CRANFIELD UNIVERSITY

Cyrille FRANÇOIS

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School of Applied Sciences
MSc Environmental Management for Business

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Academic Year: 2013 - 2014

Supervisor:
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Natacha GONDRAN, Assistant Professor, ENSMSE, Saint-Etienne
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This thesis is sponsored by:

Institut des Transports et de la Mobilité Urbaine

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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

This thesis is sponsored by:

ABSTRACT

In France, transport greenhouse gas (GHG) emissions have grown steadily since 1950 and are now the main source. Despite technological improvements and behaviours changes, urban sprawl increases the environmental stress due to car use. This study evaluated urban mobility through assessments of the transport system and travel habits. Using Life Cycle Assessment with data from a Land Use and Transport Interactions (LUTI) model, the environmental impacts of the Lyon area were estimated through nine indicators; global warming potential, energy uses, resources uses and local air pollutants.

GHG emissions are 2.83 kg CO_2-eq/inhabitant.day, strongly linked to car use, and indirect impacts are 22% of GHG emissions. To reduce substantially environmental impacts, actions on car use should be made. Sensitivity analyses on technological development and modal changes highlight the high environmental efficiency of modal actions. Finally nine classes of households were created on their income level and location, and they were assessed in order to link emissions with emitters. Higher emitters are in outer suburbs, raising questions for urban planners and transport policy makers.

Keywords:

Transport assessment, environmental indicators, urban planning, transport behaviours, public transport

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to Dr. Parsons, Dr. Gondran and Dr. Nicolas, my three supervisors, for their encouragement, cheerfulness and useful critiques. Their availability and willingness to help me have been very much appreciated. My grateful thanks are also extended to Mr. Zuccarello for his help with model data and coding.

I would like to offer my thanks to ITMU (Institut des Transports et de la Mobilité Urbaine), for offering and sponsoring this project, and to LUTB (a transport and mobility cluster) for inviting me in an interesting seminar with researchers and international companies.

I would like to extend my thanks to the PIESO and LET departments for welcoming me, exceptionally PIESO department which is in my previous school. I appreciated to see and participate at the other side of the school with lecturers and PhD students.

Finally, I wish to thank my family for their support and encouragement throughout my studies.

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LCA	Life Cycle Assessment
pkm	Person kilometre (one person on one kilometre)
vkm	Vehicle kilometre (one vehicle on one kilometre)
GHG	Greenhouse gas
LUTI	Land Use and Transport Interactions
SIMBAD	SImuler les MoBilité pour une Agglomération Durable
LET	Laboratoire d'Économie des Transports
PM	Particulate Matter
NMVOC	Non-Methane Volatile Organic Compounds
LPG	Liquefied Petroleum Gas

1 Extended introduction

France, like many other countries, faces challenges to reduce greenhouse gas (GHG) emissions. At a global level the Kyoto protocol set GHG emissions goals but it finished in 2012. In 2005, the “Grenelle de l’environnement” set a goal to reduce French emissions by a factor of four by 2050 from a 1990 basis. In 2012 France passed the threshold of 12% of reduction. But since 1990 the transport has become the main sector of emission with 27.8% and 136.4 Mt CO_2-eq (carbon-dioxide equivalent). Personal vehicles represent 57% of these emissions and individual travels account for approximately two thirds of total transport emissions (MEDD, 2014a). Individual mobility is composed of local mobility and long distance mobility (above 80 km from home). In 2008 the former represented 99% of individual journeys and 59% of total distance. However, local mobility was responsible of 69% of greenhouse gas emissions (Nicolas et al., 2012). This non proportionality between distance and emissions is due to the use of modes of transport and other parameters such as urban spread or vehicle occupancy. Moreover GHG emissions increased by 14% between 1994 and 2008 and this trend is linked to the clear increase in local travel emissions (+17%) compared to long distance emissions (+8%) (Nicolas et al., 2012).

The challenge for local authorities is to take decisions to reverse this trend and implement sustainable urban systems. Authorities can act on urban systems with Urban Mobility Plans and Local Urbanism Plans, which regulate respectively the transport network and the space organization. In order to take effective actions, public politics have to face two main challenges. Firstly, how to reconcile urban dynamics and sustainable development? Secondly, on which indicators should policy makers based theirs reflexions? A Life Cycle Assessment on the global urban system can provide some answers to these questions.

In order to understand its dynamics and to evaluate it, an “urban system” must be defined. It can be considered as a systems view of the physical concept of city. This systems approach allows analytical reflections on relationship between subsystems such as structure, population, companies and the urban environment (Archibugi, 1998). There are different levels of description for an urban system: the micro-level, which is composed by elementary units such as individuals, firms and institutions, the meso-level, which defines a city as a geographical entity, and the macro-level, which includes several cities that interact collaboratively in a controlled system. One issue with every system is the definition of a boundary and the sprawling of urban area increases the scale of an urban system. To set limits to an urban system, some authors defined it as a functional community area where local actors have frequent interactions (Bretagnolle et al., 2009).

In way to model an urban system, Wegener (1994) divided the system into eight sub-systems allocated in four categories of change frequency: slow, medium, fast and immediate (Figure 1-1). Networks and land use sub-systems change slowly because they need time to be modified and are rarely abandoned. Workplaces and housing sub-systems are in the medium category because there are linked with building lifespan. Employment and population sub-systems change quickly because they are illustrated by firms and households relocations. Finally goods transport and travel sub-systems vary with minute or hour because they are affected by demands and traffic fluctuations. With this king of categorization, the urban system rhythms and its dynamics can be analysed and modelled.

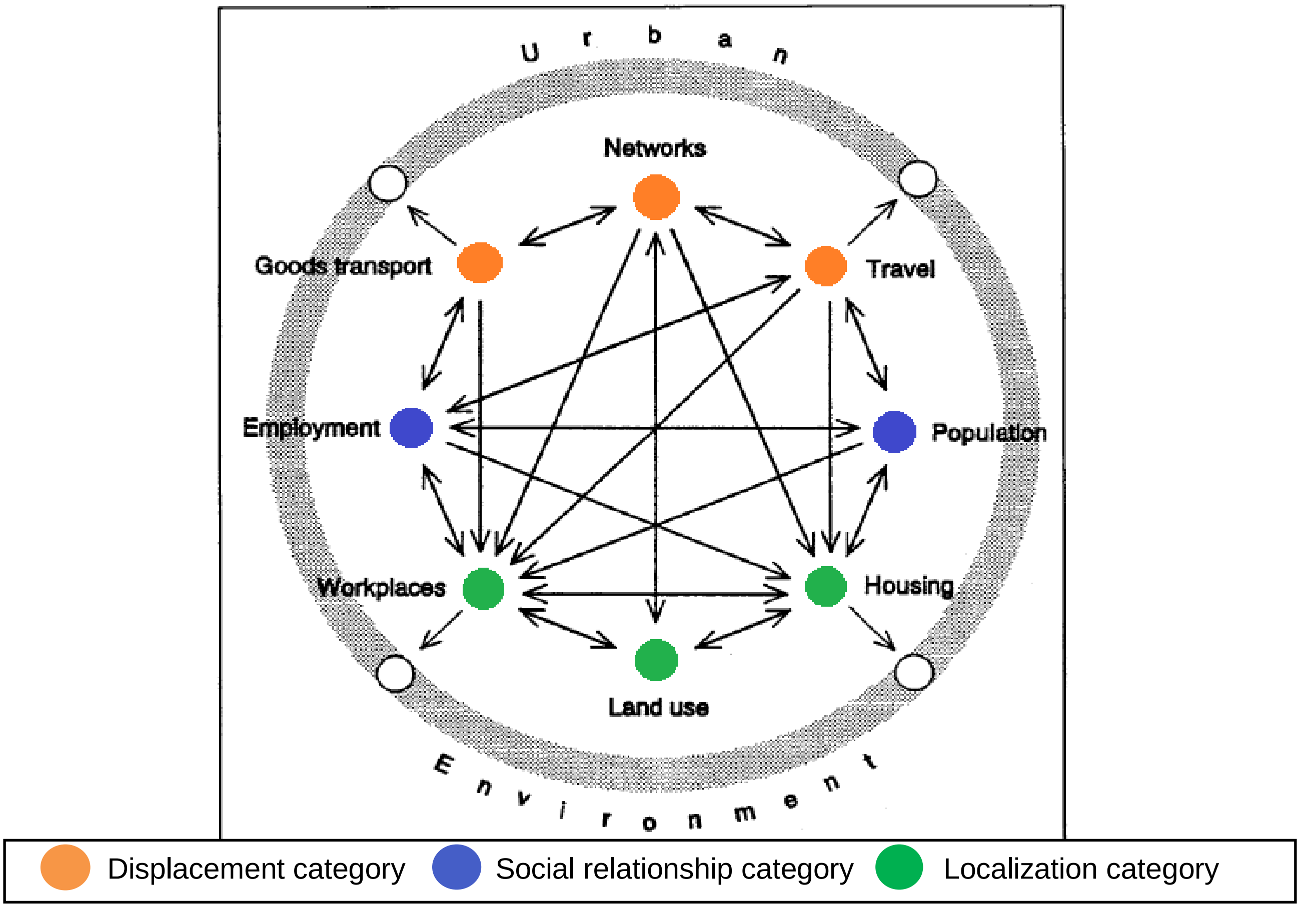

Figure 1-1 A model of urban system, source Wegener (1994)

In a Wegener's model (1994), urban mobility includes travel and goods transport sub-systems. Mobility is characterised by rapid pace of evolution. In the urban system, mobility interacts with other sub-systems; they may influence or be influenced by mobility characteristics (LeFeon, 2014). Miller et al. (2004) named several models which focus on mobility based on micro-simulations. Other sub-systems can be modelled, such as the land use, in order to develop other grounds for thought. Bonnafous and Puel (1983) advance another model approach where simulations are based on an interaction between three categories of sub-systems: location, transport and relationship (Figure 1-1). The category of location spatially distributes activities and households in the urban systems. The category of transport includes the transport network, persons and goods flows. It defines the urban mobility. Finally, the social relationship category represents social habits with the interactions between population and companies. By connecting these three categories the accessibility of the urban system can be evaluated and the urban dynamics would depend on accessibility of areas (Nicolas, 2013).

In recent years, urban systems have changed substantially due to urban sprawl. People have migrated from city centres because of expensive property cost, traffic congestion, and pollution. However, people have moved to peri-urban areas because transport efficiency has made it possible, then they can live further from work and spend the same time to commute (Macário, 2007; City of Stuttgart, 2009). This new distribution implies changes in urban mobility. Indeed this development increases the rate of car use in peri-urban area with lower vehicle occupation due to individualization of societies. In contrast city centres mobility decrease travel number and related emissions because of public transport (Nicolas et al., 2012). Some cities take ambitious actions to change substantially the centre mobility. For example London and Singapore implemented congestion charges in centre. As a result the vehicles charge decreases by 33% in London and by 70% in Singapore. In London, a major part of car users' change their mode of transport, the other part diverted around the charging zone (Beevers and Carslaw, 2005; Santos, 2004).

These actions can solve some issues in city centres but Camagni et al. (2002) suggest that the global urban system is the core of sustainable development concerns. In order to satisfy the three pillars of sustainable development (ecologic, social and environmental pillars) authorities should reduce the spatial fragmentation of urban system. This scattering leads to social disintegration and ecological stress (Boutaud, 2004). Wiel (1999) proposed a polycentric development as a solution to issues due to densification in the centre and exurban fragmentation. Other sustainable solutions can be found if they take in to account all the pillars of sustainability and solve the local and global issues, following the maxim "think global, act local" (Joumard and Nicolas, 2010; Boutaud, 2004).

In order to provide environmental indicators to public politics, several studies were undertaken using a life cycle assessment method on a transport system. Some studies, such as works from Grassot (2011), focus on direct emission from car operation and the spatial distribution of emissions in cities. Other studies include indirect impacts resulting from other stages (infrastructure, fuel production, car manufacturing, maintenance and disposal). Studies in the last category are divided into two groups, studies which evaluate transport modes and studies which evaluate transport system by city. Transport modes results are expressed per person.kilometer (pkm) because it takes into account the vehicle occupancy that affects considerably collective transport (Dave, 2010). Results show that cars cause more GHG emissions than public transport, and emissions in operation stage represent between 81% and 88% of total GHG emissions (LeFeon, 2014). To date, few studies have evaluated the impact of electric and hybrid cars, and the studies from Boureima et al. (2009) and Warburg et al. (2013) show that electric car impact is substantially less than other vehicles. However, they present results for several indicators: including GHG and also human health, fossil depletion and acidification. To complete the evaluation other indicators can be added, such as material depletion, land use and energy use but atmospheric emissions are the most common results.

To evaluate the transport system of city, researchers have combined results from mode evaluation with the distribution of modes of transport. The modal share depends on every urban system. Indeed the transport network and household habits affect modal selection (Chester et al., 2010; LeFeon, 2014). An American study carried out by Chester et al. (2010) evaluated three cities, New York, San Francisco and Chicago, which emit 220, 250 and 290 g CO_2-eq/pkm respectively. A study on French cities presents lower emissions with an average of 179 g CO_2-eq/pkm (LeFeon, 2014). Unfortunately these studies do not evaluate the urban mobility as a whole. Indeed trip distance and trip number per person per day are not included and some actions such as travel substitution or distance reduction would not affect results. Results per pkm and per inhabitant in LeFeon study (2014) lead to different conclusions. The challenge for this study is to include people's behaviours into a transport system evaluation in order to assess the entire urban mobility. In addition of sustainable indicators, public politics need more detailed results linking emissions with emitters. Household travel surveys can provide some of these results (Nicolas et al., 2012).

In order to evaluate the environmental impacts of urban mobility, this study is based on an urban system model. They are numerous models available. The models asset is the easy data acquisition from a complex system. However, changes on model can be made by varying parameters and then a sensitivity analysis will be feasible. Indeed the model may create some uncertainties due to simplifications but it also reduces gaps in data by aggregations. The use of models allows temporal variations that are relevant as regards of urban dynamics rule by different rhythms (Björklund, 2002).

The model selected for this study is named SIMBAD and it models travel in greater Lyon, second most populated area in France at a commuting scale (third position at a built-up scale, centre and agglomeration) (Pumain, 2004). SIMBAD includes 832,618 households distributed in an area of 330,000 ha. The model calculates 6,900,000 journeys per day, distributed among different modes of transport (non-motorized, personal vehicle and public transport), through micro-simulations. SIMBAD is based on a representative survey, the 2006 Household travel survey, and calculates mobility evolution to 2030 with household and company moves and evolution of the network (Nicolas et al., 2013). The aim of the SIMBAD model is to estimate economic, environmental and social aspects of the sustainability of different forecast scenarios.

Currently the environmental evaluation made by SIMBAD is limited to direct emissions of CO_2 and NOx 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. The forecasting process of SIMBAD is based on several hypotheses (some are specific to SIMBAD, others come from external sources) which may lead to errors on the horizon of 2030. A sensitivity analysis may highlight some improvement points for the model.

Looking at these academic and practical interests the aim of this paper is to provide clear, complete and relevant environmental indicators for the urban mobility in Lyon. In order to achieve this goal, several objectives were set.

- To undertake a complete 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 test the model sensitivity on environmental results
- To link emissions with emitters.

2 Methods

The aim of this study is to evaluate the environmental performance of urban mobility in Lyon area. The evaluation was made through a method based on the standardized LCA methodology from “cradle-to-grave”. The method that is proposed follows the ISO 14040 standard (AFNOR, 2006). The urban mobility was considered as a system whose function was to “enable people living or working within the Lyon 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 travel habits and location of both activities and household. In order to assess the whole system, the functional unit was expressed “per inhabitant day” then the transport system, the distance and the number of trips were taken account. 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 displacement.

As explained previously, urban mobility is a complex system and the assessment was based on a LUTI model (Land Use and Transport Interactions) named SIMBAD and developed by the LET (Laboratoire d’Économie des Transports) (Nicolas et al., 2013). The model was built on censuses and household travel survey. The last one gathers 11,229 households which were shared into 308 types depending on their characteristics (localization, size, workers, age of the household chef, number of vehicles and income per consumption unit). All households of the area (832,618) were characterised by a global census and to each household was assigned travels from a similar household in the travel survey. When all travels were assigned an origin-destination matrix was filled for peak and off-peak hours (Nicolas et al., 2013). The results of SIMBAD model were used as input data for environmental impact assessment, based on the LCA methodology.

This model fixed some system’s boundaries. Geographically, the model includes 296 towns covering 3,300km² around Lyon, the model’s centre. Temporally, it focuses on one working day excluding weekend and holidays travels. SIMBAD can model travels for different years but here the study focus on year 2006 in order to match with the Household travel survey. The model still did not take into account all modes of transportation (air transport, trains, river transport were not included). Road transport (cars and buses), tram, subway were assigned on the network, bikes and walking had modal shares but were not assigned to network. The network was formed by 100,968 road sections on which trips are distributed after a traffic calculation. Travels were generated from 9 trip purposes (working, shopping & services, home, leisure, nursery & primary school, secondary school, university, escort and others). But the distribution by purpose was lost at the assignment step (Nicolas et al., 2013). This model provides different levels of aggregation, and then it was possible to assess impacts from 9 categories of households; 3 locations (centre, inner suburb, outer suburb) and 3 income levels. These aggregations allow a better assignment of emissions to emitters who have different behaviours and transport habits.

In order to estimate transport environmental performance the evaluation should not be restrain to one or two indicators. Global warming potential and energy use are two unavoidable indicators because they measure the advancement of global environmental targets to reduce GHG emissions, to develop renewable energy and to improve energy efficiency (MEDD, 2011). However sustainable societies 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. Previous environmental indicators are at a global level but some environment impacts are local, specifically in cities with high density and population. Particulates are one local pollutant which impact particularly human health with breathing diseases. Tropospheric ozone is also a local pollutant which causes respiratory diseases and it creates smog when his concentration is high. Tropospheric ozone is created from photochemical oxidation. Finally some exhausts are acid and have an impact on the soil acidification at a continental level. This acidification damage terrestrial ecosystem and may migrate to oceanic ecosystem. Then 9 indicators are selected to evaluate the environmental performance of urban mobility. 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). The energy indicators were obtained by cumulative operations.

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	m^2a (2)	Agricultural and urban lands

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

The environmental calculation is based on traffic affectation on each section of the network. In particular, the input data was, for each road section, the speed and the vehicles charge that were 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.

Environmental impacts of the production, the maintenance and the disposal of vehicles affected to the network can be estimated with the equation (2-1):

$$Iveh = i \sum_{s \in sections} L_s C_s \tag{2-1}$$

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 charge of vehicles on the section s [vehicles/day]

i is the impact due to an average vehicle on one kilometre [impact/ vehicle.km]

The impacts per vkm were obtained by modifying Ecoinvent data to better represent the description of the actual vehicles fleet (in particular, some modifications were based on vehicles weight).

The second calculation evaluated the impacts that are generated by the extraction and refining of the fuels that are consumed during the travels. Three fuels were considered, diesel, petrol and LPG. The consumption estimations were based on the average speed of each section and consumption curves derived from COPERT IV for the defined fleet (Grassot, 2011). The SIMBAD model describes two types of traffic, off-peak traffic and peak traffic. The last one represents four hours (7 to 9 a.m. and 4 to 6 p.m.).

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

where

$Ifuel$ is the total impact due to fuels production and transport [impact/day]

L_s is the length of the 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/(km.vehicle)]

C_s^{off} and C_s^{peak} are hourly charge of vehicles on an off-peak and a peak hour on the section s [vehicles/hour]

The environmental impacts of fuel were obtained directly from Ecoinvent and here fuels were entirely made from fossil source. The electricity consumption and impact were calculated on average consumption factors with the French electricity mix.

The third calculation assessed the infrastructure impacts (Equation (2-3)). Only linear infrastructures were assessed (stations, car parks were not included).

$$Iinfra = \sum_{s \in sections} \frac{1000\, L_s i_s}{365} \quad \textbf{(2-3)}$$

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.a)]

Infrastructures were divided into categories of section (4 roads, 1 tram track and 1 subway track) and their impacts were obtained from Ecoinvent database.

The last calculation evaluated direct pollutant emissions due to vehicles operation. As fuel consumption, emissions were calculated from sections' speeds with COPERT IV for 9 pollutants (CH_4, CO, CO_2, VOC, PAH, NH_3, N_2O, NOx, PM).

$$Iexhaust = \sum_{s \in sections} L_s \sum_{p \in pollutants} i_p \left(20\, E_{sp}^{off} C_s^{off} + 4\, E_{sp}^{peak} C_s^{peak}\right) \quad \textbf{(2-4)}$$

where

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

L_s is the length of the 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 emissions factors on an off-peak and a peak hour on the section s for the pollutant p [kg of pollutant/(km.vehicle)]

C_s^{off} and C_s^{peak} are hourly charge of vehicles on an off-peak and a peak hour on the section s [vehicles/hour]

The sum of these four subtotals gave the total emissions per day. In order to obtain results per inhabitant this total was divided by the population. To express results into pkm or by displacement the total was divided by the total pkm travelled or the number of trips.

This study contains uncertainty due to the quantity of data needed to assess this system. Inputs data are subject to model errors and also temporal and spatial errors. Because of the unknown errors embedded in data the results accuracy is difficult to estimate. Nevertheless a comprehensive sensitivity analysis was undertaken on several parameters. Several car fleets were created to compare the technological dependency on results. Sensitivities on occupancy, speed, modal share were assessed.

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 theirs distances. The method used assesses the mobility effectiveness and also 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

For each ecological indicators impact were evaluated for each four steps of calculation and finally summed to obtain the total amount for the whole transport life cycle. For each indicator total and sub-total results are summarised and presented in the 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	m^2/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; it represents around two thirds of the total. The average transport performance in Lyon is estimated to 175 g CO_2-eq/pkm, to compare these results with other studies. This score is included in a range of evaluations of French cities (LeFeon, 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. For the other indicators, exhausts do not have any impacts because they are gaseous. 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 in this evaluation with 1.8% of the total energy use. The renewable rate for fuel is very low in this case because fuels are assumed to contain no biofuel; a sensitivity analysis was undertaken on biofuel (Table 3-3).

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; this amount represents the quantity and the rarity of metal use

3.2 Modal & Technological sensitivity analysis

The Lyon urban mobility is distributed into three categories of mode of transportation; personal vehicles, public transport and non-motorised modes. The last one does not contribute to environmental stress. The two motorised categories have two different environmental efficiencies. For the Lyon urban area personal vehicles emit around 396 g CO_2-eq/vehicle.km and public transport 1,904 g CO_2-eq/vehicle.km but the vehicle occupancies are very different. Public transport emits 145 g CO_2-eq/ pkm versus 278 g CO_2-eq/pkm for personal vehicles. Despite its better environmental effectiveness public transport is not the main mean of transport in Lyon urban area. The next figure shows the average modal share for a trip.

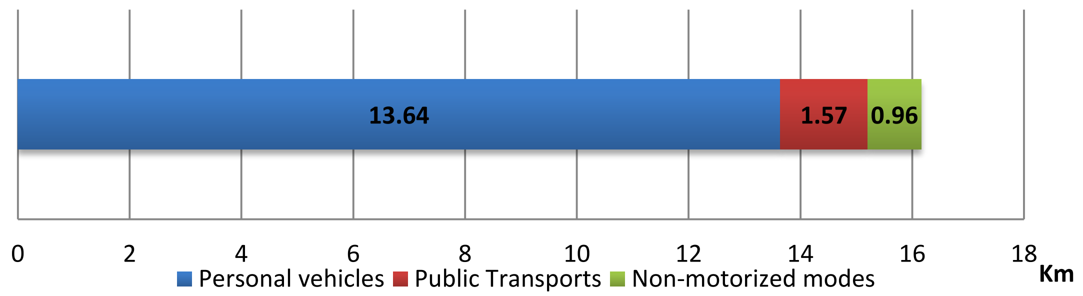

Figure 3-1 Modal share of the distance travelled for an average trip in 2006 (estimated with the LUTI model, SIMBAD)

Personal vehicles use is to a great extend the main means of transport with 84% of the total distance, public transport represents only 10% of the 16.2 km of an average trip distance. Walking and biking represent 6% of the travelled distance. This modal share combined with the efficiency for cars implies that cars represent 94% of the global warming potential impacts. For the other indicators cars are responsible for at least 87% of the total impact. The biggest impact of public transport is for the use of renewable energy, with 13% due to the electricity consumption of tram and subway.

With technological development and behavioural changes, modal share, occupancy rate and vehicles efficiencies are going to change. These variations influence the final impacts and sensitivity analyses were undertaken to estimate them. For all sensitivity analyses the baseline is the national car fleet on which changes were applied. A change of the Lyon cars fleet by the national fleet increases the use of fossil resource because national fleet has more powerful cars than Lyon fleet. Nevertheless local air pollutants are less emitted with a national fleet (Table 3-3).

The vehicle occupancy rate in Lyon urban area is equal to 1.33 persons per car; it is lower than the national rate of 1.4 for the local mobility (MEDD, 2010). For the same number of trips by car a variation of the occupancy rate would increase and decrease the use of car. A 10% raise of the occupancy rate would decrease all impacts by around 7%, because infrastructures and public transport impacts remain constant. The decrease of land occupancy is lower at just 2%. Conversely, a decrease of the occupancy rate by 10% would increase impacts by around 8%, except for the land occupancy, which would increase by 2% (Table 3-2). A decrease of the occupancy rate may happen in case of the sprawled a 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 speed would not change significantly the impact on global warming but an increase of 10% in the speed would emit around 2% more local air pollutant. A decrease in the speed by 10% would reduce local air pollutants emissions by less than 1%. For both sensitivity analyses, traffic congestion was not recalculated with new car flows. A modal transfer from personal vehicles to public transport would decrease environmental impact of the urban mobility. A transfer of 10% of travelled distance from car to public transport would decrease almost all environmental impacts by 5-7%; results depend on variation of public transport offer (Table 3-2).

These sensitivity analyses highlight the effects of behavioural changes on environmental stress. Technology developments have also effects on impacts variations especially by changing characteristics of the car fleet. The Table 3-3 shows six car fleet developments and their impacts variations based on the national fleet in 2006.

Table 3-2 Modal and speed sensitivity analysis on a national fleet basis

Impacts per inhabitant	National 2006	Car occupancy +10%	Car occupancy -10%	Average speed +10%	Average speed -10%	Modal transfer 10% from car to public transp.
Global warming potential	3.0 kg CO_2-eq /day	-7.9%	9.6%	0.5%	0.6%	-7.2%
Photochemical oxidant	14.7 g NMCOV-eq /day	-6.3%	7.7%	2.5%	-0.4%	-4.8%
Terrestrial acidification	11.6 g SO_2-eq /day	-7.1%	8.6%	1.8%	-0.3%	-5.9%
Particulate matter	4.6 g PM-eq /day	-6.8%	8.2%	2.1%	-0.6%	-5.5%
Metal depletion	221.2 g Fe-eq /day	-7.2%	8.8%	0.03%	0.03%	-6.8%
Fossil depletion	1.03 kg Oil-eq /day	-7.5%	9.1%	0.5%	0.5%	-6.8%
Non-renewable energy	50.2 MJ-eq /day	-6.6%	8.0%	0.5%	0.5%	-5.7%
Renewable energy	0.9 MJ-eq /day	-5.2%	6.3%	0.06%	0.07%	-4.0%
Land occupation	58.8 m^2a	-2.1%	2.3%	0.02%	0.02%	-2.0%

Table 3-3 Technological sensitivity analysis on a national fleet basis

Impacts 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	-1.2%	0.6%	-6.2%	-3.3%	-3.5%	3.2%
Photochemical oxidant formation	16.7 g NMCOV-eq /day	14.7 g NMCOV-eq /day	0.9%	-0.9%	-4.6%	-3.5%	-4.2%	1.6%
Terrestrial acidification	12.2 g SO_2-eq /day	11.6 g SO_2-eq /day	-0.1%	0.1%	-3.2%	-0.5%	-3.5%	5.1%
Particulate matter formation	4.8 g PM-eq /day	4.6 g PM-eq /day	1.8%	-1.8%	-2.8%	-0.6%	-3.5%	2.9%
Metal depletion	213.6 g Fe-eq /day	221.2 g Fe-eq /day	0.4%	-0.4%	36.5%	36.4%	9.1%	2.4%
Fossil depletion	0.98 kg Oil-eq /day	1.03 kg Oil-eq /day	-0.3%	0.3%	-5.5%	-3.0%	-3.1%	-3.9%
Non-renewable energy resources	47.7 MJ-eq /day	50.2 MJ-eq /day	-0.2%	0.2%	-0.5%	-1.9%	-2.7%	-3.3%
Renewable energy resources	0.9 MJ-eq /day	0.9 MJ-eq /day	0.1%	-0.1%	13.3%	23.2%	0.3%	271%
Land occupation	58.4 m^2a	58.8 m^2a	0.01%	-0.01%	0.8%	1.8%	-0.02%	197%

The French car fleet has a high proportion of diesel cars (58%) and this rate sets off political debates about fuel tax. Positive and negative variations of the proportion of diesel cars vary impacts by similar amounts in opposite direction. A variation of 10% would not change substantially the use of fossil resource and energy, but having 10% more diesel cars would decrease GHG emissions by 1.2%. A transfer of 10% of diesel to gasoline cars would increase GHG by only 0.6%, so the proportion of diesel cars has a low influence on the lifecycle global warming potential. Nonetheless local air pollutants such as particulate matters and photo-oxidants vary on the diesel rate. A 10% raise of diesel cars would increase local air pollution by 1.8% for particulates pollution and 0.9% for photo-oxidants formation. In that way diesel rate variation seems to have more impacts on local pollution than global pollution.

Unlike diesel cars, electric alternatives replace fuel propulsion by electric propulsion. Then a transfer of 10% of internal combustion engine cars to electric cars would decrease the fossil fuel use by 5.5%. Having 10% of electric cars would also decrease the emissions of GHG by 6.2%. All pollutants resulting from combustion reactions are also reduced substantially, which would reduce air pollution impacts by 2.8-4.6%. However, using electrical technology would increases metal depletion by 37% due to the use of more metal and rarer metals such as lithium. This resource stress may have impact on economy with an increase of price. By using electric cars more renewable energy is consumed but the rate of renewable energy still low with only 2% of the total energy consumption including electricity and fuel consumption. An increase of renewable energy in the electricity mix would increase this rate. In France the electricity is mainly produced by nuclear plants which have very low GHG emissions but in the rest of Europe the electricity production mix is different and emits more GHG and air pollutants. By considering a European electricity mix air impacts are bigger than with a French mix. Global warming decrease is almost halved with the European mix. In this case fossil fuel use is bigger but more renewable energies are used, the renewable energy rate is equal to 2.2%. Many developments are ongoing on electric cars and environmental performance may improve. Present results are based on 2010 inventories from Ecoinvent.

Between the internal combustion technology and the electric propulsion there is the hybrid technology which combines both technologies. In a hybrid car there is a gasoline engine and an electric engine but the battery is smaller than in an electric car then it reduces the use of lithium. Including 10% hybrid cars in the national fleet as replacement for petrol or diesel would increase the metal depletion by 9% for the Lyon urban mobility. Global warming potential decrease is lower than in case of French electric cars with a reduction of 3.5% of GHG emissions. Because hybrid cars have gasoline engine the fossil resource use is higher than electric cars. Despite the fact that hybrid cars use more fuel and emit more GHG they would emit almost the same amount of local air pollutants. For particulates emissions hybrid technology appears more efficient than electric car with a reduction of 3.5%. The comparison of hybrid cars and electric car plugged on European electricity network shows that hybrid cars have better environmental effectiveness in almost all indicators.

All three previous technological variations do not introduce significant amount of renewable energy in urban mobility but French government set objectives to achieve 10.5% of renewable energy in the transport sector (MEDD, 2014b). Biofuel is a solution to achieve this objective by incorporating it in fossil fuel. In previous evaluation incorporation rate were null. In 2014 biofuel incorporation rate can raise 5% for gasoline and 7% for diesel (IFP Énergie Nouvelle, 2012). A sensitivity analysis was made with an incorporation rate of 10% that means that every car use E10 (mix of 10% bio-ethanol and 90% gasoline) in case of gasoline car or B10 (mix of 10% bio-diesel and 90% petro-diesel) for diesel car. With this rate the renewable energy rate for the urban mobility would increase from 1.8% to 6.5% and renewable energy use would be multiplied by 3.7 from the national car fleet. Use of biofuel would decrease use of fossil fuel by 3.9% but GHG emissions increase. Despite the incorporation of carbon by crops, agriculture and treatment activities emissions are bigger and increase global warming potential by 3.2%. Biofuel use would increase also emissions of other air pollutants specifically acid emissions because of the production of fertilizer for agricultural activities. Finally biofuel need fields which contribute significantly in land occupancy indicator then the land occupancy is tripled compared to a national car fleet. Biofuel is an efficient way to introduce renewable energy in transport but it increases many other environmental stresses. Noticed that biofuel technology is improving and present results are based on 2008 inventories from Ecoinvent.

3.3 Influence of households characteristics

The environmental performances were calculated for the whole Lyon urban area which includes 1,934,000 inhabitants with different life styles. This section focuses on impacts of different types of households by aggregated households on two characteristics: income per consumption unit and location. Other characteristics could have been chosen such as the age of the head of the household, the head activity or the number of cars but with more characteristics some household classes might have small samples and create statistical errors. For this analysis 3 income levels were selected (low, medium and high) and 3 locations (centre, inner suburb and outer suburb) creating 9 classes of household. Based on the same method as previously all 9 classes were assessed and the results for the global warming potential are displayed in Figure 3-2.

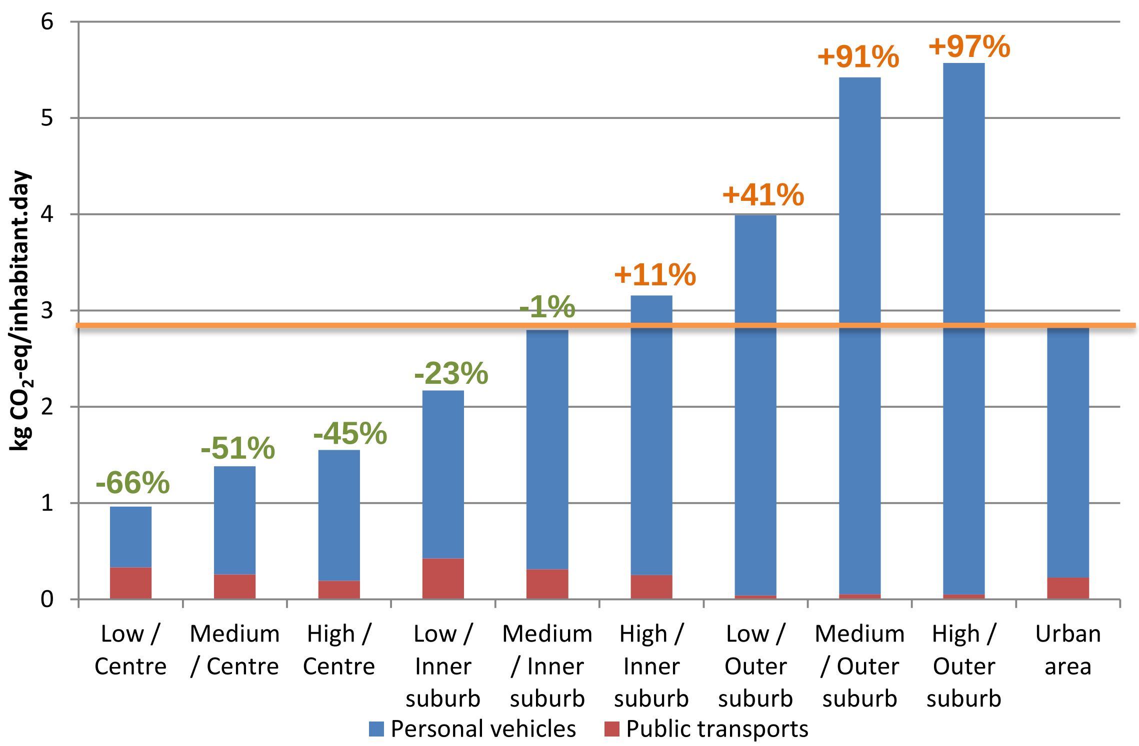

Figure 3-2 GHG emissions per household class, in 2006

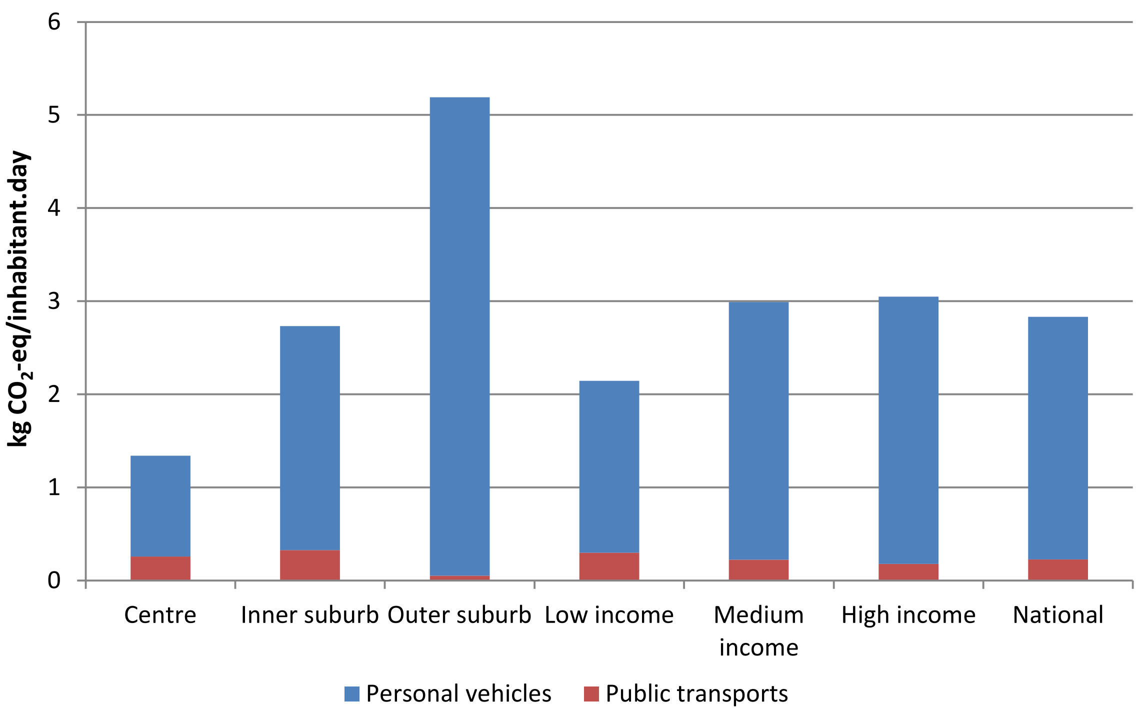

Figure 3-3 GHG emissions per household location and income level, in 2006

Figure 3-2 and Figure 3-3 show there are different impacts 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. 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. Then 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. For resource utilization indicators the deviation is bigger especially for the land occupancy for which high income households in outer suburb need 12 times more space than low income households in centre. This deviation is due to the lower number of vehicles on outer roads.

These variations between household classes are only weakly linked with car fleet characteristics because emissions per vehicle.km are very similar (less than 2.2% difference). This shows that no household class is more advanced technologically and variations are due to the modal shares, the distance of trips and the number of trips of each class.

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 Discussion

4.1 A multi-indicators assessment:

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. Resources uses 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 scenario on technological development or modal share can be assessed on these nine indicators. Then based on these indicators, positive and negative points of each scenario can be understood. Indeed for some technological development, there is a transfer of environmental issues from one impact to another. For example, electric cars reduce GHG emissions but increase the use of metal. This indicators diversity allows the assessment of technologies 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.

In order to develop an accurate environmental assessment method other impacts should be included such as water pollutions (eutrophication, eco-toxicity), water use, ionising radiation etc… In this study midpoint indicators were used to evaluate the urban mobility performance but endpoint indicators, which aggregate several environmental impacts, may be used to answer broader questions (Goedkoop et all, 2008).

4.2 Modal changes versus technological developments:

The first step of this study was to evaluate the environmental performance of Lyon urban mobility by using the LUTI model, SIMBAD. This model is realistic because it couples population and companies censuses with household travel survey. 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 (LeFeon, 2014; Chester et al., 2010). Then it is more efficient to act on this mode of transport to reduce the total impact.

The first type of actions is technological development in order to reduce the impact of the car fleet. Assessed technological developments show improvement of some environmental aspects, but also degradation on some other aspects. Other technological developments should be assessed such as EURO standards improvement in sold cars. This standard characterises cars efficiencies regarding exhaust emissions.

The second type of actions is a reduction of cars use. This reduction is possible through three types of actions. The first one is a modal transfer from personal vehicles to public transport or non-motorised modes. Because public transport is more efficient per person.kilometer, emissions would reduce significantly. This reduction is more important in case of non-motorised modes such as walking or biking. The second type of car use reduction actions is an improvement of car occupancy that would reduce the number of cars used for the same number of trips by car. Carsharing actions would improve car occupancy and then reduce emissions per person.kilometer. The last action to reduce car use is a mobility sobriety of households which reduce their need of trips, or their distances. This voluntary simplicity in mobility is possible by changing households' habits and by increasing local activities such as local shops.

Sensitivity analyses made on modal changes show those actions to reduce the use of cars are more efficient, than technological development, to reduce significantly environmental impact of the urban mobility because they remove emissions sources rather than improving them. Nevertheless modal changes can't be made without deep behaviour changes. These changes need time to occur and money to sponsor awareness campaigns. Moreover public policy needs to invest in bicycle and pedestrian infrastructures and in public transport in order to improve the offer and accessibility of these means of transport to weigh against the car usage and its flexibility. Some penalties can be implemented to reduce car usage such as speed limit, urban tolls or fuel tax.

4.3 A heterogeneous distribution of impacts on the urban system:

The final part of this study assesses different types of households inside the Lyon urban area. Indeed 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, people in centre are low emitters because of high access to public transport and non-motorized modes and short distance of trips.

The dependency on income level is less important than location but low income households have lower impacts than medium and high income. 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.

Heterogeneity of impacts due to location presents debate issues for urban planners. In recent years, outer suburbs of many cities have grown because of house price and quality of life. Then proportion of residents in centre has decreased to settle in outer suburb, this location transfer increases the environmental stress due to urban mobility. An urban scenario of dense city would have the opposite effect with households transfer from suburb to city centre where mobility impacts are small. Nevertheless local pollutions such as air pollutions or noise would be more intense in the city centre. The densification of city centres can pass through vertical growth or renewals of urban wasteland such as the Confluence district in Lyon in 2014 (Lyon Confluence, 2014). Polycentric development may decrease environmental impact by creating several urban centres connected each other by transport.

In order to assess different urban development scenarios the LUTI model, SIMBAD, can be used because it can model city evolution until 2030 (Nicolas et al., 2013). Nonetheless to estimate environmental impact of forecasted city developments environmental inventories and transport network should be updated and forecasted to be representative of future transport systems. In the aim of creating realistic forecasted scenarios, modellers should include changes of people behaviours through years because this study points out that transport behaviour is a significant parameter in urban mobility.

5 Conclusion

The paper has demonstrated a LCA model, which combines LUTI model data and environmental inventories, and assessed the environmental performance of the Lyon urban mobility. Results are expressed by inhabitant in order to include transport behaviours such as modal share, trip distance and the number of trips. Results are detailed on nine environmental indicators. This multi-indicators assessment provides environmental results at different scales (global, societal and local). With these different indicators, policy makers could have better information about the various environmental impacts within the debates about future transport and urban planning actions.

The great importance of cars on environmental performance is highlighted and reduction actions are estimated. 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 last part of this paper assesses different household classes characterized by location and income. Despite a homogeneous technological level, environmental impacts are heterogeneously distributed on the urban area. Higher emitters are located in outer suburbs due to the distance travelled and the access to public transport. This analysis raises questions about the current urban sprawl. Aggregation by income underlines that low income households have lower environmental impacts because of their low car use.

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