ATTRIBUTION METHODOLOGIES FOR MOBILITY IMPACTS

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ABSTRACT

Motorized transportation modes all consume energy and emit local pollutants – chemical and noise. Congestion can also be considered as a local pollution caused by some emitters onto some receivers. Various methods have been designed to evaluate impacts and relate them to emitters and/or receivers. Called "attribution" in environmental evaluation or "imputation" in economic analysis, these schemes' purpose is to identify the causes of impacts and to design management or compensation schemes to alleviate their negative effects.

The paper presents an analytical framework to devise attribution schemes for local mobility impacts in a territorial area applicable to every ground transportation mode. The method's first step relies on the evaluation of each trip-maker's individual contribution to local impacts. Such individual contributions can then be aggregated along any path, hence any trip between origin and destination. The trip's impact can then be attributed to the trip-maker, or the zone at the origin or destination end of the trip.

After providing with a general introduction, a bibliographical review of attribution methods, several attribution schemes are provided and discussed in this paper. Then associated computation scheme is presented and an application instance is dealt with in the final part of the article.

1 INTRODUCTION

Motorized transportation consumes energy and generates a range of emissions that eventually lead to different impacts on populations, economy and environment. According to ADEME 2015's publication [ADEME 2015], in 2014, 48.8 Mtoe (Mega-tonnes of oil equivalent) were consumed by the transportation sector in France comprising passenger and freight movements. This amount corresponds to 32.5% of total French final energy consumption. Greenhouse gas emissions, whose increase was dampened by 2008's economic crisis, were still estimated at 126 MtCO_2 in 2013, corresponding to 39% of total CO_2 emissions. Although the rates are declining, transport sector also emits considerable amounts of pollutants such as NOx (566 kilo-tonnes were emitted in France in 2014) or PM 10 (41 kilo-tonnes emitted in 2014). It is therefore not a surprise that transport is one of the target areas of public policies aiming to reduce environmental impacts.

Furthermore transport also induces socio-economic impacts: accessibility gains and wider economic benefits, value flows that irrigate the productive sphere [Leurent & Windisch 2015] but also a range of negative outcomes. In the particular case of congestion, the 2011 figures provided by INREX and analysed by CEBR in their 2012 [CEBR 2012] publication, estimate that commuters in France waste 354 million hours annually in congested traffic which amounts to 3.9 billion euros in direct costs to car-commuting households (additional fuel and lost time valuation) and 1.7 billion euros of indirect costs (higher costs of goods and services) to all households. In a similar way, noise impacts could be evaluated and its costs estimated (loss of productivity and health impairments).

These impacts are perceived by receptors at several time and space scales. Noise directly impacts neighbouring populations and trip-makers. Air pollution affects, through repeated and prolonged exposure, populations present around infrastructures, drivers and passengers themselves, but also eco-systems at larger scales since pollution is diffused, dispersed and is further transported through different media (air, soil and water). Effects of greenhouse gases are global and systemic and concern the entire planet while our present reliance on fossil fuels means energy consumption today depletes future generation's resources and impedes their access to energy.

On the other hand transportation is necessary for economic activity and daily life. Here are some figures to be weighed against those of impacts. In 2014, according to [ADEME 2015], 910 Giga-passenger.km were travelled and approximately 230 Gigatonnes.km of freight were transported in France. These are the services provided by the transportation sector, distances that would otherwise take much longer to cover, freezing the economy. For passenger travel alone, it is 59 billion trips that are made each year (2008 figures taken from [Longuar 2010]). It is as many work-, study- or leisure-related activities that are accomplished providing some gains to the trip-makers. But it is also economic activities that benefit from the transportation of its employees, clients and products.

These figures characterise the beneficiaries of the transportation service: those who actually use the transportation system to access their activities and gain some utility from them. Since these are the beneficiaries of the service, they can be considered, at least to some extent, as the emitters of the aforementioned impacts. How to relate impacts to emitters is a subject that has been dealt with in several fields leading to attribution or imputation methodologies. The causal relationship thus established between emitters and impacts, allows to design management schemes to curb the negative impacts. Such schemes could involve public policies (e.g. emission norms regulations), urban development strategy or more locally the design of an urban project or a transportation line.

A complete elimination of negative impacts is impossible since all motorized vehicles consume energy and emit some kind of pollution (at least releasing through abrasion and friction fine particles of tyres and pavement). In response, it is possible to design compensation schemes collecting funds from the emitters and redistributing some form of compensation to the receivers of the negative impacts. Such schemes include pricing (in particular congestion tolls), pollutions taxes – permits/credits – subsidies schemes (Pigouvian taxes).

It is clear that each management or compensation scheme requires on the one hand an attribution scheme to evaluate emitters' respective contributions and on the other hand an evaluation of receivers' damage.

A distinction should be made between emitted and received quantities. Indeed for most impacts there is additional transformation between emission and reception making the relationship between the quantity emitted and the amount of damage received on the receiver's end nonlinear, possibly location- and/or – time-dependent. The example of pollution is very illustrative in this respect. Given a certain quantity of pollution emitted by a vehicle, the actual exposure of a resident population will depend on: the meteorological conditions at the moment of emission guiding diffusion and dispersion; the built environment facilitating dispersion or trapping the pollution; the composition of the air and background pollution as chemical reactions can take place modifying pollutant concentrations in the air.

Evaluation of local impact exposure is a developing field with thriving modelling of ambient conditions but less attention is brought to the people's exposure in terms of their instantaneous presence. In the present article we focus primarily on emissions and will satisfy ourselves with an intermediate stage as concerns exposure. We will deal with the evaluation of emitters' contribution at various scales – the attribution schemes, several of which will be developed to cover a wide range of applications.

2 ATTRIBUTION METHODS: A BIBLIOGRAPHIC REVIEW

Impact attribution can be viewed from several viewpoints: stakeholder attribution, geographical attribution or functional unit attribution. Several scientific streams analyze how various costs or impacts are distributed in terms of production and perception and offer attribution methods that will be reviewed in this section.

2.1 Economic analysis

A minimalistic view of the transportation system includes users – clients of the transportation service, building the demand and thus the main beneficiaries of the service, and the transport operator, providing the service to its clients, building the offer. In this basic approach, the operator bears the operating costs and recovers them through fares applied to the clients, possibly making some profit. It is then of interest to understand each client's share of operating costs. As discussed in [Cervero 1981], operating costs are both time (at least peak and off-peak periods should be distinguished as well as service type such as express or local) and location (dense congested or lower-density free-flow areas) specific, making the determination of each client's share non trivial. Indeed operation costs should be determined at the link level and integrated over the entire client's trip, defined by its route and schedule. Fare equity evaluation also becomes more complex: cross-subsidization between different demand segments with heterogeneous travel patterns (time period and/or distances) might occur.

In a broader perspective, additional stakeholders are involved in a transport system, bearing or producing impacts: populations and other stakeholders directly or indirectly exposed to environmental impacts; public authorities; land development market's stakeholders could also be added as they perceive, indirectly, positive (due to a gain in accessibility) or negative (due to increased noise or pollution) impacts of a transportation system. [Hayashi 1989] proposed a systemic analysis of benefit distribution in the case of a new rail transit line and discusses financial schemes to capture value in order to finance the project. Three principles of incidence are discussed in the light of equity between actors, regions and generations. Burdens are borne according to: the amount of benefits received; the ability to pay; or the amount of cost involved. These issues are seldom discussed in the transportation economic handbooks.

2.2 Congestion cost – generalized cost

From the user's viewpoint, several resources are involved in making a trip by means of a transport service: time needed to make the trip and monetary expenses (such as fuel's cost or transit fare), that are usually combined, using a monetary valuation of travel time, into a generalized cost of transport. This generalized cost integrates user congestion cost through the amount of time spent on the trip, which increases in case of congested traffic, and/or through the value of time which increases in case of uncomfortable, congested trip (notably in transit). It is common practice to calculate user generalized cost on the trip basis and to aggregate results over a project's forecasted demand to evaluate its benefits compared to an alternative scenario.

Each user perceives the cost of congestion for himself but also contributes to hindering all other users present in the local traffic. Since each user perceives only his own cost, congestion is an externality at the level of the individual user. In order to internalize social congestion cost, congestion tolls are designed. Pricing is then based on marginal congestion cost – the congestion cost that each marginal user imposes on the overall traffic. This approach is summarized in [Walters 1961]. Congestion cost imputation is then based on the causal relationship of marginal user on the overall cost of congestion, issue that has been recently discussed in [Santos 2011].

2.3 Socio-economic evaluation of environmental impacts

In France, the "LOTI" (1982) law and subsequent "law on air and rational use of energy" (1996) established *ex ante* evaluation and *ex post* assessment as mandatory for transport projects. These assessments should evaluate, among other impacts, pollution costs (air pollution, noise and GHG emissions) and operation energy consumption and balance them against community benefits [Quinet 2000]. The methodology is well established for road inter-urban projects but is more complex for urban projects where transport and urbanization are intimately intertwined [CERTU 2002]. The assessment calls upon transport simulations to establish traffic flows and associated emissions at the local level. Global emissions can then be related to the expected use: passenger.kilometer travelled or tonnes.kilometer of freight. Several analyses are recommended: per stakeholder analysis and, when necessary, a geographic analysis by sub-area to detect problematic areas.

Additional attributional schemes can be mentioned, issued mainly by ADEME and IFSTTAR (initially INRETS, in particular [Orfeuil 1984, Hivert 1998]). They concern territorial assessments of transport energy consumption and GHG emissions. Several approaches are proposed on both the emission accounting side and attribution side (see in particular [ADEME 2011]). To account for emissions of a given territory, a cadastral-oriented approach would consider all emissions taking place in the strict geographical perimeter of the territory whereas a more accountability-oriented approach would consider all emissions due to trips (emitted or received) generated by the territory. Then these global emissions are related to the number of inhabitants, enabling global comparison of transport system's performance between territorial areas; alternatively they are related to the distance traveled in order to assess environmental efficiency of the transport system [Verry 2006].

Additional analysis can distinguish between transport modes, trip lengths and purposes, socio-demographic classes of population.

2.4 Life cycle assessment: for a broader range of environmental impacts

Previously cited approaches are limited to the use phase, mainly direct impacts, which means that a non-negligible amount of life cycle impacts are missing. To counter this, life cycle assessment (LCA) integrates impacts from "cradle to grave" covering a larger range of impacts (beyond the regulated air pollutants) and indirect impact at broader spatial scales. Initially, applications concerned buildings only but the methodology is progressively expanding to larger scales of neighborhood and territorial level. [Lotteau 2015] presents a review of the recent developments in this area. Life Cycle Assessments' attribution philosophy no longer concerns "accountability" but is mainly focused on the "functional unit" – the amount of service provided by the project. This philosophical shift allows for a more positive and action-oriented view: service provided rather than entailed costs or share of responsibility. For the neighborhood level, the functional unit of transportation is the trip characterized by its origin and destination. Until now, the LCA evaluation of mobility has been rather aggregated, approximately estimating mobility demand and its means of realization [De Bortoli 2016].

3 ATTRIBUTION SCHEMES

One of the key objectives of attribution schemes is knowledge of winners and losers. Compensation could thus be integrated at the design stage, to increase a project's acceptability. Additionally, attribution schemes could aid decision-making in policy and project design. Indeed these schemes could help identifying design parameters that bring the most impact on the overall project's performance and suggesting alternative design options. This being said, the relevant project characteristics depend on the project's type (urban development project, infrastructure project, public policy or transportation scheme etc…) and corresponding design options. Therefore, even though the quantity being attributed is the same (e.g. pollution emitted by the vehicles), several attribution schemes can be proposed depending on the purpose of the design project. In this section we propose an analytical framework and several attribution schemes.

A given kind of local impact is dealt with. Let us consider a transportation network and denote $a \in A_m$ the links composing this network. Each link is spatially located in the territory and characterized by its mode $m \in M$. Vehicles circulating on the link create local impacts such as pollution, noise or congestion. The number of vehicles on the link a is noted f_a and we will refer to the individual vehicles composing this flow as s. The number of vehicles' users on the link a will be denoted u_a and we will refer to the individual users as $\tilde{s}$. Let us also denote q – the individual emission of a vehicle per unit length travelled and $\tilde{q}$ – the individual emissions per unit length travelled attributed to a vehicle's user.

Then the following local quantities are of interest for our analysis: $q_{s,a}$ designating the emissions, per unit length travelled, of a vehicle s on the link a. This quantity may depend on local traffic conditions, notably the vehicle's speed $v_{s,a}$; each vehicle's occupancy will be denoted $u_{s,a}$, then $u_a = \sum_{s \in f_a} u_{s,a}$.

Note that the occupancy is a local variable: public transportation vehicles' occupancy changes whenever passengers leave or enter the vehicle at stations.

3.1 Locus

We can first see how vehicle's emissions can be attributed to users, considering local travelling conditions. If equal attribution of a vehicle's emissions among its occupants is admitted, then the local value of impact attributed to each user $\tilde{s}$ travelling in the vehicle s is:

$$\tilde{q}_{\tilde{s},a} = \frac{q_{s,a}}{u_{s,a}}$$

Note that $\tilde{q}_{\tilde{s},a}$ is an attribute of the user $\tilde{s}$. Along their route, users might change vehicles in which case, on a different link a' their impact would be:

$$\tilde{q}_{\tilde{s},a'} = \frac{q_{s',a'}}{u_{s',a'}}$$

From the vehicle's point of view, the mean impact per user will be denoted as:

$$\tilde{q}_{s,a} = \frac{q_{s,a}}{u_{s,a}}$$

$\tilde{q}_{s,a}$ is then an attribute of the vehicle s. This quantity allows to evaluate the vehicle's local environmental efficiency along its route.

This attribution scheme's hypothesis is that each user of the vehicle is equally accountable or benefits equally from the transportation service provided by the vehicle's use. This can be further nuanced by taking into account trip purpose, possibly different for each user, and adjusting users' weight accordingly in the attribution scheme.

Still on the local level of a network link, let us denote q_a the quantity of local impacts per unit length travelled generated by all vehicles on the link, $\tilde{q}_a$ the mean quantity of local impacts per unit length travelled per user, Q_a - the total amount of emissions produced on the link a, l_a the length of the link a. Then:

$$q_a = \sum_{s \in f_a} q_{s,a}$$

This expression preserves differentiation between individual travelling situations (e.g. different speeds for vehicles on the same link).

$$\tilde{q}_a = \frac{q_a}{u_a}$$

$$Q_a = q_a l_a$$

Mapping q_a over an area of interest can be useful to identify "hot-spot" links of local impact emissions. In a similar way, mapping $\tilde{q}_a$ enables to identify the most "costly" links in terms of local emissions per user. Then the main actions can be aimed at reducing the unitary vehicle emissions (low-emission zones), limiting flows, improving traffic management (speed limits or decongestion) or encouraging higher occupancy of the vehicles (car-pooling lanes, high occupancy lanes etc…).

3.2 Zones as traffic places

These local impacts, including all transport modes, can be aggregated at the local level of a zone to identify its share at the regional level (cadastral approach). Total impacts emitted in a zone $z \in Z$ is:

$$Q_z = \sum_{m \in M} \sum_{a \in A_m \cap z} Q_a$$

This quantity can be seen as an intermediate stage in quantifying the impacts received since the analysed zone plays a passive role, with almost no accountability. Alternative accountability-based emission's attribution schemes will be presented further.

Q_z is closer to the actual value of received impacts in the case of local pollutants evaluation where effects are indeed close-range, than in the case of global impacts such as energy consumption, whose effects are far-ranged and long-term. Comparison of zones can be performed at the regional level in particular to see how equally (or not) local emissions are distributed among various zones of the region. It is also of interest to understand how local measures can result in spill-overs on the neighbouring areas.

3.3 Path

Let us denote $p \in P_{od}$ one of the P_{od} paths linking the Origin-Destination pair $od \in O \times D$. Then the total impact caused by a user following the path p is:

$$\tilde{Q}_{\tilde{s},p} = \sum_{a \in p} \tilde{q}_{\tilde{s},a} l_a$$

Of course, the path p may include links from several modal networks whose individual contributions may be assessed.

The average value of "emission cost" per user on a path p can be determined as follows (the path p can be multimodal):

$$\tilde{Q}_p = \sum_{a \in p} \tilde{q}_a l_a$$

Knowing $\tilde{Q}_p$ for all $p \in P_{od}$, it is then possible to determine the path with the minimal impact $\tilde{Q}_{od}$, and provide the users with this information.

Using this approach, it is also possible to evaluate the overall impact-minimizing potential between a zone or a node on the network and the rest of the territory. To do so, consider the optimal route cost $\tilde{Q}_{od}, d \in D$ between the zone o of interest and the rest of the territory. By mapping this quantity high-impact O-D links can be identified. Policy actions can then be aimed at reducing individual impacts through encouraging and facilitating the use of transit and/or car-pooling.

3.4 Origin-destination pair

Let us now consider the total demand on the origin-destination pair od, it is denoted d_{od} and the users are distributed among the available connecting routes as follows:

$$d_{od} = \sum_{p \in P_{od}} x_p$$

where x_p is the number of users following the path p connecting the origin-destination pair od. The number of users on a given link a can then be written as:

$$u_a = \sum_{p \in P_{OD}} x_p \delta_{ap}, \delta_{ap} = 1: a \in p;\ \delta_{ap} = 0: a \notin p$$

Then the total impact of the flows exchanged between an origin and a destination is:

$$Q_{od} = \sum_{p \in P_{od}} x_p \tilde{Q}_p$$

Alternatively, it can be written as:

$$Q_{od} = \sum_{p \in P_{od}} \sum_{\tilde{s} \in x_p} \tilde{Q}_{\tilde{s},p}$$

This quantity can be determined for all origin-destination pairs thus yielding the OD matrix of impact quantities by OD pair: this matrix stems from O-D flows as well as local emission factors and paths characteristics. Let us denote $\bar{\bar{\mathrm{Q}}}$ this matrix.

$$\bar{\bar{\mathrm{Q}}} = [Q_{od}, o \in O, d \in D]$$

3.5 Generating zone

Once the matrix is built, it is possible to evaluate each zone individually as one end, either origin or destination, of a trip in relation to other zones. The margins of the matrix provide the total emitted impacts associated with all the trips having the zone of interest either as origin (superscript or) or destination (superscript $dest$):

$$Q'^{or}_{z} = \sum_{d \in D} Q_{zd}$$

$$Q'^{dest}_{z} = \sum_{o \in O} Q_{oz}$$

Considering that in a trip, both the origin zone and the destination zone are causing the transportation demand and are equally responsible, we propose to attribute one half of each trip's impacts to the origin zone and the other half to the destination zone. Then the total impacts attributed to a zone can be determined as follows:

$$Q'_{z} = \frac{1}{2} Q'^{or}_{z} + \frac{1}{2} Q'^{dest}_{z}$$

This can be seen as an accountability approach, to be compared with the cadastral approach presented before.

3.6 Householding zone

A different point of view would be to consider housing taxes as a mean to retrieve some of the impact's costs due to the daily mobility of the household's members. In this case, it would be of interest to aggregate the entire daily trips of an area's households' population and compare it to other zones. Let us denote $\tilde{s} \in z$ to identify the household members of the zone z and let us also note $d_{\tilde{s}}$ as the series of trip paths made by individual user $\tilde{s}$ during a day. Then, the total impact of a zone's households' mobility would amount to (see [Hivert 1998] for applications):

$$Q''_{z} = \sum_{\tilde{s} \in z} \sum_{p \in d_{\tilde{s}}} \tilde{Q}_p$$

Considering households only as generating their members' mobility is a one-sided approach to the problem. Indeed, firms located in a zone are equally accountable for their employees' and clients' mobility. Moreover, fiscal means of retrieving some externality costs of this mobility are also available. Our recommendation would therefore be to favor the fifty-fifty attribution scheme presented above.

Thus we have seen three different ways to account for impacts at the zone level: cadastral approach Q_z, accountability approach Q'_z and householding approach Q''_z.
Consider now the occupation of zone z: the trips are generated by the populations and economic activities of the area, attracting or emitting trip-makers. Several indicators can be used to characterise a zone's occupation: urbanized land surface, total floor area of various activities or, more commonly, total population and jobs. Let us note U_z the total occupation of the zone.
Then the individual contribution of an occupation unit can be measured as:

$$\frac{Q_z^*}{U_z}$$

Where Q_z^* represents one of the aforementioned approaches. Using this indicator, it is possible to compare the efficiency of urban projects at various locations, but also compare transport's lot of impacts to other contributors such as emissions related to buildings (local air and noise pollutions or energy consumption).

4 COMPUTATION SCHEME AND INPUTS

4.1 Computation scheme

Figure 1 below schematically represents a computation framework integrating the previously presented attribution schemes and their progressive derivation. In particular, the calculation of two main indicators' is presented: Q'_z and Q_z. We believe that the first one should be used to compute a zone's overall emitted mobility impacts, whereas the second one could be used as a basic approximation of the impacts this same zone receives.
We have seen in section 3.4 that two alternative ways of calculating Q_{od} are available. They correspond to two different modelling frameworks. The first framework (solid lines) is a flow-based aggregated modelling approach based, for example, on a four-step TDM model. In this approach, the assignment step provides traffic conditions such as traffic flows (f_a and u_a), as well as an average traffic speed v_a for each link in the network. Then an emission factors model is applied to calculate the average vehicle's emissions, given the fleet composition and traffic conditions. This, in turn, allows to determine the aggregate impacts q_a at the level of the network's link as an elemental locus.
Alternatively (dashed lines), each vehicle or trip-maker can be treated individually. This can be achieved using a multi-agent simulation framework or sampling from a household travel survey. This allows to expand the temporal range (and therefore impacts included) of the simulation: instead of working exclusively on the morning or evening peak periods, the entire day can be represented. This can be of particular importance when considering per-passenger environmental impacts in public transportation. Indeed off-peak occupancy of public transport's vehicles can be very low, increasing considerably per-passenger impacts on this period of time. However, household travel surveys are limited in this respect: presently, public transportation occupancy is not surveyed (but could be, at least qualitatively).

Reminding the notations used in the paper:

d_{od}	Demand between the origin o and the destination d	$q_{s,a}$	Unitary emission of the vehicle s per length travelled at the link a
l_a	Length of the link a	Q_a	Total emissions at the link a
$v_{s,a}$	Speed of the vehicle s at the network's link a	Q_{od}	Total emissions due to overall demand on the O-D pair od
u_a, f_a	Users/vehicles' number at the link a	$\tilde{Q}_p$ $/\tilde{Q}_{\tilde{s},p}$	Total emissions on travelling along the path p for an average user/ for the user $\tilde{s}$
U_z	Land use characteristic of the zone z (population + jobs /activity surfaces etc…)	Q'_z	Total emissions attributable, according to the 50-50 accountability scheme, to the zone z
q_a	Total emissions per length travelled at the link a	Q_z	Approximation of total emissions received by the zone z
$\tilde{q}_a$ $/\tilde{q}_{\tilde{s},a}$	Emissions per user and per unit length travelled at the link a for an average user/for the user $\tilde{s}$	x_p	Demand flow following the path p

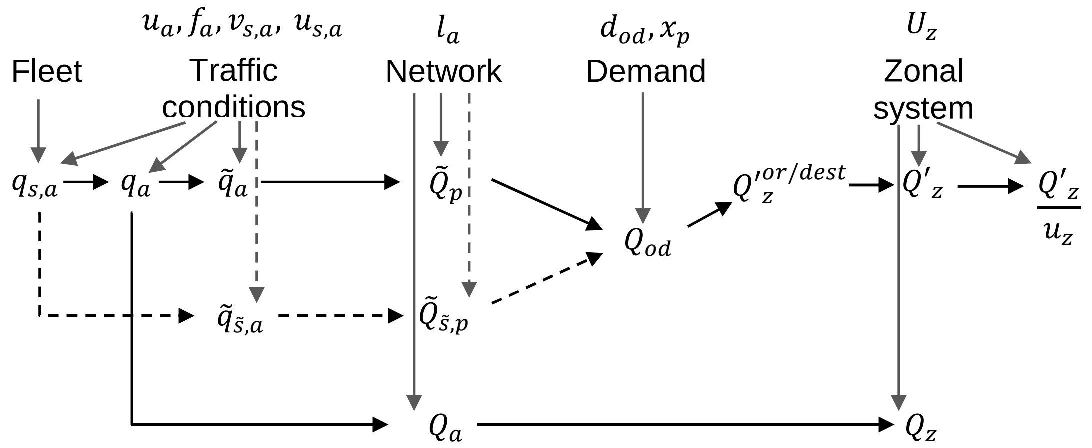

Figure 1: Computation schemes

4.2 Modelling bricks for inputs

At various stages of computation, inputs are needed from 5 modelling bricks that will can be summarised in the following way:

- Networks: comprising a model of the road and transit networks, including their geometric characteristics as well as missions and frequencies for transit modes
- Zoning system: geographically delimiting zones and assembling data concerning them, such as population and jobs available
- Demand: describing the set of trips between origin and destination pairs. Can be either simulated used a TDM or sampled from a survey.
- Traffic conditions: comprising at least flows of vehicles and users as well as traffic regime (circulation speed) at the network's link level.

- Vehicle fleet: the description of the fleet's composition should allow to determine vehicles' emissions either for an average vehicle in the flow or the individual vehicle sampled from a survey.

5 APPLICATION INSTANCE

5.1 Setting

The methodology was applied to the Paris urban area divided in TAZs with special focus at the Cité Descartes district, located (see fig. 2) approximately 15 km East from Paris, to which it is well connected via a suburban rail line; it is also served by an urban motorway. It is mainly an academic campus, with a few housing buildings, located in the northern part of the district and university buildings as well as firms located in the South part. Ecole des Ponts, in particular, is located on this campus.

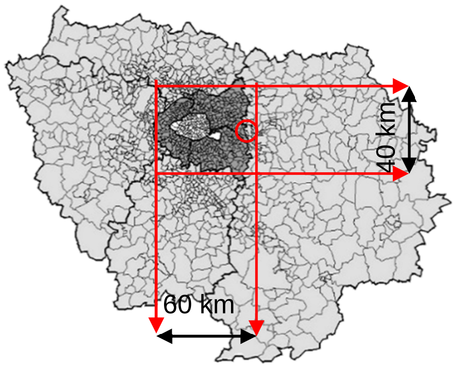

Figure 2 Ile-de-France region, Cité Descartes district circled in red, MODUS transport analysis zones

5.2 Model presentation

The general modelling chain applied to evaluate the district's mobility impacts comprises three main stages: transport demand simulation; traffic simulation; and environmental impacts simulation.

We dealt with the first two stages by using a four-step travel demand model, MODUS, provided by the DRIEA (the state Department for Regional Planning). It is a macroscopic, static model, enabling simulations at the morning and evening peak hours. Three main travel modes are dealt with: private car, transit and "soft modes". Transit is further subdivided into train, suburban rail, metro, tram, and bus.

To perform the last stage of environmental impacts evaluation, we used an emission model for each of the aforementioned modes and sub-modes. For transit electric modes, primary energy consumption and associated GHG emission (for energy production) were evaluated. For the remaining bus and private car modes, several impacts were evaluated: global impacts such as energy consumption and GHG emissions; and local impacts such as NOx and PM. MODUS does not model transit congestion therefore a static, traffic conditions-invariable emission models were used. And since road congestion is represented, we used a more detailed speed-dependent emission model for private car, based on [SETRA 2009] emission curves and regional diesel/petrol split as for 2009's fleet. Bus fleet composition from January 2009 was used, based on RATP sources (the main transit operator in greater Paris).

MODUS is a zonal model, dividing the Ile-de-France region in 1289 zones, shown in figure 2. In the case study, sensitivity to transit accessibility was of interest, therefore the transit analysis zone corresponding to the district of interest was further split in approximately 100 zones each comprising a building or small group of buildings. Road network was also refined. Part of a global evaluation project, mobility's impacts were expected at the year period. In order to do so, off-peak hour road assignments were performed whereas off-peak transit traffic and corresponding impacts were estimated based on households surveys results and lower frequencies provided in the service timetables. Daily impacts were thus reconstructed, then yearly results were estimated using traffic ratios also determined from a household travel survey.

5.3 Results

Here we present results for the morning peak hour, concerning CO2 emissions due to transit transport. Although the effects of CO2 are rather global than local, we chose it to illustrate the results since this is one of the impacts calculated for all modes, notably electric public transit.
Figure 3 shows $\tilde{q}_a$, the average CO_2 emissions in grams per passenger.kilometer (see section 3.1) for every transit link in the eastern part of the Ile-de-France region, centred on the Cité Descartes district (circled in red). A clear distinction can be made between rail modes and lower capacity modes such as buses. Rail is characterised by high-flow, low-impact links seen as large yellow sections in the centre of Paris and radially spreading on the figure 3. Buses have lower capacity hence lower flows (thinner sections in the figure 3) that tend to present with higher per-passenger impacts.
We can also note a net progression from the centre to the periphery with increasing per passenger impacts (less yellow and more blue segments). This is due to several factors. First, there are more electrical modes in the centre, which in France, due to the highly nuclear electrical mix, produce less CO_2 per kilometre travelled than diesel-powered buses. Second, vehicles' occupancy is higher in the centre than in the periphery, factor reinforced by the fact that a lot of transit lines run radially, having their terminus in the periphery: vehicles therefore fill up progressively as they travel towards Paris' centre.

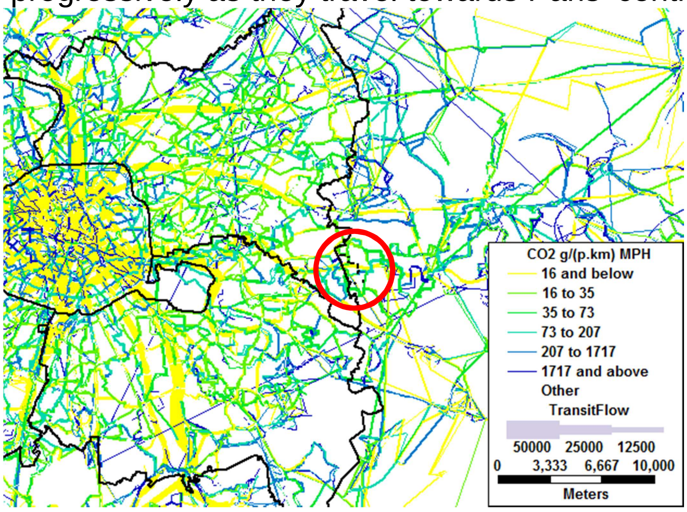

Figure 3 Local CO_2 emissions per passenger.kilometer during the morning peak hour (MPH), transit modes.

These local link impacts can be aggregated along a passenger route to determine total impacts generated between an origin and a destination, $\tilde{Q}_{od}$. Figure 4 illustrates these results for a trip-maker travelling from the Cité Descartes district as origin, to every destination in the region (colour map represents impacts, at the destination zone, of the transit trip originating at the Cité Descartes).
Further-reaching trips generally induce higher trip impacts. But, more specifically, it can be observed that trips using the suburban rail line (East-West direction) have lower impacts than those travelling by bus (North-South direction). More broadly, total trip impacts are anisotropic in space: travelling

eastwards towards Paris and its close suburbs, finely meshed with electrical modes, induces lower impacts than travelling westwards towards more peripheral suburbs. This mapping shows high- and low- potential zones. Combined with the actual demand (O-D flows), it can be used to exhibit O-D links requiring efforts to reduce per-passenger impacts through policies encouraging car-pooling or transit development (checking sufficient vehicle occupancy).

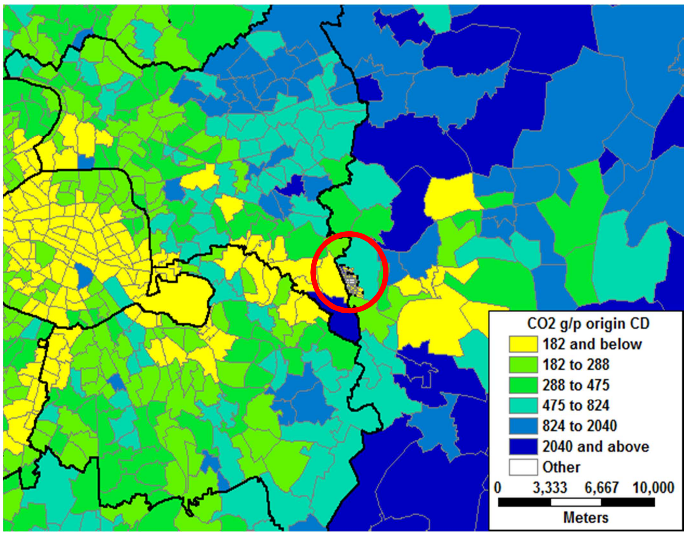

Figure 4 CO2 emissions per individual trip between the CD district and a destination zone in the Ile-de-France region

For each zone, we determined total emitted impacts associated with its travel demand (emitted and received trips), Q'_z using the procedure described in figure 1. We also aggregated, at the zone level the total impacts received, Q_z, using associated procedure described in figure 1. Then, we balanced total emitted impact versus total received impacts (Q'_z-Q_z), as shown in figure 5. Recall that transit impacts at the morning peak hour are solely considered. The map in figure 5, shows zones that emit more than they receive (green-blue zones), therefore causing impacts on other zones, and those areas that receive more impacts than they emit (white areas), bearing impacts of other zones. It can be in particular noted that emitting zones are more centrally located whereas more impact-supporting areas are located in the periphery. This imminently raises the question of cost sharing between zones.

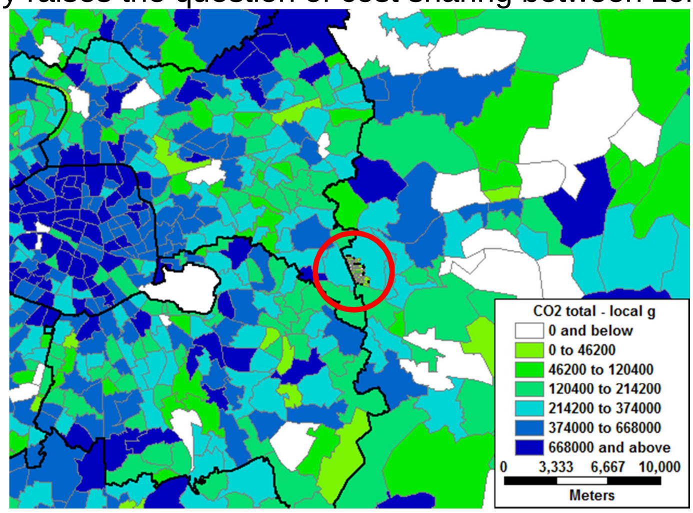

Figure 5 Balance of total CO2 emissions and total CO2 received (transit modes only)

6 SYNTHESIS AND FURTHER RESEARCH

In the present article we propose an attribution scheme to account for the overall mobility impacts of a zone in an accountability-based approach, encompassing all trips whose origin or destination are in the zone. Furthermore we believe that a trip's impacts should be distributed in a 50-50 way between the trip's origin and destination. We also suggest these emitted impacts should be weighed against the impacts received by a zone. In the present work an intermediate indicator of received impacts is proposed, that takes into account, in a cadastral-based approach, all emissions taking place geographically inside a zone.

The methodology is applicable using traditional transport simulation tools already available to the engineering consultants, combined with GIS tools for geographic analyses. Today, transport studies include local emission factor analyses: our approach adds an attribution scheme to improve on this state of practice. Thus it contributes to bringing together on the one side the link-based local emission approach and on the other side, households' mobility analyses based on household surveys' processing computing environmental impacts.

Future work could concentrate on improving the accuracy of the balance between emitted and received impacts. Indeed, the present paper focused on the emission side and a proxy was used for the reception side. Multi-agent simulation (or household surveys sampling) offers an opportunity to grasp the subtleties of the actual people's presence instead of relying on resident populations to evaluate impact exposure.

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