Empreinte GES et évaluation environnementale de la mobilité urbaine

Auteurs : Cyrille François[1,3], Natacha Gondran[1], Jean-Pierre Nicolas[2]

1. UMR CNRS 5600 Environnement Ville Société ; Ecole Nationale Supérieure des Mines de Saint-Etienne ; Institut Henri Fayol ; 158 Cours Fauriel, CS 62362, F-42023 Saint-Etienne Cedex 2
2. Laboratoire d'Economie des Transports (UMR CNRS 5593) ; Ecole Nationale des Travaux Publics de l'Etat ; Rue Maurice Audin ; F-69518 Vaulx-en-Velin Cedex
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Les déplacements de personnes et de marchandises sont responsables d'une part importante des impacts environnementaux à l'échelle de la ville (Verdon et al., 2008). Les émissions de Gaz à Effet de Serre (GES) liées aux mobilités individuelles locales, majoritairement internes aux aires urbaines, sont non seulement plus importantes que celles liées aux déplacements à longue distance, mais ont également augmenté significativement plus que les autres de 1990 à 2000 du fait de la poursuite de l'étalement urbain (Nicolas et al., 2013). L'évaluation environnementale de la mobilité est ainsi un enjeu important pour les acteurs publics afin de dégager un diagnostic des émissions de GES générées par un système de déplacements urbains dans l'objectif de les réduire tout en maîtrisant les autres impacts environnementaux.

Dans ce cadre, cette étude s'interroge sur les outils d'évaluation environnementale des mobilités et propose une méthode d'évaluation combinant Analyse de Cycle de Vie (ACV) avec une modélisation transport-urbanisme. L'analyse inclut donc non seulement les impacts générés directement par les déplacements, mais aussi ceux liés au raffinage des carburants, à la fabrication et fin de vie des infrastructures et des véhicules (notion d'« empreinte »). La modélisation permet en outre de prendre en compte les comportements de mobilité liés aux caractéristiques socioéconomiques des personnes et à leur localisation résidentielle. Afin de fournir une vision globale sur les impacts environnementaux de la mobilité, neuf indicateurs ont été choisi pour décrire l'empreinte GES, les besoins énergétiques, les utilisations de ressources naturelles et la pollution atmosphérique locale.

L'exercice a été appliqué sur l'aire urbaine de Lyon à partir du modèle SIMBAD. L'empreinte GES ainsi estimée pour la mobilité lyonnaise est de 2,83 kg CO_{2eq} par habitant par jour, fortement corrélée à l'utilisation de la voiture. Les émissions indirectes liées à la fabrication et la fin de vie des véhicules et infrastructures, ainsi qu'au raffinage des carburants représentent 33% de cette empreinte. Un Lyonnais utilise environ 1kg de pétrole équivalent et émet environ 5 g de particules pour sa mobilité quotidienne. La voiture personnelle étant la principale source d'impacts, des analyses de sensibilité ont été effectuées pour différents niveaux technologiques du parc automobile (plus ou moins de diesel, de véhicules électriques ou hybrides, de biocarburants) et différents comportements (taux d'occupation, part modale, vitesse). Si réduire la part modale de la voiture est efficace sur l'ensemble des indicateurs, l'introduction de nouvelles technologies diminue certains impacts environnementaux mais en dégrade d'autres.

SIMBAD permet d'évaluer les impacts dus à différentes classes de ménages caractérisées par le revenu et la localisation : les ménages modestes impactent moins l'environnement du fait de distances quotidiennes parcourues plus faibles tandis que les ménages éloignés du centre ont un impact supérieur aux autres, soulevant des questions en matière de dynamique urbaine et de ses interactions avec le système de transport.

Mots clés : mobilité urbaine, modèle d'interaction transport urbanisme, évaluation environnementale, analyse de cycle de vie

1 Introduction

The transport has become the main sector of GHG emission, in France, with 27.8% and 136.4 Mt CO_2-eq (carbon-dioxide equivalent), in 2012. Personal vehicles represent 57% of these emissions and individual journeys account for approximately two thirds of total transport emissions (MEDDE, 2014a). Individual mobility is composed of local versus long distance mobility (above 80 km from home). In 2008, local mobility represented 99% of individual journeys, 59% of total distance and 69% of greenhouse gas emissions. The total GHG emissions of transport increased by 14% between 1994 and 2008 due to the clear increase in local travel emissions (+17%) compared to long distance emissions (+8%) (Nicolas et al., 2013). The challenge for local authorities is to take decisions to reverse this trend and implement sustainable urban systems.

This paper focuses on conception and development of new environmental assessment tools to help public decision. It lays on three assumptions: (1) the environmental assessment should be large enough to avoid too big blind spots for the public decision, (2) it is important to link emission and emitters, which is not easy in the case of transport, and (3) urban modelling furnishes today operational tools, efficient enough to guide an assessment at a conurbation scale.

First, in the field of environmental assessment for public policies, most of applied studies still focus on direct emissions from vehicles operations, and eventually their spatial distribution inside the involved perimeter. But research on life cycle analysis shows the interest of including indirect impacts resulting from other stages, as infrastructure, fuel production, car manufacturing, maintenance and disposal (Le Féon, 2014). It is also important to enlarge the point of view by considering different kinds of emissions and impacts, which can be cumulative, or can compensate each other. Some scientific reviews provide today a good survey of the environmental impacts of transport (Joumard et Gudmunsson, 2010).

Second, it is interesting to link emissions with emitters. Lots of studies give a good estimation of the emissions and their impacts, allowing to estimate both the importance of the issue and the economic activities at stake (for example, Citepa, 2014). In the case of transport, as these emissions are due to a multitude of individuals who move for many reasons and have different constraints, that link is more difficult to establish. Emissions are then often just related to traffic levels, with no precise knowledge of who emits, which is not helpful to define more efficient and fair public policies. Nevertheless,

in order to exceed this limit, some scientific works have been hold to enhanced French household trip surveys with emission estimations, allowing a better understanding of who emits what, how much and why (Gallez et Hivert, 1998; Bouzouina et al., 2011; Verry et al., à paraître).

Lastly, in order to evaluate the environmental impacts of urban mobility, this study is based on an urban system model, which simplifies data acquisition from a complex system. The model creates some uncertainties due to simplifications but it also reduces gaps in data by aggregations and allows more easily simulations to test emission level variations in case of different evolutions of the overall context. Today, several models exists at an enough disaggregated level to have a good image of the emitters (Antoni, 2010). The model selected for this study is the LUTI (Land Use and Transport Interactions) SIMBAD model which has been developed on the Lyon urban area (Nicolas et al., 2009, Pluvinet et al., 2013).

The aim of this paper is to demonstrate the relevance and the feasibility of crossing these three assumptions by providing a clear and structured environmental balance of the urban mobility in Lyon. In order to achieve this goal, several objectives were set:

- To undertake a Life Cycle Assessment on the Lyon urban transport system
- To provide a multi-indicators evaluation of the environmental performance
- To use SIMBAD model data
- To link emissions with emitters.

2 Methods

To assess the environmental performance of urban mobility, the estimation was made through a method based on the standardized LCA methodology (AFNOR, 2006). Urban mobility was considered as a system whose function was to "enable people living or working within a urban area to travel during a working day". By this function, the urban mobility was not only defined by the transport system but it includes also trip habits and location of both activities and households (Geurs et Van Wee, 2004). In order to assess the whole system, the functional unit was expressed "per inhabitant day" to take into account the transport system, the distance and the number of trips. To provide comparison points with other studies and to discuss functional unit choices, some results were expressed in different units such as pkm and by trip.

SIMBAD is a Land Use and Transport Interactions model developed by the LET (Laboratoire d'Économie des Transports) (Nicolas et al., 2009, Pluvinet et al., 2013)

and designed on the commuting scale of Lyon, second French most populated area, distributed in 296 municipalities covering 3,300km², and offering a wide range of modes of transport. Its aim is to estimate economic, environmental and social aspects of the sustainability of different prospective scenarios. Currently the environmental evaluation is limited to direct emissions of CO_2 and NO_x from road transport, but a decision support requires detailed and complete estimates of environmental impacts. However, the model simulates a complete urban transport system with stakeholder interactions, which can be used for a more detailed environmental evaluation.

It is based on the 2006 Lyon household trip survey, and estimates mobility evolution to 2030, in interaction with household and company moves. For 2006, 1,710,000 inhabitants are considered, and the model calculates 6,900,000 journeys per day, distributed among individual car, public transport and non-motorized modes (good movements are also represented but have not been considered for that paper). All motorized trips are assigned on road network and public transport network for one peak and one off-peak representative hours of an average working day.

The results of the assignment estimated for 2006 have been used as input data for environmental impact assessment, based on the LCA methodology.

In order to estimate transport environmental performance, nine indicators were selected. Global warming potential and energy use measure the advancement of global environmental targets to reduce GHG emissions, and to improve energy efficiency (MEDDE, 2011). However societies should watch carefully at their utilization of resources and transport sector is a great user of fossil resources (Wall, 2002). Metal depletion and land occupation are also included. Some environment impacts are local, specifically in cities with high density and population. Particulates and tropospheric ozone are local pollutants which impact particularly human health with breathing diseases. Acidification damages terrestrial ecosystem and may migrate to oceanic ecosystem. The ReCiPe method was used to normalize these impacts because it evaluates most of the chosen midpoint indicators with a standard method (Goedkoop et all, 2008).

Table 2-1 Assessed impacts categories

Impact categories	Units	Substances
Global warming potential (100 years)	kg CO_2-eq	All Greenhouse gases
Particulates matter formation	kg PM10-eq	PM, SO_2, NO_x, NH_3
Photochemical oxidant formation	kg NMVOC-eq	NMVOC[1] and other photochemical oxidants
Terrestrial acidification (100 years)	kg SO_2-eq	NH_3, SO_2, NO_x
Fossil depletion	kg oil-eq	Coal, gas, oil
Metal depletion	kg Fe-eq	All metals
Non-renewable energy	MJ-eq	Coal, gas, oil, peat, uranium, primary forest
Renewable energy	MJ-eq	Hydro, wind, geo, solar, biomass energies
Land occupation	m²a [2]	Agricultural and urban lands

[1] Non-Methane Volatile Organic Compounds   [2] square meters annum

The environmental calculation is based on traffic allocation on each section of the network. In particular, the input data was, for each road section, the speed and the vehicles charge estimated by the SIMBAD model for an average off-peak and an average peak hour. The fleet details were obtained from the Household travel survey. Public transport calculation was based on the same equations than car but with a specific network. The same method is used for every indicator.

Four independent calculations were made by section:

- indirect impacts that are related to the production, the maintenance and the disposal of vehicles,
- indirect impacts that are generated by the fuel extraction and refining
- indirect impacts that are generated by the construction of infrastructures
- direct emissions that are generated by the use of vehicles.

3 Results

The environmental performance of the Lyon urban area is determined by its technology level (engine specifications, public transport, etc…), modal share and mobility habits with the number of trips and their distances. The method used assesses the mobility effectiveness and reports the impacts share into four categories (car exhaust, fuel production, car life cycle and infrastructure). The distribution of impact between personal vehicles and public transport is detailed. Data from LUTI model allow impact distribution by types of households in order to link emissions with emitters.

3.1 Average performances

Each ecological indicator was evaluated for each four steps and finally summed to obtain the total amount for the whole transport life cycle. For each indicator, total and sub-total results are presented in Table 3-1.

Table 3-1 Total and sub-total performances of Lyon urban area by inhabitant

Impacts per inhabitant	Exhausts	Fuel	Infrastructure	Vehicles life cycle	Total	Unit
Global warming potential	1.88	0.33	0.22	0.41	2.83	kg CO_2-eq/day
Photochemical oxidant formation	10.54	2.05	2.49	1.61	16.69	g NMCOV-eq /day
Terrestrial acidification	5.43	3.23	1.37	2.19	12.22	g SO_2-eq /day
Particulates matter formation	2.31	0.90	0.65	0.93	4.80	g PM-eq /day
Metal depletion	0	8.73	43.17	161.65	213.55	g Fe-eq /day
Fossil depletion	0	0.69	0.13	0.15	0.98	kg Oil-eq/day
Non-renewable energy resources	0	30.55	10.76	6.42	47.73	MJ-eq /day
Renewable energy resources	0	0.14	0.33	0.42	0.89	MJ-eq /day
Land occupancy	0	1.83	51.92	4.69	58.44	m²/annum

The global warming potential performance of Lyon urban area is evaluated at 2.83 kg of CO_2-eq/inhabitant.day. The main source of these emissions is exhaust from cars, which represents around two thirds of the total. The average transport performance in Lyon is estimated to 175 g CO_2-eq/pkm, which is included in a range of evaluations of French cities (Le Féon, 2014) and it is below New York City evaluation, 220 g CO_2-eq/pkm (Chester et al., 2010). By adding the distance dependency, the average performance is equal to 969 g CO_2-eq/trip. The GHG emissions are highly correlated with fossil resource use and non-renewable energy use because of fuel combustion. Note that French electricity is mainly produced by nuclear plants that emit few GHG, but nuclear energy is a non-renewable energy source.

For the other air pollutants, the main source of emissions is also exhaust from cars. For the photochemical oxidant formation, it represents 63% of the lifecycle impact. Infrastructures impacts are in second position with 15%. The formation of particulates by cars engines represents 48% of the total formation. Fuel production and car life cycle represent both 19% of particulates formation; nevertheless their emissions are unlikely located in cities with air quality issues. Exhausts gas represent only 44% of

the acidification potential, the second largest source of emissions is the fuel production (26%). Compared to the two previous impacts, acidification may have impacts on ecosystems at a continental scale. Energy consumption during car operation is included in the fuel category.

Fossil resource use and non-renewable energy use are both mainly correlated with the use of fuel in engines; it represents respectively 71% and 64%. For the non-renewable energy use, the infrastructures still represent 23% of the total use. The use of around one kilogram of oil equivalent per day per person highlights the dependency on a limited and imported resource. The proportion of renewable energy is low with 1.8% of the total energy use.

The average land occupancy resulting from urban mobility for a Lyon inhabitant is at least equal to 58 m² per year and infrastructures are the main accountable part with 89% of the total land occupancy. Then the total land occupancy for Lyon urban mobility is bounded from below by 113 ha of land. This underestimation is due to approximation for road width and the absence of non-linear infrastructures such as stations or car parks. A Lyon inhabitant uses around 214 g of iron equivalent per day mainly due to car manufacturing.

3.2 Influence of households characteristics

The environmental performances were calculated for the whole Lyon urban area which includes households with different life styles. For this paper, two household characteristics strongly linked with daily mobility and its environmental impacts have been considered: the income per unit consumption, in 3 classes (the 20% lowest incomes, the 60% median and the 20% wealthier) and the location, also in 3 classes (centre, inner suburb and outer suburb), creating 9 classes of households. As the results confirm it (cf. infra), the location has got a big impact on distance travelled and car use; there is also an income impact, but much lower from this distance and environmental point of view, and we retain it to highlight the social and fairness dimension of the conclusions for public policies. It was possible to choose other variables with the Simbad model, such as the age of the head of the household, the head activity, the household size, or the number of cars but as we assumed in the introduction, the main purpose of this research was more to test the methodology.

Using the estimations calculated in the previous section, all 9 classes were assessed. The results for the global warming potential are displayed in Figure 3-1.
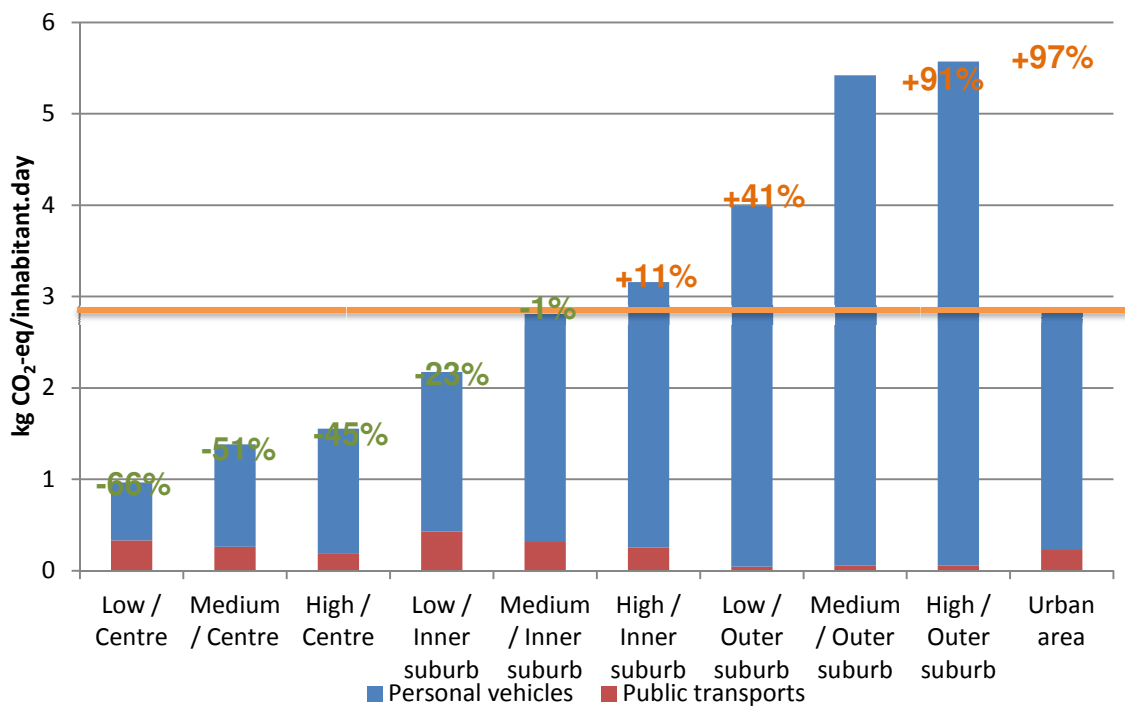
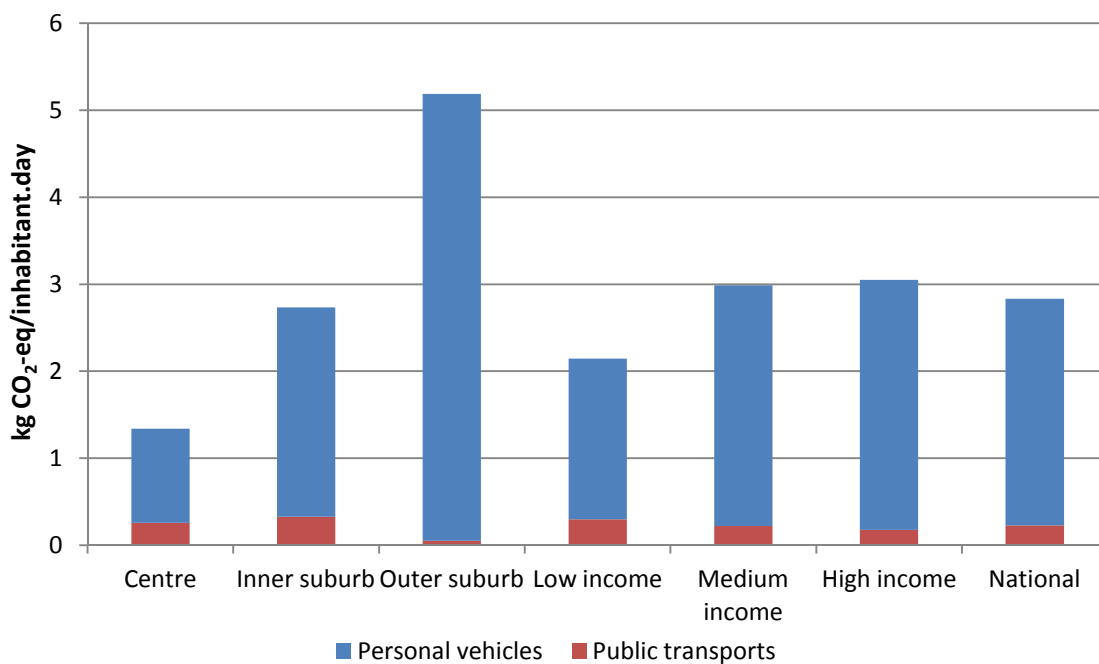**Figure 3-1 GHG emissions per household class, in 2006**

Figure 3-2 GHG emissions per household location and income level, in 2006

Figure 3-1 and Figure 3-2 show there are different GHG contributions for each type of inhabitant. Indeed one person in the outer suburb with high income causes almost six times as much GHG emissions as a person with low income in the urban centre.

Impacts are growing with the household income, specifically for low income households which emit around 2.14 kg CO_2-eq/person.day compared to 2.99 kg and 3.05 kg for medium and high income respectively. It may be due to the smaller proportion of working people in the low income class, with more students, retired, etc. In that class, the car is less used, both due to income limits and to smaller trips (the number of home-work trips, longer than the average, is lower). For the location characteristic, emissions increase with the distance of the household from the urban centre. The average GHG emissions for an inhabitant in the centre are 1.34 kg CO_2-eq/day, 2.73 kg CO_2-eq/day in the inner suburb and 5.19 kg CO_2-eq/day in the outer suburb. Thus impacts are more dependent on the location than on the income of households.

For the eight other indicators conclusions are similar than global warming potential with an increase of impacts with the income and the distance from the centre.

The distance is strongly related with the location of households. The average distance by car for an inhabitant in centre equals 5.5 km/day, 12.7 km for an inhabitant in inner suburb, and 27.2 km in the outer suburb. The distance travelled also depends on the household income, wealthiest households travel longer; the main deviation is between low and medium income households. Moreover households with low income use cars less and public transport more than higher income households. In the city centre, households with low income travel 2.5 km/person.day with public transport. In outer suburb public transport is less accessible and car share represents almost the entire travelled distance. The number of trips per day also affects the total distance travelled. Indeed people travelled more often in the outer suburbs than in the centre or inner suburbs; wealthier households travel also more than poorer households.

4 Conclusion

This study assessed the urban mobility with a LCA method. By using a LUTI model and a functional unit per inhabitant, some transport habits and behaviours were included in this analysis. The environmental performance was based on several indicators to present a broad view of environmental aspects. Some of them are global such as global warming potential and energy use. Resource use indicators focus more on the sustainability of the society with the use of metal, fossil resource and land. And finally ecological and health issues at a local scope were represented by local air pollutants indicators with particulates, photo-oxidants and acid pollutants.

This diversity of indicators may enrich and enhance policy debates about the urban system development and actions to take on the different subsystem of it. Moreover forecast scenarios on technological development or modal share can be assessed on these nine indicators. The use of different indicators, estimated for four different phases of mobility (production, maintenance and disposal of vehicles; fuel extraction and refining; construction of infrastructures and use of vehicles) may highlight some potential transfers of environmental issues from one impact to another, or one phase to another. For example, electric cars reduce GHG emissions but increase the use of metal. This indicator's diversity allows the assessment of technology's externalities which are missing in case of a single indicator assessment method. For example a method without land occupancy indicator would miss an important environmental aspect in case of biofuel development. The use of several indicators shows that technological development actions, such as electric cars, hybrid cars or biofuel, solve some environmental issues but also create others. To reduce all environmental impacts, car use reduction is the best way but need long behavioural changes.

The first step of this study was to evaluate the environmental performance of Lyon urban mobility by using the LUTI model, SIMBAD. This model couples population and company censuses with household travel surveys. The main conclusion of this evaluation is the high impact of cars in the environmental performance; it represents at least 87% of the total impact. Other transport assessment studies highlight this conclusion (Le Feon, 2014; Chester et al., 2010). Thus it is more efficient to act on this mode of transport to reduce the total impact.

The final part of this study assesses different types of households inside the Lyon urban area. Households are defined by many characteristics and different transport habits which change environmental impacts due to mobility. With only two households' characteristics, income by unit of consumption and location, impacts are distributed heterogeneously into households' classes. Higher emitters are located in outer suburb due to low access to public transport, longer distance and lower car occupancy rate. At the opposite end, people in centre are low emitters because of high access to public transport and non-motorized modes and short distance of trips. The last results highlight that poorer households have different habits of transport; they travel less often and on shorter distance than other households. Then by economical actions public policy can change transport habits and force transport sobriety, but they would put more pressure on low income households.

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