weights or technologies).

**Figure 2 – NOx emissions of diesel vehicles**




Sources: authors' elaboration from Copecete.

We consider in this research only "exhaust emissions" from road traffic and we neglect those linked to the evaporation of pollutants. As illustrated on Figure 2 for NOx, the unitary emissions depend greatly on the vehicle class and on the engine technology. For a given legal standard and a traffic speed of 15 km/h, HGVs emit three times more NOx than (diesel) LGVs, themselves polluting twice more than (diesel) PCs. Also, the effect of technological changes is substantial, especially for freight vehicles.

Considering one HGV driving at 20 km/h, Euro 4 vehicles emit around three times less NOx per kilometer than Pre-Euro vehicles. Lastly, unitary emissions are not a linear function of the traffic speed. In the case of PCs and LGVs, the U-shaped curves reach their minimal values at travel speeds of 60-70 km/h approximately.

Unitary emissions of HGVs are modeled in Copcete as a positive function of the roads' slope and of the load rates of vehicles (the higher these parameters, the higher the energy consumption, hence the emissions). Copcete also takes into account for PCs and LGVs the over-emissions due to "cold-start phases", i.e. when engines are not hot yet. Whereas the correction factor should theoretically depend on climatic conditions and on the share of distances driven at "non-stabilized regime", Copcete estimates the over-emissions based on the average trip distance.

Feeding Copcete with the outputs of the traffic assignment model is straightforward because this software has been coded to estimate pollutant emissions at the road link level. Formally, the total emissions of pollutant *j* on the link *s* ($\square\square_{\square}^{\square}$) are given by:

$$\square\square_{\square}^{\square} = \square_{\square} \times \sum_{\square}\sum_{\square} \ {}_{\square}^{\square} \times \square_{\square}^{\square} \times \square_{\square}^{\square\square}(\square^{\square}) \qquad (8),$$

where $\square_{\square}$ describes the length of link *s*, ${}_{\square}^{\square}$ the share of vehicles using the technology *x* within the total flow $\square_{\square}^{\square}$ of the vehicle class *k*, and $\square_{\square}^{\square\square}(\square^{\square})$ the emission factor of pollutant *j* for the class *k* vehicles using the technology *x*, i.e. a function of the traffic speed ($\square^{\square}$). Regarding the parameters ${}_{\square}^{\square}$, Copcete considers the precise composition of the French vehicles' fleet for a given year, in terms of vehicles' legal standards, energy types and weights.

**3. Data**

## *3.1. Socioeconomic data*

The "*Ile-de-France*" (IdF) administrative region consists of 1,300 municipalities distributed over 12,058 km$^2$. As mapped on Figure 3, we divide the metropolitan area according to the spatial classification found in the Quinet report (CGSP, 2013), i.e. the official guidelines for transport projects' appraisals in France. We add to this categorization the city of Paris, which is made of 20 administrative districts.

Despite policies implemented in the 1960's-70's to decentralize population and economic activities within IdF (Shearmur and Alvergne, 2003), Figure 3 and Table 1 show that the region remains mostly monocentric, with population densities that decline quickly with respect to the distance to Paris. Whereas the city of Paris hosted 2.2 million individuals in 2012 and had a (very high) population density of 23,700 inh./km$^2$, these figures were equal to 77,000 inhabitants and 28 inh./km$^2$ respectively for "interurban areas", i.e. rural municipalities 62 km away from Paris city on average. This spatial pattern is even more pronounced for economic activities. Paris concentrates 39% and 32% of total IdF establishments and jobs respectively, over 1% of the regional area, thus highlighting the strength of "agglomeration economies" (Glaeser, 2011). By contrast, the fringes of IdF host less than 60,000 firms and 400,000 jobs while they account for 75% of the total regional land area. Establishments located in Paris are smaller (6.3 jobs per firm on average) than those in the inner suburbs. Firms in the core of the metro area are actually mostly specialized in services and high-skilled jobs whereas (labor intensive) industries or wholesale activities need more land space and prefer peripheral locations, where rental prices are lower.

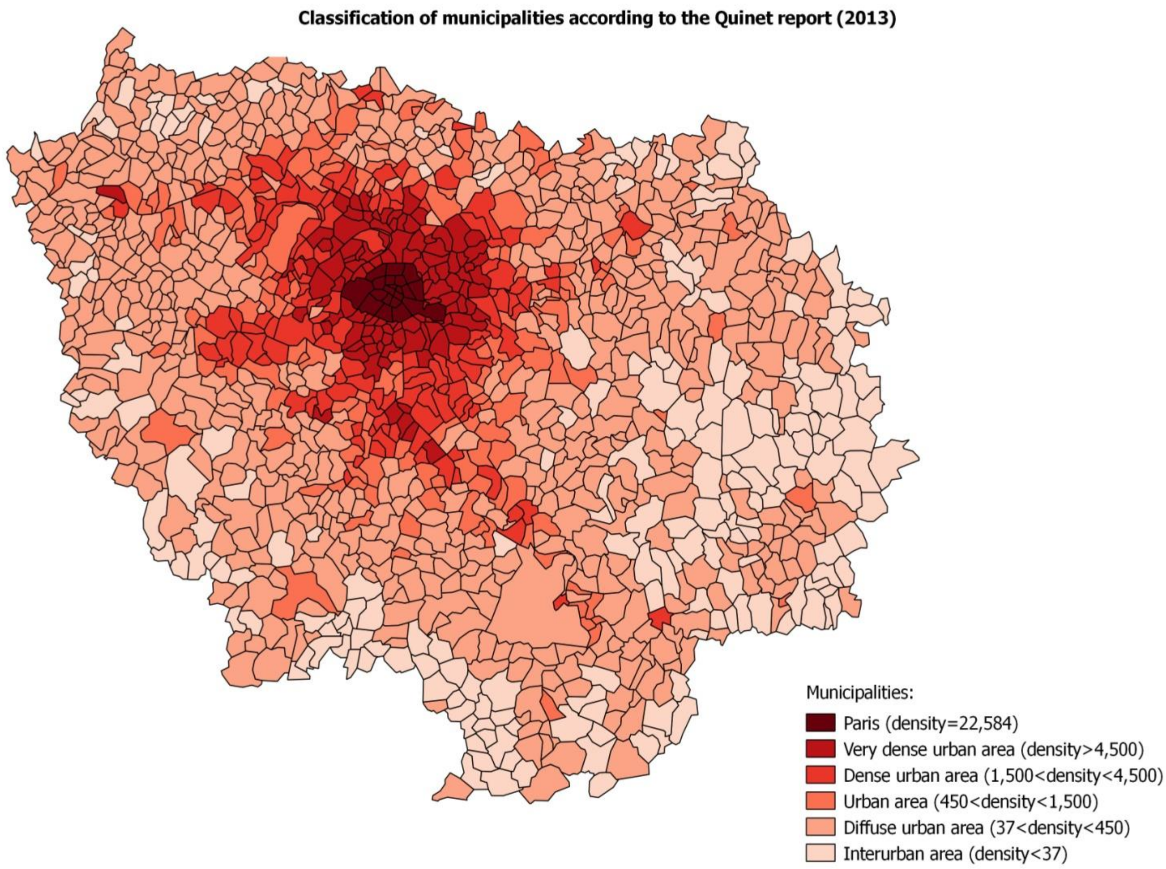
**Table 1 – Socioeconomic data (2012)**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Municipalities** | 1,300 | 20 | 110 | 141 | 161 | 660 | 208 |
| **Area** ($km^2$) | 12,058 | 105 | 556 | 968 | 1,293 | 6,432 | 2,703 |
| **Distance to Paris** (km) | 41.1 | 3.0 | 11.4 | 22.1 | 31.7 | 46.6 | 62.3 |
| **Population** (1,000) | 11,899 | 2,241 | 4,623 | 2,831 | 1,175 | 950 | 77 |
| **Pop. density** (inh./ $km^2$) | 1,709 | 23,656 | 9,646 | 3,009 | 940 | 160 | 28 |
| **Establishments** | 806,405 | 318,045 | 245,900 | 126,738 | 58,451 | 51,951 | 5,320 |
| **Jobs** (1,000) | 5,949.2 | 1,900.2 | 2,074.6 | 1,106.6 | 485.5 | 362.3 | 20.0 |
| **Jobs density** (jobs/ $km^2$) | 988 | 27,824 | 4,326 | 1,050 | 389 | 60 | 8 |
| **Estab. size** (jobs/estab.) | 5.4 | 6.3 | 7.8 | 7.8 | 7.2 | 4.9 | 2.4 |

Sources: areas and populations from "*Recensement Général de la Population*" (INSEE), economic activities from a partial "SIRENE" dataset (INSEE).

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

**Figure 3 – The « *Ile-de-France* » region**




Source: authors' elaboration from CGSP (2013) and "*Recensement Général de la Population*" (INSEE).

*3.2. OD matrices*

The economic dataset at our disposal includes information on the number of establishments per municipality, their sectoral classification and their size, but not about the nature of their premises. Accordingly, we rely on the Simetab model to "match" each observed establishment with its typological counterpart (see sub-section 2.2). This enables us to feed the Freturb software and to calculate the "generation coefficients" of the firms in IdF, as well as the transport characteristics of URF. Table 2 illustrates the outcome of this first modeling exercise.

Each establishment emits and/or receives an average of 6.3 freight operations per week (5.08 million operations/week).[7] Establishments in Paris generate fewer operations (4.9/week) than suburban firms. This heterogeneity is due to the size of the firms (smaller in Paris) but also to their economic specialization (services emit/receive fewer goods than retailing, industries, or wholesale). Moreover, around 30% of freight movements are direct trips, with a higher share in interurban areas (50%) where consolidation is less possible. Lastly, around 40% of goods' movements are operated by third party transport companies. Own account transport is slightly more represented in interurban areas (70%) because small firms (services for people, small retails) are more likely to make their deliveries and/or collections alone (Toilier et al., 2015).

**Table 2 – Characteristics of freight operations**

| | **IdF** | **PC** | **VDUA** | **DUA** | **UA** | **DIUA** | **IA** |
|---|---|---|---|---|---|---|---|
| **Operations per establishment** (/week) | 6.3 | 4.9 | 6.6 | 7.5 | 8.8 | 7.1 | 5.1 |
| **Direct trips movements** (%) | 29.8 | 26.9 | 28.4 | 29.4 | 30.1 | 34.2 | 50.7 |
| **Third party operators movements** (%) | 41.2 | 40.2 | 41.4 | 41.7 | 44.1 | 39.7 | 31.1 |

Sources: authors' calculations from Freturb and Simetab.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

By knowing the volume of operations emitted/attracted in each municipality, Freturb was then used to distribute these commercial trips across IdF, based on Euclidean distances and on their organizational features. This modeling process results in OD matrices for morning peaks (7-9 A.M.), evening peaks (5-7 P.M.) and the rest of the day. Whereas this information is differentiated across (rigid or articulated) HGVs and LGVs, Table 3 merges together the total daily URF and considers as origins and/or destinations the six types of territories illustrated on Figure 3.

Every day, around 893,000 trips in the Paris region are linked to URF. Even if these figures are not described in Table 3, about 57% of the commercial trips are made with LGVs and X% are driven during the peak periods. Moreover, 63% of URF flows are linked to Paris and/or to the very dense urban areas of IdF. By contrast, freight trips originating or serving the interurban and the diffused urban areas account for only 7.6% of regional URF flows. It is worth noting that a major drawback of Freturb relates to the flows of goods between IdF and the other French regions. Thus the OD matrix presented in Table

[7] An operation, or a movement, is either a delivery or a pick-up of freight.

3 is likely biased downward because it does not account for interregional trade, neither for through traffic.[8]

The OD matrix for PCs comes from the MODUS model. Developed by the "*Direction Régionale et Interdépartementale de l'Equipement d'Ile-de-France*" (DRIEA), MODUS is focused on passenger transport and calibrated using a regional trip survey and traffic count data. Table 3 shows that households make around 13.5 million trips by PCs every day in the Paris region (X% during the peaks). Put differently, URF accounts for 6.2% of daily motorized trips in IdF. As compared to freight flows, PCs trips having dense urban areas, urban areas and diffused urban areas as origins and/or destinations are substantial (49% of total passenger trips). In addition, the share of individual trips made by PCs and related to Paris is only 11%, in line with the high performances of public transit in the core of the metro area. Lastly, freight vehicles account for 30% of total trips on ODs linking Paris to the outer suburbs.

**Table 3 – OD matrices for urban road freight and private cars (2012)**

| | | *Daily trips from:* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **PC** | **VDUA** | **DUA** | **UA** | **DIUA** | **IA** | **Total** |
| *Daily trips to:* | **PC** | 1,129,372<br>144,280<br>(11.7%) | 495,943<br>74,516<br>(13.1%) | 107,198<br>31,665<br>(22.8%) | 28,178<br>15,990<br>(36.2%) | 25,771<br>11,649<br>(31.1%) | 1,272<br>630<br>(33.1%) | 1,787,737<br>278,732<br>(13.5%) |
| | **VDUA** | 559,999<br>74,516<br>(11.7%) | 3,270,264<br>139,509<br>(4.1%) | 747,846<br>47,617<br>(6.0%) | 213,058<br>18,984<br>(8.2%) | 109,242<br>8,481<br>(7.2%) | 5,038<br>412<br>(7.6%) | 4,905,450<br>289,521<br>(5.6%) |
| | **DUA** | 93,349<br>31,665<br>(25.3%) | 770,811<br>47,617<br>(5.8%) | 1,877,459<br>48,785<br>(2.5%) | 463,366<br>24,457<br>(5.0%) | 262,432<br>13,860<br>(5.0%) | 14,975<br>620<br>(4.0%) | 3,482,394<br>167,007<br>(4.6%) |
| | **UA** | 27,449<br>15,990<br>(36.8%) | 208,650<br>18,984<br>(8.3%) | 460,160<br>24,457<br>(5.0%) | 682,293<br>17,397<br>(2.5%) | 267,952<br>11,884<br>(4.2%) | 23,106<br>860<br>(3.6%) | 1,669,611<br>89,575<br>(5.1%) |
| | **DIUA** | 21,253<br>11,649<br>(35.4%) | 114,038<br>8,481<br>(6.9%) | 286,320<br>13,860<br>(4.6%) | 276,152<br>11,884<br>(4.1%) | 759,846<br>15,884<br>(2.0%) | 45,135<br>1,669<br>(3.6%) | 1,502,746<br>63,429<br>(4.1%) |
| | **IA** | 1,288<br>630<br>(32.8%) | 5,799<br>412<br>(6.6%) | 18,329<br>620<br>(3.3%) | 26,290<br>860<br>(3.2%) | 47,055<br>1,669<br>(3.4%) | 66,091<br>411<br>(0.6%) | 164,855<br>4,604<br>(2.7%) |
| | **Total** | 1,832,712<br>278,732<br>(13.2%) | 4,865,507<br>289,521<br>(5.6%) | 3,497,314<br>167,007<br>(4.6%) | 1,689,340<br>89,575<br>(5.0%) | 1,472,301<br>63,429<br>(4.1%) | 155,619<br>4,604<br>(2.9%) | 13,512,795<br>892,872<br>(6.2%) |

Sources: authors' calculations from Freturb for URF and from DRIEA for PC.

Notes: 1) "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

2) The underlined figures refer to trips made by LGVs and HGVs, the percentages in brackets describe the share of URF on a given OD.

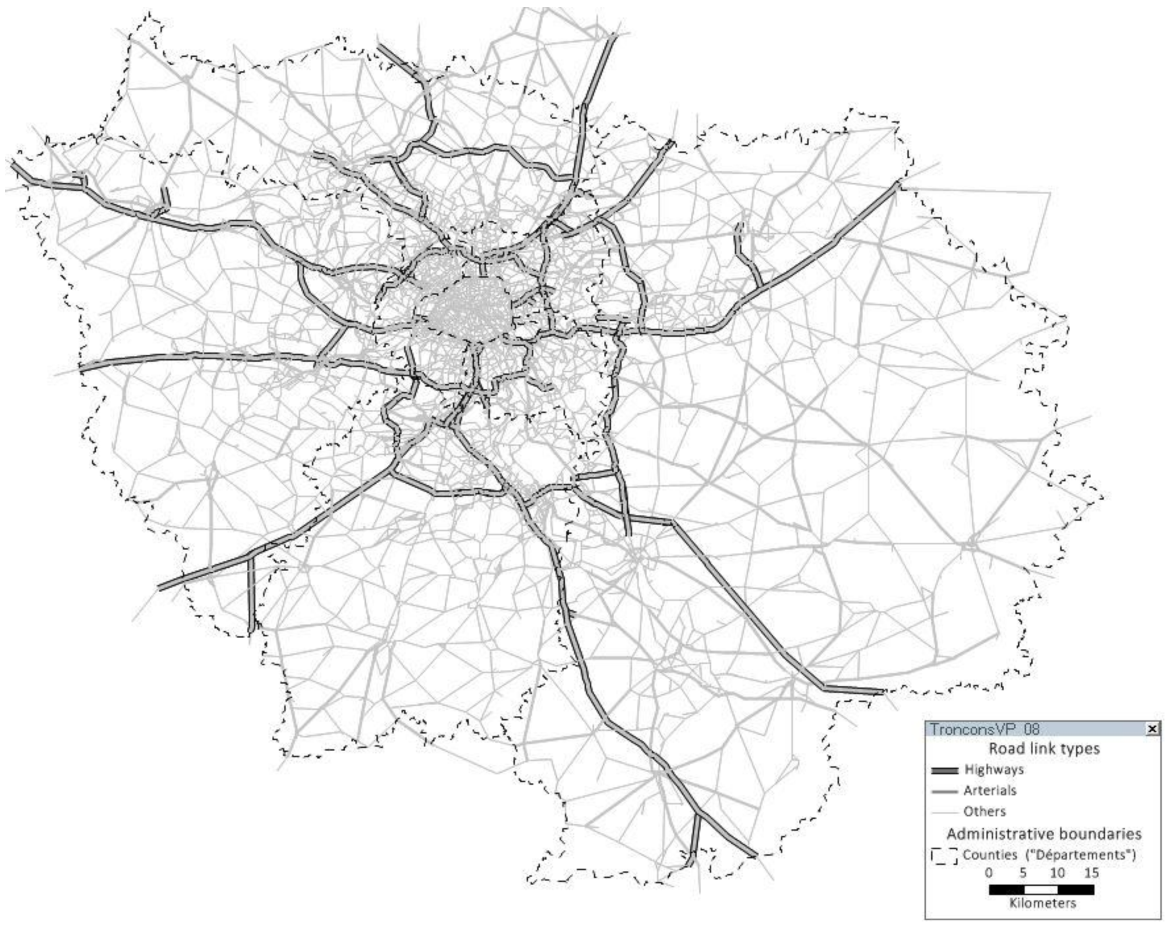
[8] According to the survey "*Enquête transport routier de marchandises*", the Paris region received 10,052 million tons-kilometers from other French regions in 2012 and emitted 8,231 million tons-kilometers towards.

## *3.3. Road network*

Data relative to the road network are also extracted from MODUS and correspond to year 2008. The modeled network comprises 39,420 segments, for a total length of 20,500 km (see Appendix 7.1). It includes the most important roads in IdF (freeways, arterials, collectors) but not small streets in cities or rural/local roads in the outer suburbs.

As depicted on Figure 4, the road network is strongly radial, yet with three concentric bypasses. Road density – a proxy of road supply - declines with distance to the urban center and the maximal (legal) speeds are higher in peripheral areas (63 km/h in diffused areas vs. 44 km/h in Paris). Let us mention that theoretical capacities (see Appendix 7.1) are slightly biased upward for central Paris. The Ring-Road (i.e. the biggest urban highway in Europe) officially belongs to the municipality of Paris, which partly explains the high mean road capacity for this zone. This being said, on average each kilometer of road in IdF could accommodate a flow of 1,700 vehicles per hour.

**Figure 4 – Road network for the Paris region**




Source: authors' elaboration with TransCAD, from DRIEA.

*3.4. Traffic equilibrium*

The traffic assignment model relies on individuals' trade-offs between travel time and monetary costs. The parameters used to determine the generalized cost of trips are presented in Appendix 7.1. They refer to the usage costs of vehicles[9], their individuals' occupancy and their load weight, and the values of travel time savings (for passengers, professional drivers and goods).

Based on these, the TransCAD software is used to determine the traffic equilibrium, thereby providing traffic flows and vehicle speeds at the link level. Table 4 shows that the mean flow of PCs on one kilometer of road is 745 vehicles per hour during the peaks (7-9 A.M. and 5-7 P.M) and 303 vehicles per hour during the off-peaks. By contrast, the average flow of freight vehicles is equal to 61 vehicles per hour (33 LGVs/hour and 28 HGVs/hour) and to 37 vehicles per hour respectively (20 LGVs/hour and 17 HGVs/hour). Considering the PCE factors and the theoretical road capacities, we deduce an average "flow-to-capacity ratio" of 0.45 during the peaks (0.20 during the rest of the day). This interaction between road demand and supply implies a mean travel speed of 41.2 km/h during the peaks (51.3 km/h during the off-peaks).

**Table 4 – Results of the traffic assignment model**

| | **IdF** | **PC** | **VDUA** | **DUA** | **UA** | **DIUA** | **IA** |
|---|---|---|---|---|---|---|---|
| *Peak periods:* | | | | | | | |
| **Flow of PC** (veh./h) | 745 | 1,146 | 858 | 664 | 646 | 526 | 404 |
| **Flow of LGV** (veh./h) | 33 | 95 | 40 | 23 | 17 | 10 | 3 |
| **Flow of HGV** (veh./h) | 28 | 69 | 33 | 22 | 18 | 11 | 3 |
| **Flow-to-capacity ratio** | 0.45 | 0.62 | 0.53 | 0.44 | 0.37 | 0.30 | 0.22 |
| **Vehicle speed** (km/h) | 41.2 | 20.7 | 31.8 | 40.6 | 49.4 | 61.4 | 70.3 |
| *Rest of the day:* | | | | | | | |
| **Flow of PC** (veh./h) | 303 | 477 | 350 | 272 | 257 | 209 | 146 |
| **Flow of LGV** (veh./h) | 20 | 59 | 25 | 14 | 10 | 6 | 2 |
| **Flow of HGV** (veh./h) | 17 | 42 | 20 | 13 | 11 | 6 | 2 |
| **Flow-to-capacity ratio** | 0.20 | 0.29 | 0.24 | 0.20 | 0.16 | 0.13 | 0.08 |
| **Vehicle speed** (km/h) | 51.3 | 33.0 | 44.3 | 50.8 | 58.0 | 67.5 | 74.5 |

Sources: authors' calculations from TransCAD.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

When looking at territorial differences (see Appendix 7.1 for a map of the network's usage during the morning peaks), we observe a clear relationship between population densities, traffic flows and travel speeds. The Parisian roads are the most heavily used (1,310 veh./h during the peaks), implying the lowest average speed (20.7 km/h at these times). At the other extreme, mean flows are smaller in diffused or interurban areas and traffic speeds are higher (61-70 km/h during the peaks). Regarding freight vehicles, LGVs are more intensively used than HGVs in the central areas of IdF.

[9] For the sake of simplicity, we consider constant unit energy costs, whereas Copcete would allow endogeneizing them according to traffic speed and the consumption of diesel or gasoline. See Patil (2016) for a model which endogeneizes fuel consumption.

The results of the traffic assignment model can be aggregated by summing the distances traveled by each vehicle class, within each macro-zone (see Table 5): Around 155 million vehicle*kilometers (vkm) are traveled daily in IdF, of which 33% are driven during the peaks. Paris concentrates 11% of motorized mobility whereas the fringes of the metropolitan region account for 30% of traveled distances. In addition, URF makes up around 8% of total driven kilometers. However, these average figures hide heterogeneous patterns. LGVs and HGVs are responsible for 16% of traveled distances in the French capital city while they account for only 2.6% of traffic in interurban areas. This difference is explained by higher jobs per capita ratios in dense areas, explaining the intensity of freight transport vs. passenger transport.

**Table 5 – Aggregated traffic data**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total vkm** (M/day) | 154.5 | 16.5 | 37.0 | 30.9 | 23.8 | 38.8 | 7.6 |
| **Share in total vkm** (%) | 100.0 | 10.7 | 23.9 | 20.0 | 15.4 | 25.1 | 4.9 |
| **Share during the peaks** (%) | 33.0 | 31.5 | 32.7 | 32.7 | 33.2 | 33.5 | 34.2 |
| **Vkm by LGV** (M/day) | 6.4 | 1.5 | 2.0 | 1.3 | 0.7 | 0.8 | 0.1 |
| **Vkm by HGV** (M/day) | 5.7 | 1.1 | 1.7 | 1.2 | 0.8 | 0.9 | 0.1 |
| **Vkm by PC** (M/day) | 142.4 | 13.9 | 33.3 | 28.4 | 22.3 | 37.1 | 7.4 |
| **Share of URF** (%) | 7.8 | 15.8 | 10.0 | 8.1 | 6.3 | 4.4 | 2.6 |

Sources: authors' calculations from TransCAD.
Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

**Table 6 – Aggregated generalized costs**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total generalized costs** (M euros/day) | 90.0 | 13.4 | 24.4 | 18.2 | 12.3 | 18.3 | 3.4 |
| **Share in total generalized costs** (%) | 100.0 | 14.9 | 27.1 | 20.2 | 13.7 | 20.3 | 3.8 |
| **Share during the peaks** (%) | 37.7 | 41.0 | 38.9 | 37.4 | 35.8 | 35.0 | 35.3 |
| **Generalized costs for LGV** (M euros/day) | 4.0 | 1.1 | 1.3 | 0.7 | 0.4 | 0.4 | 0.1 |
| **Generalized costs for HGV** (M euros/day) | 7.6 | 1.7 | 2.3 | 1.5 | 0.9 | 1.0 | 0.1 |
| **Generalized costs for PC** (M euros/day) | 78.4 | 10.5 | 20.8 | 16.0 | 11.0 | 16.9 | 3.2 |
| **Share of URF** (%) | 12.9 | 20.9 | 14.8 | 12.1 | 10.6 | 7.7 | 5.9 |

Sources: authors' calculations from TransCAD.
Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

Lastly, it is possible to convert the total time spent on roads (around 3.16 million hours per day) into monetary equivalents and to add these resources to the vehicle usage costs (see Appendix 7.1). By doing so, we find aggregated generalized costs of road traffic in IdF equal to 90 million euros per day. "Expenditures" supported in central Paris and/or during the peaks are more than proportional to the share of vkm driven there/at these times. Moreover, total generalized costs incurred to URF operators are substantial (12.9% of the total bill), due to higher kilometric costs of LGVs and HGVs (as compared with PCs, see Appendix 7.1) but also to the larger share of vkm driven in denser areas, at lower traffic speeds.

*3.5. Pollutants and vehicle fleet*

The combustion of gasoline or diesel implies the emission of various pollutants. Whereas Copcete allows estimating exhaust emissions for a huge variety of pollutants (30; see Demeules and Larose, 2012), we restrain our analysis to $CO_2$, $PM_{10}$ and NOx.

**Table 7 – Pollutants under study**

| **Pollutant** | **Share of regional emissions due to road transport (2010)** | **2012 emission factors at 50 km/h (g/km)** | | | **2012 emission factors at 30 km/h (g/km)** | | |
|---|---|---|---|---|---|---|---|
| | | *PC* | *LGV* | *HGV* | *PC* | *LGV* | *HGV* |
| *$CO_2$* | 29% | 166.22 | 212.99 | 733.67 | 201.13 | 276.67 | 933.02 |
| *NOx* | 55% | 0.50 | 0.79 | 4.97 | 0.61 | 0.99 | 6.97 |
| *$PM_{10}$* | 25% | 0.07 | 0.09 | 0.64 | 0.07 | 0.10 | 0.67 |

Sources: Airparif (2013) and authors' calculations from Copcete.
Notes: emission factors are based on a roads' slope of 0°, on a load rate of 50% for HGV and on an average distance of 6 km (for the over-emissions due to "cold-start phases").

As illustrated in Table 7, road transport is responsible for a significant share of the total regional emissions. Motorized traffic emits the majority of NOx in IdF (55%), as well as 25% of the $PM_{10}$ and 29% of the $CO_2$.[10] In addition of providing a spatialized analysis of pollutant emissions in the Paris region, as opposed to Airparif (2013), it seems particularly relevant to focus on the environmental impact of URF because the average emission factors of LGVs and HGVs are larger than those of PCs. In line with Figure 2, we see that slow vehicles tend to pollute more (André and Hammarstrom, 2000). Remind that we ignore here the emissions linked to the evaporation of pollutants.

**Table 8 – 2012 vehicle fleet distribution (in % of traveled distances)**

| | **PC** | | | **LGV** | | **HGV** |
|---|---|---|---|---|---|---|
| | **Gasoline** | **Diesel** | **Others** | **Gasoline** | **Diesel** | **Diesel** |
| *Pre-Euro* | 1.9% | 1.3% | - | 0.2% | 2.1% | 0.2% |
| *Euro 1* | 2.6% | 3.1% | - | 0.1% | 3.6% | 0.6% |
| *Euro 2* | 5.4% | 6.3% | - | 0.2% | 7.0% | 7.9% |
| *Euro 3* | 4.4% | 19.9% | - | 0.2% | 23.5% | 23.6% |
| *Euro 4* | 7.7% | 28.1% | - | 0.2% | 38.7% | 33.6% |
| *Euro 5* | 3.7% | 15.1% | - | 0.1% | 24.1% | 34.1% |
| *Total* | 25.7% | 73.8% | 0.5% | 1.0% | 99.0% | 100% |

Sources: Copcete and "*Enquête Parc Auto – IFSTTAR*".

Copcete considers the detailed structure of the vehicles' fleet in France, from 1990 to 2030, based on the analyses and projections of one large scale annual survey ("*Enquête Parc Auto – IFSTTAR*"). The percentages in Table 8 do not refer to the share of PCs, LGVs or HGVs complying with the different Euro standards, but rather to the share of the total distances traveled with these vehicles. Whereas Copcete provides details on the weights' distribution of each vehicle class, the categories have been

[10] Copcete does not allow estimating PM below 10 micrometers: $PM_{2.5}$ and $PM_1$ are considered into $PM_{10}$.

here merged but we shall use the disaggregated information for estimates.[11] Diesel vehicles make up the huge majority of kilometers driven in IdF. This specificity can be explained by the national tax system that favored, until recently, diesel fuels (Santos, 2017). Above all, Euro 2 or older vehicles account for no more than 12.5% of the fleet in 2012, with a low share of 8.7% for HGVs. For freight vehicles, Euro 4 or 5 technologies are the most represented.

## 4. Environmental analysis

### *4.1. Pollutant emissions*

For ease of interpretation, results in Tables 9 to 11 - initially computed at the link level and for each time period - are aggregated over one full day and for each macro-zone of IdF.[12] Looking first at the daily amounts of pollutants emitted in the Paris area by road traffic, we find overall figures of 31,271 tons of $CO_2$, 122.5 tons of NOx and 14.8 tons of $PM_{10}$. The relative orders of magnitudes are consistent with those proposed by Aiparif (2013) in the frame of the regional emissions inventory. Moreover, around 33% of these pollutants are emitted during the peak periods.

**Table 9 –$CO_2$ emissions**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total** (tons/day) | 31,271 | 4,256 | 7,970 | 6,219 | 4,485 | 7,014 | 1,327 |
| **Share in total emissions** (%) | 100.0 | 13.6 | 25.5 | 19.9 | 14.3 | 22.4 | 4.2 |
| **Share during the peaks** (%) | 34.2 | 35.9 | 35.0 | 34.0 | 33.3 | 33.2 | 33.8 |
| **Emissions from URF** (tons/day) | 6,066 | 1,443 | 1,848 | 1,201 | 714 | 773 | 88 |
| *From LGV (tons/day)* | 1,688 | 421 | 509 | 324 | 190 | 219 | 25 |
| *From HGV (tons/day)* | 4,378 | 1,022 | 1,339 | 877 | 524 | 554 | 63 |
| **Emissions from PC** (tons/day) | 25,205 | 2,813 | 6,122 | 5,018 | 3,771 | 6,241 | 1,239 |
| **Share of URF** (%) | 19.4 | 33.9 | 23.2 | 19.3 | 15.9 | 11.0 | 6.6 |

Sources: authors' calculations from Copcete.
Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

As compared with Airparif (2013), our methodology allows highlighting huge spatial differences in emissions patterns. The inner city of Paris is responsible for nearly 13-14% of regional emissions whereas interurban areas account for only 4% of them. In order to further investigate this issue, we compute a spatial indicator of emissions intensity by dividing - for a given pollutant - the share of regional emissions from a given zone with the corresponding share of total traffic. As shown in

[11] Table 8 does not differentiate rigid and articulated HGVs in whereas Copcete will do so for the calculations. Also, we should ideally work with the vehicle fleet in IdF. Because this information is hardly available, we use the composition proposed at the national level.
[12] Copcete estimates PCs and LGVs emissions only for speeds ranging from 10 km/h to 130 km/h. For HGVs, the range is 12-86 km/h. As a consequence, the traffic speeds given by the traffic assignment model were adjusted to feed Copcete. Changes are negligible, except for HGVs in interurban areas where the mean speed drops from 73.8 km/h to 69.7 km/h (interurban areas account for only 2% of total road links). Moreover, pollutants estimates are based on a roads' slope of 0°, on a load rate of 50% for HGVs and on an average distance of 6 km (for the over-emissions due to "cold-start phases" of PCs and LGVs).

Appendix 7.2, this indicator is decreasing with respect to the population density, thus stressing that urban areas characterized by low traffic speeds represent a disproportionate share of regional emissions in relation to the volume of road traffic that they receive.

**Table 10 –NOx emissions**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total** (tons/day) | 122.5 | 17.5 | 30.5 | 23.7 | 17.5 | 27.9 | 5.4 |
| **Share in total emissions** (%) | 100.0 | 14.3 | 24.9 | 19.3 | 14.3 | 22.8 | 4.4 |
| **Share during the peaks** (%) | 32.6 | 34.9 | 33.4 | 32.1 | 30.9 | 31.5 | 33.3 |
| **Emissions from URF** (tons/day) | 35.9 | 9.0 | 11.1 | 7.0 | 4.1 | 4.2 | 0.5 |
| *From LGV (tons/day)* | 5.9 | 1.5 | 1.8 | 1.1 | 0.7 | 0.7 | 0.1 |
| *From HGV (tons/day)* | 30.0 | 7.5 | 9.3 | 5.9 | 3.4 | 3.5 | 0.4 |
| **Emissions from PC** (tons/day) | 86.6 | 8.5 | 19.4 | 16.7 | 13.4 | 23.7 | 4.9 |
| **Share of URF** (%) | 29.3 | 51.4 | 36.4 | 29.5 | 23.4 | 15.1 | 9.3 |

Sources: authors' calculations from Copcete.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

We next move to our main research question, i.e. the environmental impact of URF. We find that freight vehicles account for 20-30% of $CO_2$, NOx and $PM_{10}$ emitted by road traffic in IdF. Note also that HGVs pollute systematically more than LGVs whereas they account for 43% of the total freight trips presented in the OD matrix (Table 3) and 47% of the distances traveled with freight vehicles (Table 5).[13] From a spatial perspective, the share of emissions caused by URF is highly heterogeneous. Whilst representing approximately half of total NOx and $PM_{10}$ tonnages emitted in Paris, LGVs and HGVs circulating in the fringes of IdF generate a much smaller share of these emissions (10%).

**Table 11 –$PM_{10}$ emissions**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total** (tons/day) | 14.8 | 1.9 | 3.7 | 3.0 | 2.2 | 3.4 | 0.6 |
| **Share in total emissions** (%) | 100.0 | 13.0 | 25.2 | 20.0 | 14.8 | 22.9 | 4.2 |
| **Share during the peaks** (%) | 31.8 | 31.6 | 32.4 | 30.0 | 31.8 | 32.4 | 33.3 |
| **Emissions from URF** (tons/day) | 4.4 | 0.9 | 1.3 | 0.9 | 0.6 | 0.6 | 0.1 |
| *From LGV (tons/day)* | 0. 7 | 0.2 | 0.2 | 0.1 | 0.1 | 0.10 | 0.00 |
| *From HGV (tons/day)* | 3.7 | 0.7 | 1.1 | 0.8 | 0.5 | 0.5 | 0.1 |
| **Emissions from PC** (tons/day) | 10.4 | 1.0 | 2.4 | 2.1 | 1.6 | 2.8 | 0.5 |
| **Share of URF** (%) | 29.6 | 46.4 | 35.1 | 30.3 | 26.0 | 18.9 | 11.3 |

Sources: authors' calculations from Copcete.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

When contrasting these emission figures with the total distances traveled by LGVs or HGVs, the indicator of emissions intensity exhibits interesting results (see Appendix 7.2). First, the ratio between the shares of URF emissions and vkm driven is very large (2.5-4), due to higher emission factors of freight vehicles. Second, the indicator does not evolve continuously with respect to the population

[13] This conclusion may be moderated if one considers ton-kilometer measures instead of traveled distances as the relevant indicator of freight activities.

density, in line with the non-monotonic relationship between travel speed and emission factors. As made clear in Table 12, per kilometer emissions greatly vary across urban spaces. In the case of $PM_{10}$ for instance, maximal emissions of HGVs are found in interurban areas, because of high traffic speeds therein (Table 4), and minimal values of LGVs are found in dense urban areas. As a consequence, our methodology makes it possible to have a spatially differentiated look at the pollutant emissions from URF.

**Table 12 – Averaged emission factors**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **$CO_2$ by PC** (g/km) | 177.00 | 202.37 | 183.84 | 176.69 | 169.10 | 168.22 | 167.43 |
| **$CO_2$ by LGV** (g/km) | 263.75 | 280.67 | 254.50 | 249.23 | 271.43 | 273.75 | 250.00 |
| **$CO_2$ by HGV** (g/km) | 768.07 | 929.09 | 787.65 | 730.83 | 655.00 | 615.56 | 630.00 |
| **NOx by PC** (g/km) | 0.61 | 0.61 | 0.58 | 0.59 | 0.60 | 0.64 | 0.66 |
| **NOx by LGV** (g/km) | 0.92 | 1.00 | 0.90 | 0.85 | 1.00 | 0.88 | 1.00 |
| **NOx by HGV** (g/km) | 5.26 | 6.82 | 5.47 | 4.92 | 4.25 | 3.89 | 4.00 |
| **$PM_{10}$ by PC** (g/km) | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.08 | 0.07 |
| **$PM_{10}$ by LGV** (g/km) | 0.11 | 0.13 | 0.10 | 0.08 | 0.14 | 0.13 | 0.10 |
| **$PM_{10}$ by HGV** (g/km) | 0.65 | 0.64 | 0.65 | 0.67 | 0.63 | 0.56 | 1.00 |

Sources: authors' calculations from Copcete.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

*4.2. Exposure to local pollutants*

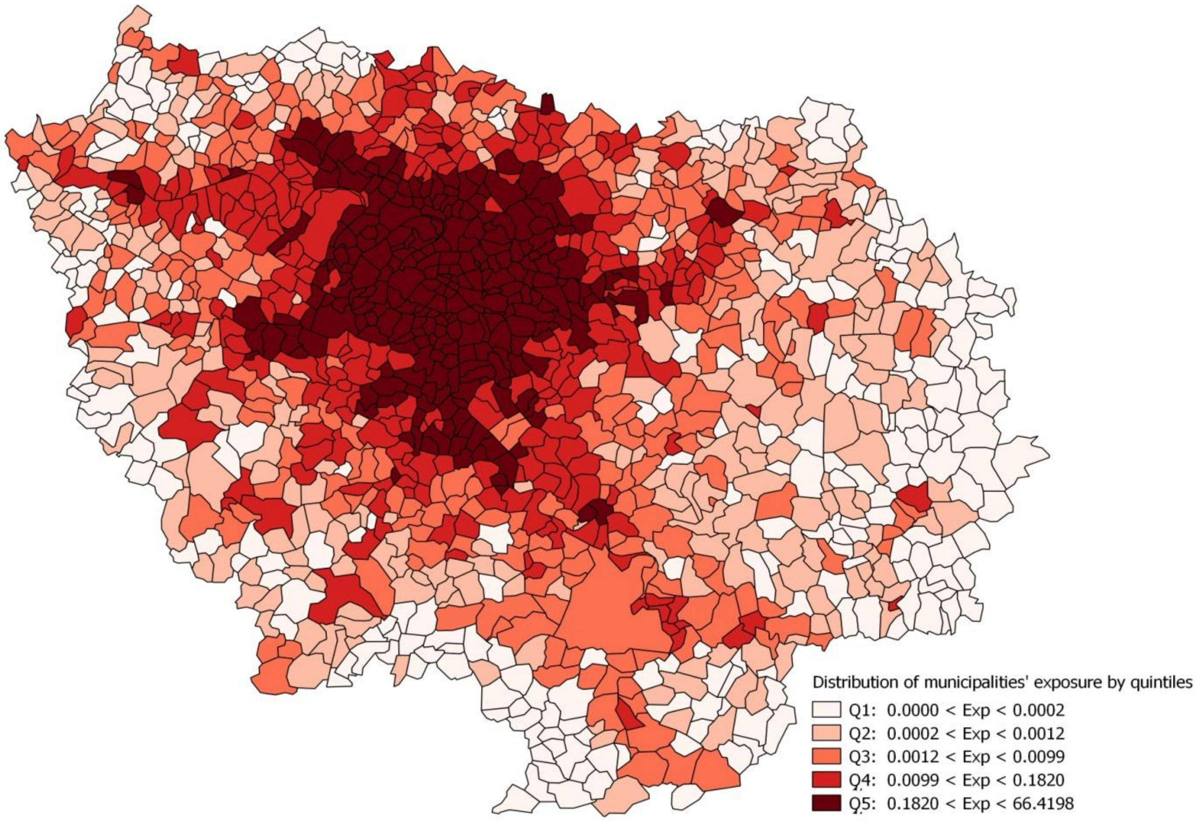
Road transport is not the only determinant of air quality in the Paris region (see Table 6). The concentration of local pollutants in the atmosphere depends on other emissions' sources (residential or commercial buildings, industries…), located either in IdF or in other French regions. This is also a function of climatic conditions and of the urban topography, these factors affecting the dispersion of pollutants (Di Sabatino et al., 2007). Moreover, the exposure of the individuals varies with respect to the distance from the emission point (the roads in our case study) and to the share of the daily time spent outdoor (Karner et al., 2010). Therefore, a detailed impact assessment would require additional modeling exercises (Shorshani et al., 2015), beyond the scope of this research.

To put our results in perspective, we can nevertheless propose a simple indicator of exposure to local pollutants (excluding $CO_2$, the environmental impact of which operating at a global scale). We want our indicator to be an increasing function of the concentration of local pollutants, but also of the number of exposed people. Therefore, we simply multiply the density of "present" individuals in municipality i ($\square\square\square\square\square\square\square\square\square_{\square}$) by the density of NOx plus $PM_{10}$ in that city ($\square\square\square\square_{\square} + \square\square\square_{\square}$):

$$\square\square\square_{\square} = \frac{\square\square\square\square\square\square\square\square\square_{\square} \times (\square\square\square\square_{\square} + \square\square\square_{\square})}{\square\square\square\square\square\square\square\square\square_{\square\square\square} \times (\square\square\square\square_{\square\square\square} + \square\square\square_{\square\square\square})} \quad (9).$$

In order to consider the spatial mismatch between residence and work places, $\square\square\square\square\square\square\square\square\square_{\square}$ is computed as a weighted average between inhabitants (during 16 hours) and jobs (during 8 hours) densities in municipality i. Moreover, $\square\square\square_{\square}$ is a "standardized" indicator since we divide the cross-product fond for municipality i by its regional average (so that the mean value is equal to the unity).

**Figure 5 – Indicator of exposure to local pollutants from all road traffic**

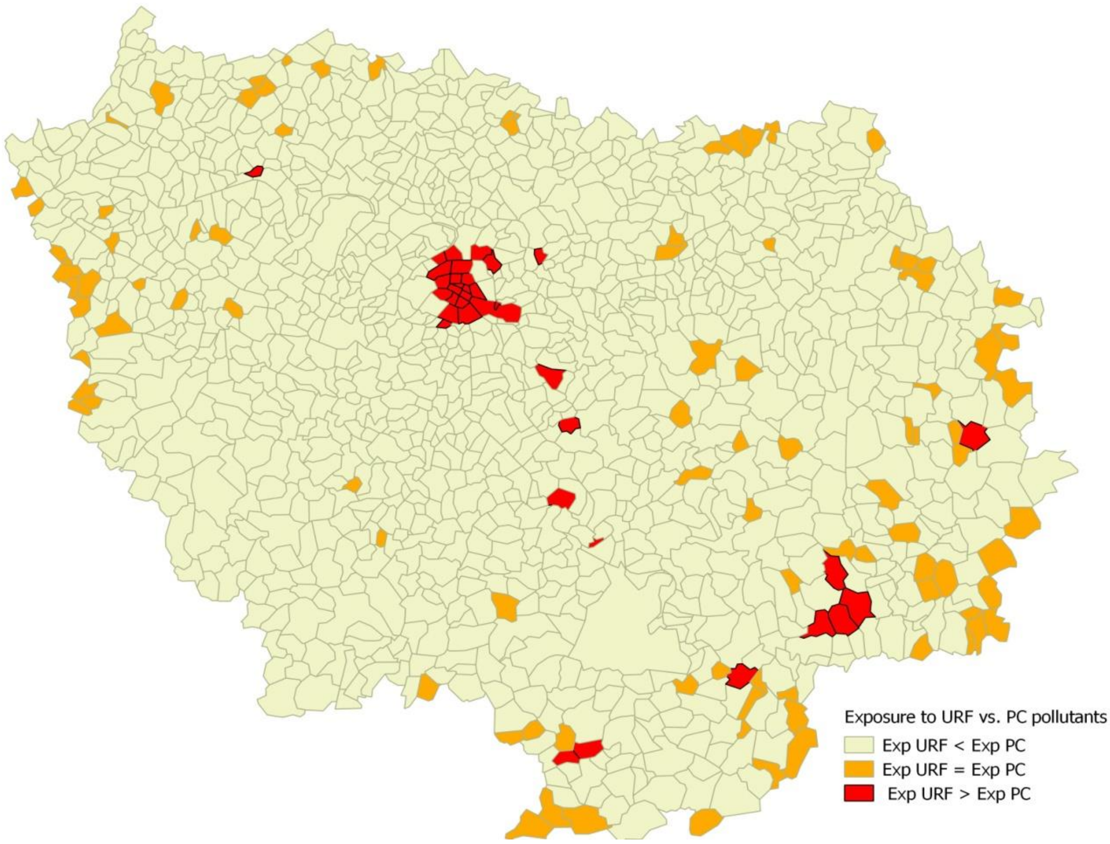



Source: authors' elaboration.

As mapped on Figure 5, this simple indicator highlights huge spatial variations in exposure to local pollutants from road traffic (see the averages of the indicator within each macro-zone in Appendix 7.2). The 20% most exposed municipalities are almost all located in the core of the Paris region whereas the 20% less polluted areas are mostly found in the fringes of IdF. Looking at the ranges of the different quintiles, we understand that our proposed indicator is highly skewed (the median is 0.004). Actually, the very large values computed for Paris and municipalities in very dense urban areas are driving this asymmetrical distribution, thus suggesting that exposure to local pollutants is incredibly concentrated in the core of the metro area, where traffic speed is the lowest and more people are impacted by pollutant emissions.

We find very similar results when looking at the indicators that focus separately on pollutants emitted by either PCs or by URF vehicles (see Appendix 7.2). By contrast, it is more interesting to look at the difference between these two indicators, at the municipality level. As illustrated on Figure 6, we observe that the vast majority of cities (89.7%) are relatively more exposed to local pollutants emitted by PCs rather than to those from URF. Whilst recognizing that a few municipalities (7.5%) present an equal indicator for these two emissions' sources, it is noticeable that 36 administrative territories (4.8%) are relatively more impacted by HGVs and LGVs emissions. These municipalities are mostly located in the East side of IdF. They also contain the Eastern districts of central Paris. Such result may be due to the concentration of important emitter and/or receiver establishments there. Another potential explanation would come from the locations of roads intensively used by URF vehicles in these jurisdictions.

**Figure 6 – Differences in relative exposure to emissions from URF and from PC**




Source: authors' elaboration.

Obviously, these figures remain rough estimates, as state-of-the-art indicators would involve considering the precise locations of buildings relatively to road infrastructures, and more generally the location of individuals over the course of the day. Despite its limitations, we believe our indicator provides a useful picture on the heterogeneous exposure to (and impacts of) local pollutants in IdF.

*4.3. Social costs of air pollution*

Local pollutants are "costly" because exposed individuals are more likely to face health problems, inducing potential earnings' losses for households and hospital expenditures for society (Kampa and Castanas, 2008; Ricardo-AEA, 2014; WHO, 2016). They also entail agricultural losses and building deteriorations. Since road users rarely pay specific taxes aimed at covering these damages (Small and Verhoef, 2007; Santos, 2017), economists generally refer to the "external costs" of air pollution. A large literature proposes parameters to translate the emissions of local pollutants from road traffic, and their corresponding damages, into monetary values (CGSP, 2013; Ricardo-AEA, 2014).

We conclude this research by calculating the social costs of air pollution caused by road traffic in IdF, and by isolating the contribution of URF. Parameters used for computations come from the official

Quinet report (CGSP, 2013).[14] They reflect social damages linked to NOx, $PM_{10}$, but also to sulfur dioxide ($SO_2$) and to non-methane volatile organic compound (NMVOC), neglected in this research. Table 13 shows that diesel vehicles are more costly for society than gasoline ones. The external costs are logically increasing with respect to the density of exposed population.

**Table 13 – Marginal external costs of air pollution**

| | PC/VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|
| **Gasoline PC** (euros/100 vkm) | 4.137 | 1.195 | 0.552 | 0.460 | 0.460 |
| **Diesel PC** (euros/100 vkm) | 18.754 | 5.056 | 2.022 | 1.471 | 1.011 |
| **Gasoline LGV** (euros/100 vkm) | 5.792 | 1.747 | 0.827 | 0.735 | 0.735 |
| **Diesel LGV** (euros/100 vkm) | 30.980 | 8.366 | 3.218 | 2.298 | 1.471 |
| **HGV** (euros/100 vkm) | 171.541 | 34.014 | 16.272 | 8.641 | 5.884 |

Sources: authors' calculations from CGSP (2013).

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

By crossing these marginal external costs with the vkm figures presented in Table 5, we find that local pollutants from road traffic represent social losses for the Paris region valued at 15.8 million euros/day. Considering that the population of IdF added up to 11.9 million in 2012, this amounts to a social cost of 1.3 euros per capita per day. We can also transpose the total figure of 15.8 million euros to a full year. By doing so, the total environmental losses linked to emissions from PCs and freight vehicles (5,767 million euros) correspond to 0.94% of the regional GDP (612,323 million euros in 2012). This figure belongs to the upper-bound of estimates found for European countries (de Palma and Zaouali, 2007). Since the Paris region is denser, our results seem consistent. Lastly, remind that aggregated (private) generalized costs amount to 90 million euros per day (Table 6). As a consequence, a policy aimed to internalize the external costs of local pollutants in IdF should target an increase in total resources supported by road users of 17.6%.[15]

Our methodology makes it possible to decompose the social costs of local pollution between areas and vehicle classes. From a spatial point of view, we see that Paris and the very dense urban areas of IdF concentrate more than 80% of the total bill. By contrast, externalities in interurban areas are almost negligible. Very notable, URF is responsible for 42% of the total losses whereas LGVs and HGVs represent only 8% of total traveled distances in IdF. The social costs of freight trips are especially high in the core of the agglomeration, where HGVs and LGVs account for 55% of total wastes. In addition, the influence of HGVs is 4-5 larger than LGV's. Hence, social costs linked to the local pollutants emitted by HGVs represent 0.32% of the regional GDP (0.07% for LGV). Put differently, public policies should try to ban large freight vehicles from very dense central areas. One possible intervention would substitute large vehicles by LGVs. However, this solution may be complicated by organizational features of URF. As illustrated in Appendix 7.1, HGVs carry 6.6 times more goods (expressed in

[14] External costs presented in Table 13 were adjusted in line with official recommendations to take into account the progress of engines over 2010-2012 (emissions decrease by 6%/year) and the increase in individuals' wealth (real income is assumed to grow by 2%/year). Because the densest territory proposed by the Quinet report is characterized by a lower bound of 4,500 ind./$km^2$, we cannot differentiate external costs in central Paris and those in the very dense urban areas.

[15] This constitutes a lower bound because total private costs at the "optimum" would be lower than figures presented in Table 6, given the expected decrease in road traffic.

tonnages) than LGVs. Since the corresponding ratios for external costs never exceed 5.5, the switch from large to smaller vehicles will not automatically coincide with savings in pollution costs. An alternative option would consist in introducing an environmental toll in the Paris region. One can calculate that such internalizing charge should increase the average private cost of HGVs and LGVs usage by 71% and 30% respectively.[16]

**Table 14 – Social costs of local pollutants in the Paris region**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total social costs** (M euros/day) | 15.8 | 4.4 | 8.5 | 1.7 | 0.5 | 0.5 | 0.1 |
| **Share in total social costs** (%) | 100.0 | 27.8 | 53.8 | 10.8 | 3.2 | 3.2 | 0.6 |
| **From URF** (M euros/day) | 6.7 | 2.4 | 3.5 | 0.5 | 0.1 | 0.1 | 0.0 |
| *From LGV (M euros/day)* | 1.2 | 0.5 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 |
| *From HGV (M euros/day)* | 5.4 | 1.9 | 2.9 | 0.4 | 0.1 | 0.1 | 0.0 |
| **From PC** (M euros/day) | 9.1 | 2.1 | 5.0 | 1.2 | 0.4 | 0.4 | 0.1 |
| **Share of URF** (%) | 42.4 | 54.5 | 41.2 | 29.4 | 20.0 | 20.0 | 0.0 |

Sources: authors' calculations.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

Finally, the figures in Table 14 do not consider the worldwide damages linked to the emissions in the atmosphere of $CO_2$ (Tol, 2009). For that purpose, we can rely on the (official) value of 35.8 euros/ton of $CO_2$ for 2012 (CGSP, 2013). Adding the external costs related to climate change does not really affect the results (see Appendix 7.2). The additional losses are only equal to 1.0 million euros/day (5% of total environmental costs). If one trusts the monetary equivalents of environmental damages proposed by economists, more energy should be devoted to decrease the emissions of local pollutants in dense cities rather than those of $CO_2$. By contrast, public interventions should try to improve the $CO_2$ balance of freight vehicles for interregional trips, when high traffic speeds imply large emission factors and where only a few individuals are harmed by local pollutant emissions.

## 5. Conclusion

This analysis aimed to improve the knowledge on the environmental impacts of urban road freight (URF). For that purpose, we have combined three modeling exercises and we have proposed an empirical case study, using data from the Paris region. Our results provide the following conclusions.

First, Simetad and Freturb models are powerful tools to generate and to distribute URF flows over a given urban area, OD matrices for vans and trucks being rarely available at that geographical scale. In the case of the Paris region, we have seen that each economic establishment emits and/or receives 6.3 goods' movements per week in 2012, thus inducing 890,000 freight trips per day. Heterogeneity in the freight behaviors of firms and spatial concentration of activities explain why a huge majority of URF is linked to the core of the Paris region.

[16] Based on Tables 5, 6 and 14, we find that average generalized costs equal to 1.333 euros/vkm for HGVs (0.625 euro/vkm for LGV). By contrast, average external costs of local pollutants are equal to 0.947 euro/vkm for HGVs and to 0.188 euro/vkm for LGVs.

This information was useful to determine the traffic assignment equilibrium in a multi-class framework, where Light Goods Vehicles (LGVs) and Heavy Goods Vehicles (HGVs) share the roads with private cars (PCs). Using the TransCAD software and following Wardrop's principles, we have found that URF corresponds to 7.8% of total distances traveled in the Paris region, with a higher share in the core of the metropolitan area (15-10%). Our results clearly exhibit that the more densely populated the areas, the higher the traffic flows and the lower the vehicles' speed. Important differences across peak and off-peak periods were also observed.

This knowledge being available at the road-segment level, we were finally able to estimate pollutant emissions from PCs, HGVs and LGVs thanks to the Copcete calculator. Freight vehicles are responsible for 20-30% of total emissions and the share of $CO_2$, NOx and $PM_{10}$ emissions due to URF is at least 2.5 times larger than the share of freight vehicles in regional traffic. Moreover, we have made explicit that the contribution of LGVs and HGVs to air pollution is larger in the central areas of the Paris region, where more people are exposed to the environmental nuisances. Finally, social costs of air pollution caused by road traffic in general amounts to 0.9% of the regional GDP in 2012. If we consider only freight vehicles, collective losses are very important relatively to the volume of traffic: 0.4% of the regional wealth.

While the negative environmental footprint of URF has been empirically confirmed in the case of the Paris region, this article calls for further research.

Among the many directions to follow, a first one would consist in simulating the effects of various policy scenarios aimed to reduce the negative externalities from URF (Demir et al., 2014; Russo and Comi, 2016). As discussed above, an intervention targeting the substitution of HGVs by LGVs may be worthy of investigation, given the observed differences in vehicles' load rates but also the varying impacts of these vehicles on the road capacities. Moreover, the equilibrium assignment model could be adapted to consider environmental tolls, speeds limits or zoning strategies (such as urban consolidation centers or low emission zones) and to look at changes in the route choices drivers. With that respect, a sound modeling framework should integrate possibilities of mode shifts (towards cargo-bikes for instance) for the freight operators, as well as their equipment choices (towards cleaner vehicles).

A second valuable research agenda is linked to the evolution of URF in the Paris region over years. Freturb actually enables one to isolate URF trips for a variety of economic activities. Given the growing interest around the so-called "logistics sprawl" phenomenon (Aljohani and Thompson, 2016), our methodology would allow assessing the environmental impact linked to the relocation of warehouses towards the fringes of the metropolitan area. Opposite effects may be at stake here since more peripheral logistics facilities will coincide with increased traveled distances only if customers (e.g. goods' receivers) have moved to a lesser extent. In addition, we have shown that pollutant emissions greatly depend on the traffic speed, and their societal impacts are a function of the density of exposed people. As a consequence, an accurate environmental analysis of the logistics sprawl observed in the Paris region over the last decade should consider all these dimensions, which is made possible thanks to the research protocol presented here.

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## 7. Appendices

### *7.1. Additional data for the traffic assignment model*

**Table 15 – Characteristics of the road network**

| | **IdF** | **PC** | **VDUA** | **DUA** | **UA** | **DIUA** | **IA** |
|---|---|---|---|---|---|---|---|
| **Road segments** | 39,420 | 4,688 | 10,959 | 10,184 | 6,370 | 6,406 | 813 |
| **Total roads' length** (km) | 20,480 | 1,033 | 3,220 | 3,479 | 2,990 | 7,554 | 2,204 |
| **Road density** (km/km$^2$) | 1.7 | 9.8 | 5.8 | 3.6 | 2.3 | 1.2 | 0.8 |
| **Maximal speed** (km/h) | 58.2 | 43.7 | 54.8 | 61.4 | 64.1 | 63.3 | 62.6 |
| **Theoretical capacities** (veh./h) | 1,709 | 2,121 | 1,702 | 1,564 | 1,660 | 1,701 | 1,705 |

Sources: authors' calculations from DRIEA and TransCAD.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

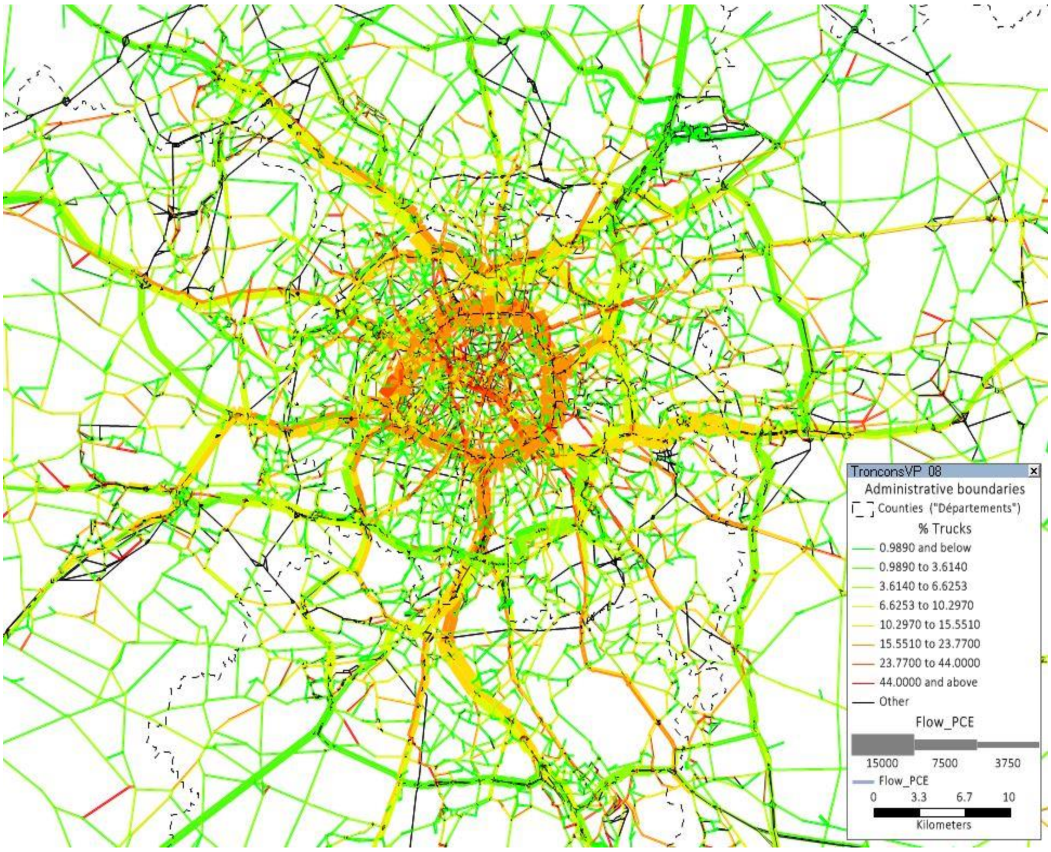
**Table 16 – Costs and technical parameters**

| | **PC** | **LGV** | **HGV** |
|---|---|---|---|
| **Monetary costs** (euro/km) | 0.271 | 0.365 | 0.842 |
| **Vehicle occupancy** (ind./veh.) | 1.3 | 1.0 | 1.0 |
| **Time value of individuals** (euros/h) | 10.7 | 9.8 | 9.8 |
| **Load weight** (tons/veh.) | 0.0 | 0.294 | 1.941 |
| **Time value of goods** (euro/ton/h) | 0.0 | 0.6 | 0.6 |
| **Private car equivalency factors** | 1.0 | 1.5 | 2.0-2.5 |

Sources: Beziat et al. (2017).

Note: we consider a PCE factor of 2 is for rigid HGV and a value of 2.5 for articulated HGV.

**Figure 7 – Usage of the road network in the morning peaks**




Source: authors' elaboration with TransCAD.

## *7.2. Additional data for the environmental analysis*

**Table 17 – Indicator of emissions intensity**

| | | **PC** | **VDUA** | **DUA** | **UA** | **DIUA** | **IA** |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | *All traffic* | 1.27 | 1.07 | 1.00 | 0.93 | 0.89 | 0.86 |
| | *From URF* | 2.15 | 2.32 | 2.38 | 2.52 | 2.50 | 2.54 |
| **NOx** | *All traffic* | 1.34 | 1.04 | 0.97 | 0.93 | 0.91 | 0.90 |
| | *From URF* | 3.25 | 3.64 | 3.64 | 3.71 | 3.43 | 3.58 |
| **$PM_{10}$** | *All traffic* | 1.21 | 1.05 | 1.00 | 0.96 | 0.91 | 0.86 |
| | *From URF* | 2.94 | 3.51 | 3.74 | 4.13 | 4.30 | 4.35 |

Sources: authors' calculations.
Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

**Table 18 –Indicators of exposure to local pollutants**

| | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|
| **From all road traffic** | 35.15 | 4.55 | 0.52 | 0.11 | $8*10^{-3}$ | $3*10^{-4}$ |
| **From URF (1)** | 41.21 | 3.81 | 0.32 | 0.05 | $3*10^{-3}$ | $7*10^{-5}$ |
| **From PC (2)** | 29.43 | 5.25 | 0.70 | 0.16 | 0.01 | $5*10^{-4}$ |
| **Difference (1) – (2)** | 11.78 | -1.44 | -0.38 | -0.10 | -0.01 | $-5*10^{-4}$ |

Sources: authors' calculations.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.

**Table 19 – Social costs of air pollution (including $CO_2$) in the Paris region**

| | IdF | PC | VDUA | DUA | UA | DIUA | IA |
|---|---|---|---|---|---|---|---|
| **Total social costs** (M euros/day) | 16.8 | 4.5 | 8.8 | 1.9 | 0.6 | 0.8 | 0.1 |
| **Share in total social costs** (%) | 100.0 | 26.8 | 52.4 | 11.3 | 3.6 | 4.8 | 0.6 |
| **From URF** (M euros/day) | 6.8 | 2.4 | 3.6 | 0.6 | 0.1 | 0.1 | 0.0 |
| *From LGV (M euros/day)* | 1.3 | 0.5 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 |
| *From HGV (M euros/day)* | 5.5 | 1.9 | 3.0 | 0.5 | 0.1 | 0.1 | 0.0 |
| **From PC** (M euros/day) | 10.0 | 2.2 | 5.2 | 1.3 | 0.5 | 0.7 | 0.1 |
| **Share of freight** (%) | 40.5 | 53.3 | 40.9 | 31.6 | 16.7 | 12.5 | 0.0 |

Sources: authors' calculations.

Notes: "PC" refers to Paris city, "VDUA" to very dense urban area, "DUA" to dense urban area, "UA" to urban area, "DIUA" to diffused urban area and "IA" to interurban area.