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Environmental assessment of urban mobility: combining life cycle assessment with land-use and transport interaction modelling – application to Lyon (France)

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Highlights

- Life cycle assessment and a Land Use and Transport Interactions model were combined.
- The environmental impacts generated by four lifecycle phases of mobility were estimated.
- Higher emitters are located in the outer suburbs, whereas people living in the centre are low emitters.

Abstract

In France, greenhouse gas (GHG) emissions from transport have grown steadily since 1950 and transport is now the main source of emissions. Despite technological improvements, urban sprawl increases the environmental stress due to car use. This study evaluates urban mobility through assessments of the transport system and travel habits, by applying life cycle assessment methods to the results of mobility simulations that were produced by a Land Use and Transport Interactions (LUTI) model. The environmental impacts of four life cycle phases of urban mobility in the Lyon area (exhausts, fuel processing, infrastructure and vehicle life cycle) were estimated through nine indicators (global warming potential, particulate matter emissions, photochemical oxidant emissions, terrestrial acidification, fossil resource depletion, metal depletion, non-renewable energy use, renewable energy use and land occupancy). GHG emissions were estimated to be 3.02 kg CO_2-eq inhabitant^{-1}day^{-1}, strongly linked to car use, and indirect impacts represented 21% of GHG emissions, which is consistent with previous studies. Combining life cycle assessment (LCA) with a LUTI model allows changes in the vehicle mix and fuel sources combined with demographic shifts to be assessed, and provides environmental perspectives for transport policy makers and urban planners. It can also provide detailed analysis, by allowing levels of emissions that are generated by different categories of households to be differentiated, according to their revenue and location. Public policies can then focus more accurately on the emitters and be assessed from both an environmental and social point of view.

1 Introduction

The transport sector has become the main source of GHG emissions in France, producing 136.4 Mt CO_2-eq (carbon-dioxide equivalent), 27.8% of the total GHG, in 2012. Personal vehicles represent 57% of these emissions, and individual mobility accounts for approximately two-thirds of total transport emissions – the other third being generated by freight transport (MEDDE, 2014a). Individual mobility comprises local and 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 from internal travel by French residents increased by 14% between 1994 and 2008, due to a significant increase in local travel emissions (+17%) compared to long-distance travel emissions (+8%), mainly linked with population growth (+6%) (Nicolas et al., 2013). The challenge for local authorities is to take decisions to reverse this trend and implement urban transport systems with lower environmental impacts without increasing social disparities.

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

Firstly, in the field of environmental assessment for public policies, although some scientific reviews now provide a good survey of the environmental impacts of transport (Joumard and Gudmunsson, 2010), most applied studies still focus on direct emissions from vehicle operation and their spatial distribution inside the defined perimeter. However, research on life cycle analysis shows the importance of including indirect impacts resulting from other stages, such as infrastructure, fuel production, car manufacturing, maintenance and disposal (Le Féon, 2014). It is also important to enlarge the scope by considering different kinds of emissions and impacts, which can be cumulative or can compensate each other. Indeed, public policies may have both environmental advantages and disadvantages if various environmental impacts and the whole lifecycle of transport are taken into account. For example, promoting electric vehicles may reduce urban atmospheric pollution, but it also generates additional environmental impacts during the fabrication of batteries and electricity production. This study contributes to identifying some of these combined factors in order to simulate cascading effects of transport policy in a more realistic manner.

Secondly, it is necessary to link emissions with emitters to be able both to evaluate policies more accurately and to take social inequality into account. Many studies give good estimates of transport emissions and their impacts at various territorial scales (for example, EEA, 2012 at the European level, or, for France, Citepa, 2014 at a national level and Aurenche, 2010 at a local scale), allowing estimation of the importance of the issue and the economic activity at stake. However, 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. Assessments often simply link emissions to traffic levels, with no precise knowledge of who emits, which is not helpful in defining fairer and more efficient public policies. To overcome this limitation, some research has employed household travel surveys enhanced with emission estimates, allowing a better understanding of who emits what, how much and why (Brand and Preston, 2010; Dupont-Kieffer et al., 2010; Nicolas and David, 2009). This may help local authorities to better target their actions and avoid penalizing those who do not emit.

Lastly, evaluating environmental impacts of urban mobility is made possible by using land use and transport interaction models (LUTI models), which allow long-term scenarios to be tested and give outputs for large scale urban transport systems. Of course, such a choice encounters some limitations: the simplifications and hypotheses intrinsic to modelling allow a limited range of prospective scenarios, as well as introducing some biases and uncertainties. On the other hand, once the initial investment to develop such a tool is made, its use simplifies data acquisition from a complex system, and it then facilitates simulations to test the effect of developments in the overall context (public policies, economic trends, demographic evolutions, behaviour changes, etc.) on emission levels. Several models now exist at a sufficiently disaggregated level to give a good picture of the emitters (see Antoni, 2010 for France and Hund et al, 2005 or Wegener et al., 2004 at an international level). The model selected for this study is SIMBAD (SImuler les MoBilités pour une Agglomération Durable, ie Simulate Mobility for a Sustainable City), which has been developed for the Lyon urban area (Nicolas et al., 2009).

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

- To undertake a life cycle assessment of the environmental impacts of Lyon's urban transport system using a multi-indicator evaluation
- To integrate the LCA with data resulting from a LUTI model

- To link emissions with emitters.

2 Methods

To assess the environmental impacts of urban mobility, estimates were made using a method based on standard LCA methods (ISO, 2006). Urban mobility was considered as a system whose function is to enable people living or working within an urban area to travel during a working day. Using this functional definition, urban mobility is defined not only by the transport system, but also includes journey habits and locations of both activities and households (Geurs and Van Wee, 2004). In order to assess the whole system, the functional unit was expressed as 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 per person kilometre (pkm) and per trip.

SIMBAD is a Land Use and Transport Interactions model developed by the Laboratoire Aménagement Économie Transports (LAET) (Nicolas et al., 2009). It is designed on a city commuting scale, in order to estimate economic, environmental and social impacts of alternative public policies in urban and transport planning. It simulates the location changes for households and companies over a 25 year timeframe, in interaction with a complete urban transport system (public transport, car and non-motorized modes for individuals, and goods movements due to economic activities).

It has been applied to the case of Lyon, the second most populous area in France, covering 3,300 km^2 distributed in 296 municipalities and 777 IRIS, which are used as the spatial unit basis[1] and are represented in Figure 1. The location modelling has been calibrated and estimated using 1999 census data for households and 1999 SIRENE[2] data for companies. Public transport and road networks have been built and validated in the model for the same year and are regularly updated to take changes into account. Goods movements are generated with the FRETURB model developed by the Laboratoire Aménagement Économie Transports (LAET) to simulate the

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[1] The French National Institute for Statistics, INSEE, developed a system for dividing the country into units of equal population size (about 2000 inhabitants). IRIS (acronym for 'aggregated units for statistical information') represent the fundamental unit for dissemination of infra-municipal data. Towns with more than 10,000 inhabitants, and a large proportion of towns with 5,000–10,000 inhabitants, are divided into several IRIS units. France is composed of around 16,100 IRIS (seehttp://www.insee.fr/en/methodes/default.asp?page=definitions/iris.htm)

[2] SIRENE is the French national system of identification and directory of companies and of their establishments.

transport of goods in urban areas (Routhier and Toilier, 2007), and the individual trip model has been calibrated using the 2006 Lyon household travel survey (SYTRAL, 2006).

For the case study presented here, which tests the feasibility and relevance of combining LUTI output with a life cycle assessment to assess an urban transport system, a 2006 simulation was conducted and used. This study focused on individual daily mobility; goods movements were not considered. Currently the area has a population of 1,710,000 people, and the model calculates 6,900,000 journeys per day distributed among individual car, public transport and non-motorized modes. All motorized trips were allocated to the road network and public transport network in one representative peak hour or one representative off-peak hour of an average working day. The flows of vehicles simulated on each network section for 2006 were used as input data for environmental impact assessment, based on the LCA methodology (ISO, 2006).

In order to estimate the environmental impacts of the transport system, nine indicators were selected. Global warming potential and both renewable and non-renewable energy use measure the achievement of global environmental targets to reduce GHG emissions and improve energy efficiency (MEDDE, 2011). However, the transport sector is a large user of fossil resources in need of monitoring, so fossil fuel utilization was also chosen as an indicator (Wall, 2002). Metal depletion and land occupancy were also included. Some environment impacts are local, especially in cities with high density and population. Particulates and tropospheric ozone are local pollutants, which particularly impact human health through respiratory diseases. Acidification damages terrestrial ecosystems and may migrate to oceanic ecosystems. The ReCiPe method (Goedkoop et al., 2008) was used to normalize these impacts because it evaluates the chosen indicators at a midpoint level using a standard method, rather than endpoint indicators, which aggregate impacts. The environmental calculation was based on the traffic on each section of the network. In particular, the input data, for each road section, included the speed and the vehicle load estimated by the SIMBAD model for an average off-peak and an average peak hour. The vehicle fleet details were obtained from the household travel survey. The public transport calculation was based on the same equations as for cars, but with a specific network. The same method was used for every indicator.

Four independent calculations were made for each section:

- indirect impacts that are related to the production, maintenance and disposal of vehicles;
- indirect impacts that are generated by fuel extraction and refining;
- indirect impacts that are generated by the construction of infrastructure (road, tracks, etc.); and
- direct emissions that are generated by the use of vehicles.

The environmental impacts of the production, maintenance and disposal of vehicles on the network model were estimated by

$$Iveh = i \sum_{s \in sections} L_s C_s \quad \textbf{(1)}$$

where

- $Iveh$ is the total impact due to car production, maintenance and disposal [impact/day]
- L_s is the length of the section s [km]
- C_s is the daily load of vehicles on the section s [vehicles/day]
- i is the impact due to an average vehicle (v) on one kilometre [impact/vkm]

The impacts *i* per vehicle km were obtained from the Ecoinvent database which is one of the most commonly used databases for LCA in the European context. This Swiss national database accommodates more than 2500 background processes often required in LCA case studies (Frischknecht and Rebitzer, 2005). As data is often based on the Swiss demand patterns some data were adapted to better represent the description of the French context. In particular, some modifications were based on vehicle weight and car occupancy rate.

The second calculation evaluated the impacts that are generated by the extraction and refining of the fuels that are consumed during the journeys. Three fuels were considered, diesel, petrol and LPG. The consumption estimates were based on the average speed of each section and consumption curves (Grassot, 2011) derived from COPERT IV (Computer Program to calculate Emissions from Road Transport) (Gkatzoflias et al., 2012) for the defined vehicle fleet. The SIMBAD model describes two types of traffic, off-peak and peak traffic (7 to 9 a.m. and 4 to 6 p.m.).

$$Ifuel = \sum_{s \in sections} L_s \sum_{f \in fuels} i_f \left(20\, F_{sf}^{off} C_s^{off} + 4\, F_{sf}^{peak} C_s^{peak} \right) \quad \textbf{(2)}$$

where

- $Ifuel$ is the total impact due to fuel production and transport [impact/day]
- L_s is the length of section s [km]
- i_f is the impact due to one kilogram of fuel f [impact/kg]
- F_{sf}^{off} and F_{sf}^{peak} are fuel consumption factors on an off-peak and a peak hour on the section s for the fuel f [kg/vkm]
- C_s^{off} and C_s^{peak} are the hourly vehicle loads in an off-peak and a peak hour on the section s [vehicles/hour]

The environmental impacts of fuel were obtained directly from Ecoinvent database, considering fuels that were entirely made from fossil sources. The electricity consumption and impact were calculated using average emission factors with the French electricity mix.

The third calculation assessed the infrastructure impacts. Only linear infrastructure types were assessed, excluding infrastructures such as stations and car parks.

$$Iinfra = \sum_{s \in sections} \frac{1000\, L_s i_s}{365} \qquad \textbf{(3)}$$

where

- $Iinfra$ is the total impact due to infrastructures [impact/day]
- $L_s$is the length of the section s [km]
- i_s is the annual impact due to one meter of section s [impact $m^{-1}a^{-1}$]
- Infrastructure was divided into section categories (4 types of road, 1 tram track and 1 subway track) and their impacts were obtained from the Ecoinvent database.

The last calculation evaluated direct pollutant emissions due to vehicle operation. As for fuel consumption, emissions were calculated from section speeds using COPERT IV for 9 pollutants (CH_4, CO, CO_2, VOC, PAH, NH_3, N_2O, NO_x, PM).

$$Iexhaust = \sum_{s \in sections} L_s \sum_{p \in pollutants} i_p \left(20\, E_{sp}^{off} C_s^{off} + 4\, E_{sp}^{peak} C_s^{peak}\right) \qquad \textbf{(4)}$$

where

- $Iexhaust$ is the total impact due to exhaust pollutants [impact/day]

- L_s is the length of section s [km]
- i_p is the impact due to one kilogram of pollutant p [impact/kg]
- E_{sp}^{off} and E_{sp}^{peak} are emission factors on an off-peak and a peak hour on section s for the pollutant p [kg of pollutant/(vkm)]
- C_s^{off} and C_s^{peak} are the hourly loads of vehicles in an off-peak and a peak hour on the section s [vehicles/hour]

Each ecological indicator was evaluated for the four steps and summed to obtain the total amount for the whole transport life cycle.

This study contains uncertainty due to the quantity of data needed to assess this urban mobility system. The Ecoinvent database describes and, sometimes, quantifies uncertainty of material flow data on the level of each individual input and output of the unit processes (Frischknecht and Rebitzer, 2005). However, uncertainty is very difficult to estimate for the simulations of flows of vehicles because the input data are subject to model errors and also temporal and spatial errors. Because of the unknown errors embedded in data, uncertainty was not estimated in this prospective study. However, a comprehensive sensitivity analysis was undertaken on several parameters. Several car fleets were created to compare the technological dependency of the results. Sensitivities to land occupancy, speed and modal share were assessed.

3 Modal and technological sensitivity analysis

In the model, urban mobility was divided into three mode of transport categories – personal vehicles, public transport and non-motorised modes – according to modal shares. The average trip length was 13.64 km in personal vehicles, 1.57 km on public transport and 0.96 km for non-motorized modes (estimates made with the LUTI model, SIMBAD). The environmental impacts of non-motorised modes were assumed to be negligible.

With technological development and behavioural changes, modal share, occupancy rate and vehicle efficiencies are expected to change. These variations will influence the final impacts, so sensitivity analyses were undertaken to estimate them. For all sensitivity analyses the baseline was the Lyon vehicle fleet, on which changes were applied to the emission factors and vehicle impacts. A change from the Lyon vehicle fleet to the national vehicle fleet increased the use of fossil resources, because the national vehicle fleet contains more powerful cars than an urban fleet as in Lyon. However, local air pollutant emissions were lower with the national fleet (Table 3).

The vehicle occupancy rate in the Lyon urban area is 1.33 persons per car, which is lower than the national rate of 1.4 for local mobility (MEDD, 2010). For the same number of trips by car, a variation in the occupancy rate would have a complementary effect on car use. In these analyses, traffic flows were assumed to be constant despite variations in vehicle loads. A 10% increase in the occupancy was estimated to decrease all environmental impacts by around 7%, because the infrastructure and public transport impacts remained constant. Conversely, a decrease of the car occupancy rate by 10% was estimated to increase impacts by around 8%, except for the land occupancy, which would increase by 2% (Table 2). A decrease in the occupancy rate may happen in the case of a sprawling city where people are more isolated.

The network could be modified to increase or reduce the traffic speed. A global increase or decrease of 10% in the traffic speed would not significantly change the impact on greenhouse gas emissions, but an increase of 10% in the traffic speed was predicted to cause and increase of about 2% in emissions of local air pollutants. Conversely, decreasing the traffic speed by 10% reduced local air pollutant emissions by less than 1%. For both sensitivity analyses, traffic congestion was not recalculated with the new car flows. A modal transfer from personal vehicles to public transport would decrease the environmental impact of urban mobility. A transfer of 10% of travelled distance from car to public transport would decrease almost all environmental impacts by 5-7%, depending on the public transport offered (Table 2).

These sensitivity analyses highlight the effects of behavioural changes on environmental stress. Technological developments that change the characteristics of the vehicle fleet also have effects on environmental impacts. Table 3 shows six vehicle fleet developments and the predicted effect on impacts, based on the Lyon vehicle fleet in 2006. It appears, for example, that electric cars contribute to reduce GHG and local air pollutants emissions, but increase the use of metal (especially during vehicle fabrication) as well as energy consumption for the whole lifecycle. It is also noticeable that technological changes have less impact than behavioural changes.

4 Results and discussion

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

4.1 Average impacts

For each environmental indicator, the results for each life cycle phase (car exhaust, fuel production, car life cycle and infrastructure) and the total are presented in Table 4. The estimated global warming potential from urban mobility in Lyon was 2.83 kg CO_2-eq person^{-1} day^{-1}. The main source of these emissions was exhaust from cars, which represented about two-thirds of the total. The average transport GHG emissions in Lyon were estimated to be 175 g CO_2-eq/pkm, which is within a range of estimates for French cities (Le Féon, 2014) and is less than an estimate for New York City of 220 g CO_2-eq/pkm (Chester et al., 2010). Including the distance dependency, the average emissions were 969 g CO_2-eq/trip. The GHG emissions were highly correlated with fossil resource use and non-renewable energy use through fuel combustion. Note that French electricity, which is the main source for public transport such as trams or underground railways, is mainly produced by nuclear plants, which have low GHG emissions, but depend on a non-renewable resource with specific risks for its production and waste management.

For the other air pollutants, the main source of emissions was also exhaust from cars. For photochemical oxidant emission, car exhaust represented 63% of the lifecycle impact. Infrastructure impacts were the second largest, at 15% of the total. The emission of particulates by cars engines represented 48% of total particulate emissions. Fuel production and car life cycle each represented 19% of particulates emissions; however their emissions are unlikely to be located in cities with air quality issues. Exhaust gas represented 44% of the acidification potential and the second largest source of acidification potential was fuel production (26%). Unlike the two previous categories, acidification may have impacts on ecosystems at a continental scale. Energy consumption during car operation was included in the fuel category.

Fossil resource use and non-renewable energy use were both mainly correlated with the use of fuel in engines, which represented 71% of fossil resource use and 64% of non-renewable energy use. For non-renewable energy use, infrastructure represented 23% of the total use. The use of around 1 kg oil-eq $person^{-1}day^{-1}$ highlights the dependency on a limited and imported resource. The proportion of renewable energy was low, at 1.8% of the total energy use.

The average land occupancy resulting from urban mobility for a Lyon inhabitant was at least 58 m^2/year, and infrastructure accounted for 89% of the total land occupancy. The total land occupancy for Lyon urban mobility was bounded below by 113 ha of land. This result is probably underestimated because it only takes into account road width, neglecting non-linear infrastructure, such as stations or car parks. The average metal depletion was about 214 g Fe-eq $person^{-1}day^{-1}$, mainly due to car manufacturing.

4.2 Influence of household characteristics

The environmental impacts were calculated for the whole Lyon urban area, which included households with different lifestyles. For this paper, two household characteristics strongly linked with daily mobility and its environmental impacts were considered: the income per consumption unit, in 3 classes (the 20% lowest incomes, the 60% median and the 20% wealthier), and the location, also in 3 classes (centre, inner suburbs and outer suburbs), creating 9 classes of households. The results from SIMBAD showed that the location had a big effect on the distance travelled and car use; there was also an effect of income, but it was smaller. Although the environmental impact of income was small, it was retained to highlight the social dimension of the conclusions for public policies. It would have been possible to choose other variables within SIMBAD, such as the age of the head of the household, the head activity, the household size, or the number of cars but, as stated in the introduction, the main purpose of this research was to test the methodology.

Figures 2 and 3 show that there are different GHG contributions for each type of inhabitant. Indeed one person in the outer suburbs with high income may emit almost six times the GHG emissions of a person with low income in the urban centre. The impacts increased with household income, particularly from low income households, which emitted around 2.14 kg CO_2-eq/person.day, to medium and high income households, which emitted 2.99 and 3.05 kg CO_2-eq/person.day respectively. This was primarily due to the smaller proportion of working people in the low income class, with more students, retired, etc. In that class, the car was used less, both due to income constraints and to shorter journeys (the number of home-work trips longer than the average, was lower). For the location characteristic, emissions increased with the distance of the household from the urban centre. The average GHG emissions were 1.34 kg CO_2-eq/day for an inhabitant in the centre, 2.73 kg CO_2-eq/day in the inner suburbs and 5.19 kg CO_2-eq/day in the outer suburbs. Thus impacts were more dependent on the location than on the income of households.

For the eight other indicators, the conclusions were similar to those for global warming potential, with an increase of impacts with the income and the distance from the centre.

The distance travelled was strongly related to the location of the household. The average distance by car was 5.5 km/day for an inhabitant in centre, 12.7 km for an inhabitant in the inner suburbs, and 27.2 km in the outer suburbs. The distance travelled also depended on the household income: wealthier households travelled further and the largest difference was between low and medium income households. Moreover households with low income used cars less and public transport more than higher income households. In the city centre, households with low income travelled 2.5 km/person.day by public transport. In the outer suburbs, public transport is less accessible and car share represented almost the entire distance travelled. The number of trips per day also affected the total distance travelled: people in the outer suburbs travelled more often than those in the centre or inner suburbs, and wealthier households travelled more than poorer households.

5 Conclusions

In the course of this study an urban mobility assessment tool was created by combining a life cycle assessment with a LUTI model. Its effectiveness was then tested through the assessment of the environmental impacts of urban mobility in Lyon. The method used allows the evaluation of urban mobility for the whole city, and also in finer detail through the modelling of transport habits and mobility behaviours of households. To present a broad view of the environmental aspects, the assessment is based on nine indicators. Some of these are global, such as global warming potential and energy use. Others represent environmental and health issues at a local scale from air pollutants (particulates, photo-oxidants and acid pollutants). Finally resource use indicators, such as use of metal, fossil resource and land, focus more on the sustainability of the system.

This diversity of indicators chosen could enrich and enhance policy debates about the development of urban transport systems and actions to take on its different subsystems. Moreover forecast scenarios for technological development or modal share can be assessed using these nine indicators. The use of different indicators, estimated for four life cycle phases (production, maintenance and disposal of vehicles, fuel extraction and refining, and construction of infrastructures and use of vehicles) may highlight some potential transfers of environmental issues from one impact to another, or one life cycle phase to another. For instance, if only GHG emissions are considered, electric vehicles appear preferable to diesel or gasoline cars. However, if the costs and impacts of vehicle fabrication and energy production are taken into account, electric vehicles have greater impacts on metal depletion and energy consumption than conventional vehicles. Thus, the diversity of indicators allows the assessment of externalities, which may be missing in from a single-indicator assessment method. The use of several indicators shows that technological development actions, such as electric cars, hybrid cars or biofuel, mitigate some environmental issues but also exacerbate others. Reducing car use is the best way to reduce all the environmental aspects of large urban mobility systems, but long term behavioural and land-planning changes are needed. Due to the high level of detail in both the LUTI model and the LCA, results can be disaggregated by mode of transport, by life cycle phase or by class of household. By knowing the sources and the quantities of emissions, environmental issues can be better determined and policies can be developed to target the correct offenders and/or practices in need of change.

Finally the LUTI model used in the evaluation process provides dynamic data from different scenarios of urban and transport development. Thus the tool can explore changes in the vehicle mix and fuel sources as well as demographic shifts. These possibilities extend the potential scope of evaluation from assessments of transport systems to social policies. As the assessment tool is now effective and functional, it could be applied to work on prospective scenarios with the urban system considered as a whole, with land use changes, transport system modifications, daily mobility adaptations and their interactions.

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REFERENCES

Antoni J-P. (ed.), (2010), *Modéliser la ville. Forme urbaine et politiques de transport*. Paris, Economica, coll. Méthodes et Approches.

Aurenche, M. (2010), *Etat de l'art des méthodes d'évaluation des impacts environnementaux*. Paris Institute of Technology, Paris. 167 p.

Brand C., Preston J., 2010, '60-20 emission' - The unequal distribution of greenhouse gas emissions from personal, non-business travel in the UK. *Transport Policy* 17, pp. 9–19

Chester, M. V., Horvath, A. and Madanat, S. (2010), "*Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions", Atmospheric Environment,* no. 44, pp. 1071-1079.

CITEPA - Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique (2014), *Inventaire des émissions de polluants atmosphériques et de gaz à effet de serre en France – Format Secten*. Rapport pour le Ministère de l'Ecologie, du Développement Durable et de l'Energie.

Gkatzoflias, D et al., 2012. COPERT 4 Computer programme to calculate emissions from road transport - Users Manual, European Topic Center on Air and Climate Change - ETC-ACC.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R. (2008), *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.*

Dupont-Kieffer A., Merle N., Hivert L., Quételard B., (2010), Environment Energy Assessment of Trips (EEAT): An updated approach to assess the environmental impacts of urban mobility. The case of Lille Region*.* 12th *World Conference on Transport Research*, Lisbon, 11-15 July 2010.

Geurs K.T., Van Wee B., (2004), "Accessibility evaluation of land-use and transport strategies: review and research directions", *Journal of Transport Geography* n°12, pp. 127-140.

Grassot, L. (2011*), Estimation des émissions de CO2 & NOx liées au trafic : impact des hypothèses de composition du parc*, Laboratoire d'Economie des Transport, Vaulx-en-Velin.

EEA - European Environment Agency, 2012, *The contribution of transport to air quality - TERM 2012: Transport indicators tracking progress towards environmental targets in Europe*. Copenhagen, EEA Report No 10/2012.

Frischknecht, R. & Rebitzer, G., 2005. The ecoinvent database system: a comprehensive web-based LCA database. Journal of Cleaner Production, 13(13–14), pp.1337–1343.

Hunt, J.D., Kriger, D.S., Miller, E.J. (2005), "Current operational urban land-use-transport modeling frameworks: a review". *Transport Reviews*, Vol. 25, no. 3, pp. 329-376.

ISO (2006), ISO 14040: 2006. Environmental management -- Life cycle assessment -- Principles and framework

Joumard R., Gudmundsson H. (ed.), (2010), *Indicators of sustainability in transport – an interdisciplinary approach to methods*. INRETS research report, Bron, France.

Le Féon, S. (2014), *Evaluation environnementale des besoins de mobilité des grandes aires urbaines en France : approche par analyse de cycle de vie*, Ecole Nationale Supérieure des Mines de Saint-Etienne.

MEDDE, Ministère de l'Écologie du Développement Durable et de l'Energie (2011), *Les modalités du Paquet Energie Climat*, available at: (assessed 18 June 2014).

MEDDE, Ministère de l'Ecologie, du Développement Durable et de l'Energie (2014a), *Emissions de gaz à effet de serre (Monde, Europe, France)*, available at: http://www.developpement-durable.gouv.fr/Emissions-de-la-France,33791.html (assessed 20 May 2014).

Nicolas, J-P., Verry, D. and Longuar, Z. (2013), "*Evolutions récentes des émissions de CO2 liées à la mobilité des Français : analyser les dynamiques à l'œuvre grâce aux enquêtes nationales Transports de 1994 et 2008", Economie et Statistique,* no. 457-458, pp. 161-183.

Nicolas J-P. (dir), Bonnel P. (dir), Cabrera J., Godinot C., Homocianu M., Routhier J-L., Toilier F., Zuccarello P., (2009), *Simuler les mobilités pour une agglomération durable*. Laboratoire d'Economie des Transport, Vaulx-en-Velin. 211 p.

Nicolas J.-P., David D., (2009), Passenger transport and CO_2 emissions: What does the French transport survey tell us? *Atmospheric Environment* n°43, pp. 1015-1020.

Routhier J-L., Toilier F. (2007), "FRETURB V3, A Policy Oriented Software of Modelling Urban Goods Movement". *11th World Conference on Transport Research*, June 2007, Berkeley, United States.

SYTRAL (Syndicat mixte des Transports pour le Rhône et l'Agglomération Lyonnaise) (2006) Enquête Ménages et Déplacements 2006 de l'aire métropolitaine lyonnaise. 2006

Verdon, B.,Varnaison – Revolle, P., Lebondidier, C., Verry, D., (2008). Mobilité urbaine et réduction des émissions de gaz à effet de serre, *TEC* n°198 – avril - juin 2008

Wall, G. (2002), *"Conditions and tools in the design of energy conversion and management systems of a sustainable society"*, *Energy Conversion and Management*, no. 43, pp. 1235-1248.

Wegener, M. (2004), "Overview of land-use transport models", in Hensher D.A., Button K. (Eds.), *Transport Geography and Spatial Systems*. Handbook 5 of the *Handbook in Transport*. Pergamon/Elsevier Science, Kidlington, UK, 127-146.

Table 1. Assessed impact categories

Impact categories	Units	Substances
Global warming potential (100 years)	kg CO_2-eq	All Greenhouse gases
Particulate matter emissions	kg PM10-eq	PM, SO_2, NO_x, NH_3
Photochemical oxidant emissions	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 occupancy	m^2a (2)	Agricultural and urban lands

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

Table 2. Modal and speed sensitivity analysis

Impact per inhabitant	Lyon 2006	Car occupancy +10%	Car occupancy -10%	Average speed +10%	Average speed -10%	Modal transfer 10% from car to public transport
Global warming potential	2.8 kg CO_2-eq /day	-7.8%	9.5%	0.8%	0.5%	-7.1%
Photochemical oxidant	16.7 g NMCOV-eq /day	-6.6%	8.0%	2.6%	-0.4%	-5.2%
Terrestrial acidification	12.2 g SO_2-eq /day	-7.1%	8.7%	2.1%	-0.7%	-6.0%
Particulate matter	4.8 g PM-eq /day	-6.9%	8.4%	2.4%	-0.9%	-5.6%
Metal depletion	213.6 g Fe-eq /day	-7.1%	8.7%	0.04%	0.02%	-6.7%
Fossil depletion	0.98 kg Oil-eq /day	-7.4%	9.0%	0.7%	0.4%	-6.7%
Non-renewable energy	47.7 MJ-eq /day	-6.5%	7.9%	0.6%	0.3%	-5.6%
Renewable energy	0.9 MJ-eq /day	-5.1%	6.1%	0.08%	0.05%	-3.9%
Land occupancy	58.4 m^2a	-2.0%	2.3%	0.03%	0.02%	-2.0%

Table 3. Technological sensitivity analysis on the Lyon vehicle fleet basis

Impact per inhabitant	Lyon 2006	National 2006	Diesel +10%	Gasoline +10%	electric 10% FR	electric 10% EU	Hybrid 10%	Biofuel 10%
Global warming potential	2.8 kg CO_2-eq /day	3.0 kg CO_2-eq /day	-0.4%	0.4%	-5.7%	-2.6%	-2.9%	3.1%
Photochemical oxidant emissions	16.7 g NMCOV-eq /day	14.7 g NMCOV-eq /day	-1.6%	1.6%	-5.7%	-4.1%	-4.8%	1.3%
Terrestrial acidification	12.2 g SO_2-eq /day	11.6 g SO_2-eq /day	-1.4%	1.4%	-3.5%	-0.9%	-3.8%	4.5%
Particulate matter emissions	4.8 g PM-eq /day	4.6 g PM-eq /day	0.8%	-0.8%	-3.0%	-1.0%	-3.8%	2.6%
Metal depletion	213.6 g Fe-eq /day	221.2 g Fe-eq /day	0.6%	-0.6%	38.2%	38.1%	9.8%	2.3%
Fossil depletion	0.98 kg Oil-eq /day	1.03 kg Oil-eq /day	0.1%	-0.1%	-5.3%	-2.6%	-2.7%	-3.9%
Non-renewable energy resources	47.7 MJ-eq /day	50.2 MJ-eq /day	0.1%	-0.1%	-0.03%	-1.5%	-2.3%	-3.2%
Renewable energy resources	0.9 MJ-eq /day	0.9 MJ-eq /day	0.2%	-0.2%	13.9%	24.1%	0.6%	256%
Land occupancy	58.4 m^2a	58.8 m^2a	0.05%	-0.05%	0.8%	1.9%	-0.04%	183%

Table 4. Total and sub-total environmental impacts of transport in Lyon urban area by inhabitant

Impact per inhabitant	Exhausts	Fuel	Infrastructure	Vehicle life cycle	Total	Unit
Global warming potential	1.88	0.33	0.22	0.41	2.83	kg CO_2-eq/day
Photochemical oxidant emissions	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
Particulate matter emissions	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	m^2/annum

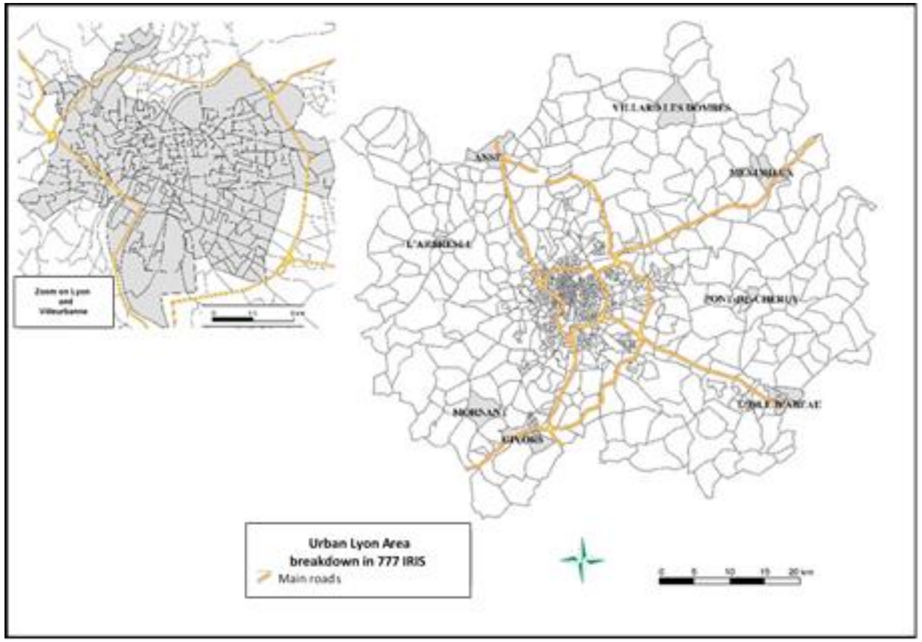

Figure 1. SIMBAD perimeter and the 777 IRIS of Lyon urban area (Source: Nicolas et al., 2009)

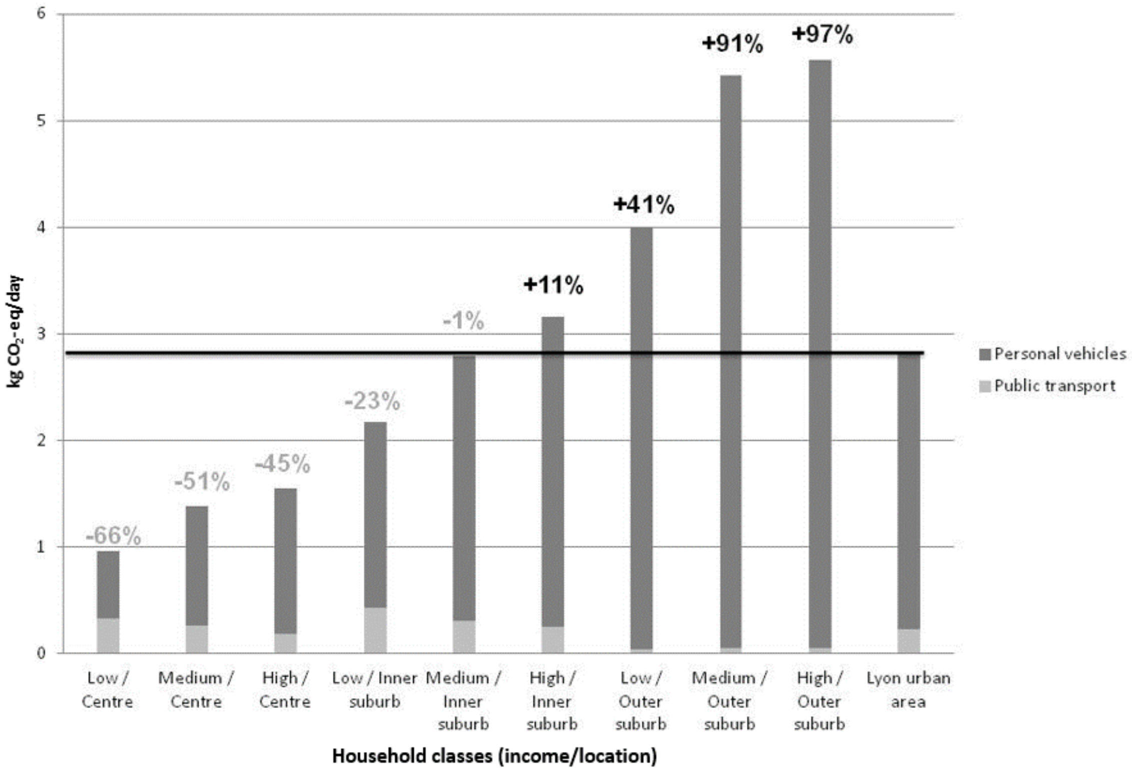

Figure 2. GHG emissions by household class in 2006

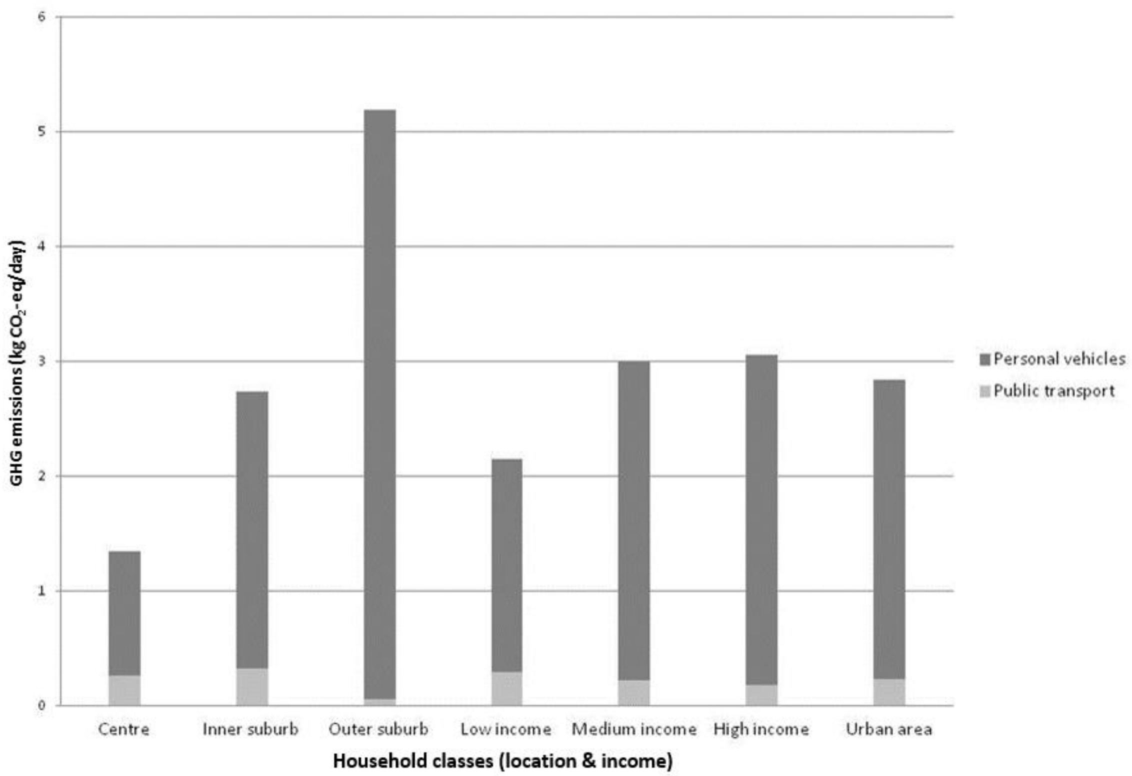

Figure 3. GHG emissions by household location and income level in 2006