A modelling tool for designing urban mobility alternatives and evaluating their direct and indirect environmental impacts

Emmanuel Krieger, Mathieu Mangeot, Jean-Yves Courtonne, Guillaume Mandil, Peter Sturm

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Krieger Emmanuel[1], Mangeot Mathieu[2] Courtonne Jean-Yves[1], Mandil Guillaume[1], Sturm Peter[1]

emmanuel.krieger@inria.fr ; mathieu.mangeot@inria.fr ; jean-yves.courtonne@inria.fr ; guillaume.mandil@inria.fr ; peter.sturm@inria.fr

[1]*Univ. Grenoble Alpes, CNRS, Inria, LJK , STEEP,* 38000 Grenoble, France

[2]*Univ. Savoie Mont Blanc, CNRS, Inria, LJK, STEEP,* 38000 Grenoble, France

Currently, most cities' technical and administrative services are organized in silos, thus hindering any holistic approach to urban planning. In the case of urban mobility, they tend to focus only on direct emissions of greenhouse gases and particles harmful to health, but indirect impacts such as material requirement and associated environmental pressures are usually overlooked. This is problematic in a systemic perspective as ecological transitions policies (e.g. development of renewables energies) typically rely on larger metal consumption and imply additional resource constraints. One should therefore check that suggested mobility policies are feasible from a resource point of view. In this context, a prototype tool based on a bottom-up analysis for the city of Lyon was created. The preliminary results show that a main parameter for reducing the impact of urban mobility is the rate of motorized personal vehicle ownership, and that changing the modal share is not enough to have a beneficial effect on all indirect impacts. Another result is that a reduction in vehicle mass through the substitution of steel by aluminium is more environmentally impactful in terms of indirect manufacturing indicators. In the end, the aim of this tool is to be used as a pedagogical model to engage a dialogue with the stakeholders of the territory considered by informing the debate on possible socio-technical alternatives for city/territorial planning.

Keywords — urban mobility, modelling tool, scenario creation, stakeholder participation

I. INTRODUCTION

Transportation plays a particular role in urban planning since general human activity depends directly on the possibility of human to move through the town and its surroundings.(Grosclaude, Rajendra, and Tubiana 2014) Transports are a source of many questionings on their sustainability, including health issues caused by direct air pollution,(Lamsal et al. 2013) contribution to climate change(Fragkias et al. 2013) among many other issues.(Nieuwenhuijsen 2020) The reduction of air pollution together with the elimination of CO_2 emissions to invent the post-carbon city has been lately a major subject of literature.(Intergovernmental Panel on Climate Change 2007; Zawieska and Pieriegud 2018)

The main approach to tackle the issue of sustainable mobility has been to promote the technological evolution of the transport fleet, notably through electric vehicles, (Emberger 2017) and "the strategy seems to be to replicate the existing car in terms of functionality, size and vehicle autonomy" (Grosclaude, Rajendra, and Tubiana 2014). However, this approach misses the point when it comes to consider this issue under a systemic point of view. Indeed, this prism of study is too restrictive to capture the situation holistically and while this solution effectively decreases the air pollution in cities, it doesn't address several problems such as the requirements for resources to build vehicles or the impacts of their manufacture. Yet, such considerations are of primary importance. Indeed, purely technological changes towards low-carbon emission technologies are resource-intensive and reports on critical raw material for emerging technologies "reveal a consensus on potentially limiting resources for the electrified vehicle industry" (Directorate-General for Internal Market et al. 2018; Hernandez et al. 2017; Jin, Kim, and Guillaume 2016). In this regard, maintaining the current modal split of transportation in cities while adopting low-emission propulsion technologies has shown to increase resource consumption and waste generated by cities (Gassner et al. 2021). It is therefore important to take into account not only technological developments, but also other variables, such as the modal split, when seeking a more sustainable city in terms of emissions and rationalization of resource use.

In this context, it is necessary to provide a possibility for local actors, whether they are decision makers or citizens, to compare the different possibilities for mobility development of their city. Indeed, Banister, (2008) has highlighted that among seven elements which are necessary to promote sustainable mobility, two key elements were the information provided and the involvement of the actors. In this sense, Hickman & Banister, (2015) have identified that scenario building offers a viable solution to explicitly include sustainable mobility in city development. One example of application is the four scenarios constructed for the urban transport of the city of Vienna until 2050 by Gassner et al., (2021). They shed lights on possible future material turnovers thanks to a bottom-up Material Flow Analysis (MFA) approach. Notably, their study estimates the future stocks and flows of material in the city of Vienna for all types of transport and for their required infrastructures. However, because this study is highly detailed, it is complicated to replicate their methodology to other cities in a short period of time since the need of local data is too important. In addition, their scenario tool was not designed to be easily used to create other sets of scenarios.

This being said and more generally, our article is embedded in a wider project that aims to provide information and raise awareness about systemic issues of stakeholders of a territory, whether a city or a wider region. To achieve this goal, we believe that it is interesting to highlight different strategies for structuring human activity through the co-construction of scenarios which present different impacts on the socio-technical organisation of society and on our

environment. Achieving sustainable urban mobility is an interesting case study because it includes many possible choices of development. For sustainable mobility, an aspect of the transition which is too often neglected for decision making seems to be the materials required for the scenarios. This can be detrimental in the future as the ecological transition from a system dependent on fossil fuels to one dependent on metallic resources invariably raises questions about the vulnerability and the impacts of such an evolution. Thus, the present article aims at investigating the creation of a simple prototype tool exploring futures for urban mobility. It could be manipulated by stakeholders with a systemic perspective. In order to achieve this goal, the tool should notably take into account resources use, based on the work that has been achieved by Gassner et al., (2021), which is, to our knowledge, the most in-depth article on this issue.

This article will therefore first present the methodology of Gassner et al., (2021) to model the projection of material stocks and flows in Vienna through scenarios. In the next section, the authors' position will be described with respect to the previously presented article, together with the main hypothesis for the prototype's scope. The final section will describe the construction of an initial prototype of a participatory decision support tool for the French city of Lyon, according to what has been stated in the previous sections.

II. Methodical approach of Gassner et al. (2021)

A. *Description of the functionning of the model*

Gassner et al. (2021) based their model on a bottom-up dynamic stock-flow MFA to determine the future material flows and stocks of the city of Vienna until 2050. They considered specific service units (SU), such as the number of vehicles or the length of metro networks, combined with specific material intensities to calculate flows of material for each year and by deduction, the addition and substraction to the stock each year. Different scenarios have been created by calculating possible development of the SUs in order to model several possible futures. The time window analysed begins in 2016 and ends in 2050. Two specific phases can be differentiated: the first one from 2016 to 2030 gives an evolution of SUs based on current projects of network extension and is common to all scenarios, while the period from 2030 to 2050 is different for each scenario depending on the policies assumed.

The scope of the transport system analysed is the one comprised within the administrative border of Vienna. With regard to the transport system itself, the objects of study are the materials used for new transport infrastructure, maintenance of existing infrastructure and demolition of old transport infrastructure, as well as the materials used solely for the manufacture of vehicles. Concerning vehicles, both freight and passenger vehicles are considered. Finally, with regard to materials, 13 materials expressed in mass units are taken into account: "asphalt & bitumen; aluminium; batteries; brickwork; concrete; copper; glass; gravel & sand; iron & steel; other metals; others (e.g. rubber); plastics; and wood" (Gassner, Lederer, and Fellner 2020).

B. *Scenarios and results of their model*

The four different scenarios devised all start in year 2030 and each represents a possible future pathway, namely:

- the "Business as usual scenario" which extrapolates the current state, e.g., keeps the current modal and type of propulsion steady;
- the "Battery electric vehicle fleet scenario" which mainly replaces fossil fuelled cars by non-emitting alternatives;
- the "Public transport scenario" which reflects a significant modal shift from car to public transport together with a switch to non-emitting alternatives;
- the "Active mobility scenario" which reflects a significant modal shift from car to active mobility, e.g., walking and cycling, together with a switch to non-emitting alternatives.

For all their scenarios, Gassner et al. considered that the population development of Vienna would lead to a more than 10% increase in population in 2050, and the demand of passenger travel would remain stable as well as the material intensity per SU.

Regarding the results, their model has shown that, even though infrastructures have a long lifespan, the material stock evolution from 2030 to 2050 directly depends on the scenario. Indeed, a high modal share of motorized individual transport keeps the material stock constant to around 54 t/capita, while a significant shift in the modal split could reduce the material stock per capita of the infrastructure system up to 46 t/capita, and this, taking into account the expected population increase by 2050. The scenario with higher resource intensity is the one that use high private vehicle fleet rates. In this sense, the "battery electric vehicle fleet scenario" presents the highest vehicle material stock of 1.6 Mt whereas the "Public transport scenario" presents the smallest vehicle material stock of 0.76 Mt in 2050, thus showing the impact of a different choice of development of the modal split for the future.

In the case of the present article, major changes are made to greatly simplify this model and certain aspects are added to give greater variability to the scenarios.

III. Purpose and assumptions for building a prototype aiming at raising awareness on systemic issues

A. *Awareness raising on systemic issues through the use of a modelling tool*

As it has been said in introduction, the aim of the modelling tool is to sensitise the different actors of the city to a systemic approach, particularly with regards to materials issues which are not well known. Our approach is intended to be collaborative, based on a participatory research framework, giving stakeholders the opportunity to illustrate a possible future based on the set of parameters they want to explore. Thus, the tool provided must be simple enough to be accessible to all and integrate a diversity of key variable parameters which must be determined.

The two key parameters identified by Gassner et al., (2021) concerning the variation of materials were the modal split of transportation and the evolution in the type of vehicles propulsion, which respectively changes considerably future material demand and increases waste generation, notably of batteries. Therefore, we want to reiterate the possibility to choose between these two parameters in the prototype.

However, we also want to add other parameters that can structure the material demand as well as indicators that must provide the user information to evaluate the scenario.

Such a goal therefore implies major changes in the scope of Gassner et al.'s study as well as on the calculation methodology to be applicable in our case.

B. *Simplifications of the model*

Many simplifications have been made, both in the quantity of data and in the functioning of the model to allow the variation of key parameters. The four most important changes are:

- a "timeless" scenario logic, i.e., the description of a point of arrival in the future without depicting the path to get to that point,
- the shift to a purely annual flow logic,
- the limitation to the transportation of passenger through 3 vehicles and finally,
- the change in the material scope to only a limited number of metals used in vehicles.

The first change is focused in the very logic of scenario representation. While Gassner et al., (2021) have tackled the issue of describing possible future developments for the city of Vienna transport system until 2050, the prototype we carry out describes alternatives without a time logic. These alternatives can be conceived as "possible arrival points". In practice, the scenarios are made by allowing the user to vary the base parameter set, such as the modal split, the rate of occupancy of vehicles, the weight of vehicles, etc…, and by giving user feedback on the impact of the arrival state using several indicators, which can be for instance greenhouse gas (GHG) emissions or a quantity of material. As said before, the logic is thus to put forward alternatives of operation and to quantify their desirability based on indicators, rather than creating scenarios based on parameters which vary through annual change until 2050. To obtain this, the arrival state is therefore perceived as a stationary state in which the variations in the stock, being the flows, are constant.

Regarding the shift from a stock and flow accounting model to a purely flow model, this simplification arises from the fact that one wants to place oneself timelessly in an alternative which makes it difficult to describe the state of stocks since they are directly linked to the evolution of flows through time.

Concerning vehicles, only cars, bus and bicycles were considered as they each represent a type of transport, e.g., motorized private transport, public transport and active transport (see TABLE II.). It allows the user to understand orders of magnitude for the category of transport studied. Moreover, two types of propulsion for motorized vehicles have been taken into account: Internal Combustion Engines (ICE) vehicles and electric vehicles.

TABLE I. Vehicles included in the study

Table Head	**Type of vehicles**				
	Public transport vehicles		***Personal motorized vehicles***		***Active mobility vehicles***
Vehicles	ICE bus	Electric bus	ICE car	Electric car	Bicycle

Finally, only the materials used to build the vehicles are used, and among them, only details about three metals: aluminium, copper and steel. The choice not to take into account infrastructures is made because the global material stock is not modelled making it complicated to estimate the requirements of infrastructures flows based on vehicle flows since many infrastructures are already existing in the city. Moreover, it is to be noted that "although the annual material turnover for the vehicles is more than one order of magnitude smaller in comparison to the one for the built infrastructure, the materials used in vehicles are much more valuable and their production or disposal is associated with significantly higher environmental impacts, implying that their reduction is most probably more important for the overall environmental performance of the transport system." (Gassner et al. 2021) Concerning the choice to take into account only three metals for the description of vehicles, it is because their summed weight represent more than 70% of the weight for each considered vehicle when data provided by Gassner et al., (2021) are used. Furthermore, the respective masses of each metal in the batteries for electric vehicles have been taken into account and added to their respective material category, so that batteries are no longer a material in itself. This differs from the study by Gassner et al. where batteries were counted as a material on its own.

These simplifications have also been set up to handle the complexity and to keep it to a decent level because as we will see in the next section, other parameters have been added with the idea of increasing the modelling possibilities. The monitoring indicators have also been extended to describe different impacts on the vehicles in order to assess the relevance of the scenarios thus created.

C. *Additional parameters included in the collaborative prototype tool*

As for Gassner et al. (2021), the main point of the prototype is to make scenarios based notably on evolutions of the city modal split and on electrification. In this perspective, the tool does include these two parameters. However, as said previously, the tool is intended to offer more parameter sets.

To this end, several parameters have been added. All of them are taken into account in the study of Gassner et.al. but in contrast to their study, they are not set on long-term trends or considered fixed over time.

Indicators are also major components of the prototype as they provide information on the impact of the scenario created. Two types of indicators have been incorporated: some reflect the impact of simply buying a vehicle, such as the material amount and its impact on water use, and others reflect the use of the car, such as the direct greenhouse gas emitted during its use.

Each indicator has been taken to highlight a different issue regarding urban mobility. For example, the material quantity has been taken to represent the material vulnerability, particulate matter with a diameter of less than 10 micrometers (PM10) emissions account for air pollution which is a major issue of city mobility, GHG emissions are able to give information on the impact of transportation evolution on climate and water use represents the direct needs in water which already suffers scarcity in some regions (Seckler, Barker, and Amarasinghe 1999).

IV. DESCRIPTION OF THE PROTOTYPE FOR STUDYING MOBILITY IN THE CITY OF LYON

A. Presentation of the model[i]

To model an alternative scenario, the user is invited to use different sliders which represent the choices for the evolution of the key parameters presented above. Therefore, several sliders have been structured in such a way that it is possible to vary all the following parameters:

- The mobility demand per capita (varies between 0 and 20 000 p.km/capita);
- The modal split for mobility between buses, cars and bicycles (a rate between 0 and 100% for each vehicle);
- The average number of cars and bicycles per capita (comprised between 0 and 1 for both vehicles);
- The average lifespan of cars, buses and bicycles, which make it possible to renew vehicles to a greater or lesser extent (varies between 5 and 30 years, depending on the vehicles considered);
- The electrification rate of cars and buses (a rate between 0 and 100%);
- The rate of mass reduction, whether by substitution of steel by aluminium, as assumed by a forward-looking scenario established by Rauzier et al., (2020), or by a cut into the mass of the vehicle, arising from the idea of a sobriety in material uses (a rate between 0 and 100% representing the implementation of mass reduction measures).

To understand the consequences of a change in a parameter, indicators in the form of vertical bars or pie charts give the results of the scenario to the user in real time. Namely, they are:

- The percentage share of each type of vehicle purchased for the scenario (pie chart);
- The total material required to build these vehicles, with a distinction between the 3 metals considered, the 3 metals in the Li-ion batteries, the rest of metals for the batteries and the rest of materials required to build the vehicles (under the form of a vertical bar);
- The total amount of water used to process materials (vertical bar);
- The total amount of GHG emitted for the manufacture of metals, and also the emission during the usage phase of the vehicle (vertical bar);
- The total amount of PM10 particles emitted during the manufacture of the metals, as well as the emissions during the usage phase of the vehicle (vertical bars). PM10 take into account tyres, brakes and exhaust emissions for each type of vehicle, except for bicycles where their value is considered to be 0 during the usage phase.and then moving down to the next line. This is the author sequence that will be used in future citations and by indexing services. Names should not be listed in columns nor group by affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization).

B. Assumptions for calculation and parametrisation

After having described the main features in the first section, the calculations to obtain the different results of the scenarios will be detailed thereafter. Concerning the superscripts present on the different variables, the "ref" stands for "year of reference" which is based on real data from the year 2015 and accounts thus for a constant. Other variables are based on the input of the user.

More precisely, the first five equations will detail how the inputs of the users are taken into account to calculate the base data to produce a scenario. The first variable to be calculated is the number of vehicles for the scenario. It is calculated differently depending on vehicles. Buses are assumed to be bought directly based on the demand of transport of inhabitants (eq. 1). The assumption made for this calculation is that the covered mobility demand per buses remains constant over time.

$$N_{bus} = \frac{(d * r_{bus}) * N_{bus}^{ref}}{d^{ref} * r_{bus}^{ref}} \quad (1)$$

where N_{bus} is the number of buses purchased, d is the mobility demand per capita and r_{bus} is the percentage of the mobility demand assigned to buses per capita.

Concerning cars and bicycles, they are underused in average compared to the distance they could travel per year when taking national travel average made per inhabitant (Association négaWatt 2017), so only their age and the rate of vehicle per inhabitant is a factor of renewal. (eq. 2)

$$N_{pv} = \frac{i^{ref} * n_{pv}}{a_{pv}} \quad (2)$$

where N_{pv} is the number of personal vehicles purchased, which can be cars or bicycles, i is the number of inhabitants in the considered territory, n_{pv} is the number of vehicles per inhabitant and a_{pv} is the average lifespan of the vehicle.

Then, for cars and buses, it is possible to implement a rate of electrification which will give the final number of vehicles by propulsion (eq. 3 and eq. 4).

$$N_{pv/bus}^{EV} = N_{pv/bus} * r_{EV} \quad (3)$$

$$N_{pv/bus}^{ICEV} = N_{pv/bus} * (1 - r_{EV}) \quad (4)$$

where $N_{pv,bus}^{EV}$ and $N_{pv,bus}^{ICEV}$ are respectively the number of electric buses and cars and the number of internal combustion engine buses and cars and r_{EV} is the rate of electrification.

Finally, the user can also change the mass of the cars only, whether by substitution of steel by aluminium, or by reducing the global weight of the car by sobriety of design, according to equation 5. Although the substitution of steel for aluminum may be seen as weakening vehicles, it is now considered an important factor in weight reduction foresights (Rauzier et al. 2020).

$$m_{EV/ICEV} = m_{EV/ICEV}^{ref} + r_{subsitution} * \left(-c^{steel} * q_{EV/ICEV}^{steel} + c^{alu} * q_{EV/ICEV}^{alu}\right) - r_{sobriety} * c^{sobriety} * m_{EV/ICE}^{ref} * \left(\frac{q_{EV,ICEV}^{steel}}{q_{EV/ICEV}^{mtot}} + \frac{q_{EV,ICEV}^{alu}}{q_{EV/ICEV}^{mtot}} + \frac{q_{EV,ICEV}^{copper}}{q_{EV/ICEV}^{mtot}}\right) \quad (5)$$

where $m_{EV/ICEV}$ is the total weight of a single electric or internal combustion engine car, $r_{subsitution}$ and $r_{sobriety}$ are rates that go from 0 to 100 % which account for the implantation of weight reduction measures, c^j with j in [steel,

alu, sobriety] (see TABLE III.), refers to a constant of maximum mass change comprised between 0 and 1 and finally $q^{k}_{EV/ICEV}$ with k in [steel, alu, copper, mtot], refers to the quantity of each metal per vehicle with $q^{mtot}_{EV/ICEV}$ representing the quantity of the summed mass of the 3 metals in the vehicle considered.

Based on the calculation of these values, a total amount of material is displayed to the user as well as GHG emissions and water used to produce these materials. The calculation of the total mass of materials is simply the multiplication of the unit mass value of vehicles by their number. However, a distinction is made in the final display of the scenario by differentiating between the three metals considered for the vehicles, the three metals used for their battery and the remaining mass of the vehicle being composed of other materials.

Concerning the water use, GHG and PM10 emissions related to manufacture of metals, they are calculated as follow (eq. 6):

$$M_{water/GHG/PM10} = \sum_{pv,bus} \sum_{l} m^{l}_{pv,bus} * N_{pv,bus} * I^{l}_{water/GHG/PM10} \quad (6)$$

where $M_{water/GHG/PM10}$ is the total mass of water used or GHG and PM10 emitted for the current scenario, $m^{l}_{pv,bus}$ is the mass of the metal with l in [steel, aluminium, copper] in the considered vehicle, and $I^{l}_{water/GHG/PM10}$ is the impact of the metal manufacture expressed in kg of water used or in kg of GHG and PM10 emitted per kg of metal l used.

The impact $I^{l}_{water/GH\ /PM10}$ takes into account 2 kinds of process: a process for virgin materials, and a process for recycled materials. Therefore, $I^{l}_{water/GHG/PM10}$ can be further decomposed (eq. 7) :

$$I^{l}_{water/GHG/PM10} = r^{l,ref}_{recycled} * I^{l,recycled}_{water/GHG/PM10} + \left(1 - r^{l,ref}_{recycled}\right) * I^{l,virgin}_{water/GHG/PM10} \quad (7)$$

where $r^{l,ref}_{recycled}$ is a fix rate of recycled material l used in the French national economy and $I^{l,recycled}_{water/GHG/PM10}$ and$I^{l,virgin}_{water/GHG/PM10}$ are the respective impacts of the recycled and virgin metal manufacture expressed in kg of water used or in kg of GHG emitted per kilogram of metal l used.

Finally, direct emissions are also calculated for GHG and PM10, based on the mobility demand for each vehicle according to equation 8.

What can be seen is that direct emissions of the whole usage phase of the vehicles are considered.

$$I_{GHG/PM10} = \sum_{pv,bus} \frac{N_{pv,bus} * I^{km}_{pv,bus} * d_{pv,bus} * a_{pv,bus}}{p_{pv,bus}} \quad (8)$$

where $I_{GHG/PM10}$is the total emission in tons of GHG or PM10 concerning usage phase of vehicles for the current scenario, $I^{km}_{pv,bus}$ is the emissions of GHG or PM10 per vehicle and is expressed in t/p.km, $d_{pv,bus}$ is the mobility demand of the vehicle, $a_{pv,bus}$ is the average age of the type of vehicle considered and $p_{pv,bus}$ is the average number of passenger per vehicle.

C. Results

With these assumptions and calculations, it is now possible to create several scenarios. Some typical scenarios are imagined here, but it is possible for the user to create new different scenarios.

TABLE II. Value of the different constants changing the mass of vehicles

	Constants		
	c^{steel}	c^{alu}	$c^{sobriety}$
Percentage	54 %	35 %	20 %

As a reference scenario, the year 2015 for the city of Lyon and its hinterland (the metropole and the rest of the Rhone department) is modelled with actual statistics at the Lyon and at the national scale. This scenario does not return the number of vehicles purchased according to official sources in 2015, but the number of vehicles estimated to be purchased in 2015 from the modelling. The difference between the output of the model regarding the number of vehicles that should be purchased in 2015 and the real vehicle purchases according to official statistics of 2015 is of less than 3% for each type of vehicle when taking the calibration made with the data in the "reference scenario" from table 3. Thus, the assumptions of calculations of the prototype are relevant since they allow to describe a reality rather precisely. In addition to this base scenario, five others have been created to understand the implications of different strategies to change the urban mobility.

A first scenario looks at the impact of an all-electric switch from 0.91 to 100%, while maintaining the current modal split and vehicle characteristics. The results in table 4 show that for such a scenario the total weight of vehicles materials increase from 20%, while the mass of the 3 metals covered decreases from approximately 17%. This is due to the fact that electric vehicles are less demanding in steel while this metal makes up the majority of the car's body. Apart from steel, this scenario requires more aluminium and copper which quantity increase by respectively 72% and 662 %. This has direct consequences on the water necessary to manufacture these 3 metals since the water demand increases by 64 %, accounting for approximately 760 000 tons (or m3) of supplementary water required. The same effect is observed on GHG emissions required for the manufacture, i.e., an increase of 13%. These two increases are due mainly to the aluminium manufacturing process which requires a lot more water (up to a factor 75) than the process of steel, and releases more GHG.

A remarkable effect of the switch to electric is that the GHG emissions in usage phase have decrease by 85%, of approximately 1 Mt, thanks to a French electricity mix with very little direct carbon emissions. Exhaust emissions have also drastically decreased, since PM10 emissions have been cut by 65%. Yet, more than one third is still remaining because tires and brakes are still emitted in the same quantity, as the number of cars has not decreased. So, we see that although direct GHG and PM10 emissions have been reduced, copper consumption has exploded and aluminium consumption and water resources needed to manufacture these vehicles have increased significantly. Thus, this scenario would be more relevant from a climate and urban health perspective. However, it would also be less suiting from a water use

TABLE III. Different scenarios and their parameters

Scenarios	d (p.km/capita)	r_{bus} (%)	r_{car} (%)	n_{cars} (n/1000 capita)	$n_{bicycles}$ (n/1000 capita)	a_{cars} (years)	a_{bus} (years)	$a_{bicycles}$ (years)	r_{EV} (%)	$r_{substitution}$ (%)	$r_{sobriety}$ (%)
Reference scenario	12262	9,44	89	485	960	17	10	20	0.91	0	0
Electrified scenario	12262	9,44	89	485	960	17	10	20	100	0	0
High reduction in mass of cars	12262	9,44	89	485	960	17	10	20	0.91	100	100
High share of bus and bicycle hpv[a]	12262	47.2	44.5	485	960	17	10	20	0.91	0	0
High share of bus and bicycle lpv[b]	12262	47.2	44.5	100	960	17	10	20	0.91	0	0
Low impact scenario	6131	90	0	0	1000	17	15	30	100	0	0

[a.] "hpv" means "with high personal vehicle ownership"

[b.] "lpv" means "with low personal vehicle ownership"

perspective and from the new vulnerability created and linked to the copper supply.

A second scenario, the "High reduction in mass of cars" has been made to look at the consequences in a decline in the average mass of cars. As it might be expected, the total mass of materials decreases, by more than a factor two. As for the electrification scenario, the needs in water drastically increase from approximately 76% because of the substitution between steel and aluminium. This effect would not have been seen if only a sobriety reduction in mass would have been implemented. Concerning GHG and PM10, both emissions linked to manufacture decrease because of the overall lower demand for metals. Emissions linked to usage phase are stable because the reduction of pollutant emissions together with the mass of the vehicle has not yet been implemented. However, a reduction from 3 to 7% of energy requirements can be expected per 10% reduction in mass (Serrenho, Norman, and Allwood 2017). Overall, this scenario allows mainly for a reduction of material resource uses but increases water consumption due to a greater use of aluminium as it consumes between 10 and 75 times more water than steel, depending on whether it is a recycled material or not.

A third and a fourth scenarios are dedicated to modelling the increase in the modal share of public transport and cycling with however one assumption that differentiates the two: the rate of car ownership as well as its use. While in the first scenario, ownership of cars remains the same and only its use decreases, in the second scenario, both ownership of cars and its use decline. Assumptions for scenario one is that the use of both bicycles and buses is increased by a factor 5, and use of car is decreased by the corresponding amount of p.km.

For the scenario with low-rate ownership, car ownership is decreased approximately by a factor 5 and the use of car by a factor close to 4.5. The loss of travel by car is compensated by the increase of bus use by a factor 5 and a lot more of active mobility share in mobility.

The results of these two scenarios are drastically different. Indeed, while the amount of material required for the scenario with high level of car ownership is 14% higher than the base case of 2015, the scenario with low level of car ownerships allows to divide by a factor close to 2.6 the material requirements. Impacts of material manufactures such as water use and GHG and PM10 emissions follow the same trend: they are proportional to the quantity of materials required. However, due to a different ownership of cars, direct emissions are not the same since less cars are available to emit which implies increased carpooling at constant car travel demand. Therefore, the scenario with high modal share of public transport and high car ownership already decreases by a factor of around 2 direct emissions due to the greater efficiency of the bus in terms of emissions per passenger. But the second scenario goes further by diminishing direct GHG and PM10 emissions by a factor of almost 10 compared to the reference scenario. Thus, the rate of ownership of personal vehicles, as well as their use, is a determining factor both for the amount of material used and for direct emissions.

The last scenario, called the "low impact" scenario, pushes the use of buses and bicycles to the extreme, while reducing the global travel demand per capita. It is assumed that no one has a personal vehicle anymore, that the travel demand is halved and fulfilled to 90% by buses and that every inhabitant

TABLE IV. Results of the different scenarios

	Total weight of vehicles (t)	Mass of the 3 metals (t)	Mass of the 3 metals in Li-ion batteries (t)	Total water used for all metals (t)	Total GHG emitted by metals manufacture (t)	Total GHG emitted in usage phase (t)	Total PM10 emitted in usage phase (t)	Total PM10 emitted by metals manufacture (t)
Reference scenario	79176	56239	47	1203824	122487	1148366	213	73
Electrified scenario	94765	46937	5147	1971429	138767	171677	75	74
High reduction in mass of cars	49088	26151	47	2124817	97749	1148366	213	51
High share of bus and bicycle hpva	90005	64986	48	1458851	143282	579211	107	85
High share of bus and bicycle lpvb	30310	22807	11	588523	52251	123498	23	31
Low impact scenario	15064	10132	191	348622	25819	708	1	15

has a bicycle. Electrification of buses is 100% and the age of vehicles before being bought back is increased by 5 years for buses and 10 for bicycles. This scenario is roughly a lower limit of what can be done in terms of impacts on all aspects of materials, water use and emissions. The material and indirect impacts are divided by a factor more than 5 and direct emissions of GHG are divided by close to 4 orders of magnitude.

V. CONCLUSION

To elaborate a systemic participatory tool on urban mobility, a study of the modelling methodology related to the materials requirements of the urban transport system of Vienna by Gassner et. al, (2021) has been conducted. The objective and assumptions for the construction of our prototype aiming at raising awareness of some systemic problems of urban mobility has then been presented. Finally, first results of the prototype have been highlighted.

More precisely, the results have shown that a main parameter for reducing the impact of urban mobility is personal vehicle ownership, and that changing the modal share is not enough to have a beneficial effect on all indirect impacts. This must be combined with a reduction in vehicle mass, an extension of vehicle life and a reduction in the number of vehicles on the road. In addition, the prototype has shown that general trend towards electrification can indeed drastically reduce GHG and PM10 emissions in France, but poses more significant material and water use problems.

Several perspectives exist for the continuation of this work. Firstly, a technical improvement of the prototype is envisaged on several points to arrive at a more sophisticated tool. Secondly, multi-criteria assessment with social and economic fields is also envisaged, as environmental assessment alone is far from fully reflecting the situation. This can be seen in particular in the scenario of a drastic reduction of vehicles, which does not reflect the general trends and individual aspirations of our current society. Thirdly, the concrete use of this tool in a participative framework is envisaged with urban actors in real conditions.

The long-term objective of the authors is to generalize this approach to all sectors of the economy and to pinpoint systemic interactions between sectors and environmental pressures.

REFERENCES

[1] Association négaWatt, 2017. Scénario négaWatt 2017-2050 : hypothèses et résultats. https://negawatt.org/Scenario-negaWatt-2017-2050-hypotheses-et-resultats (accessed September 2, 2021)

[2] Banister, D. 2008. The sustainable mobility paradigm. *Transport Policy*, 15(2): 73–80

[3] Directorate-General for Internal Market, I., Bobba, S., Claudiu, P., et al., 2018. Report on critical raw materials and the circular economy. *Publications Office of the European Union.*

[4] Emberger, G. 2017. Low carbon transport strategy in Europe: A critical review. *International Journal of Sustainable Transportation*, 11(1): 31–35.

[5] Fragkias, M., Lobo, J., Strumsky, D., et al., 2013. Does Size Matter? Scaling of CO2 Emissions and U.S. Urban Areas. *PLoS One*, 8(6): e64727.

[6] Gassner, A., Lederer, J., and Fellner, J. 2020. Material stock development of the transport sector in the city of Vienna. *Journal of Industrial Ecology*, 24(6): 1364–1378

[7] Gassner, A., Lederer, J., Kovacic, G. et al., 2021. Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna. *Journal of Cleaner Production*, 311: 127591.

[8] Grosclaude, J.-Y., Rajendra, K. P., and Tubiana, L. 2014. *Regards sur la terre 2014, Dossier: Les promesses de l'innovation durable*. Armand Colin.

[9] Hernandez, M., Messagie, M., De Gennaro, M. et al., 2017. Resource depletion in an electric vehicle powertrain using different LCA impact methods. *Resources, Conservation and Recycling*, 120 : 119–130.

[10] Hickman, R., and Banister, D. 2015. *Transport, Climate Change and the City*. Routledge.

[11] Intergovernmental Panel on Climate Change (Ed.). 2007. Transport and its infrastructure. In *Climate Change 2007—Mitigation of Climate Change*: *Working Group III contribution to the Fourth Assessment Report of the IPCC*, 323–386. Cambridge Univ. Press.

[12] Jin, Y., Kim, J., and Guillaume, B. 2016. Review of critical material studies. *Resources, Conservation and Recycling*, 113, 77–87.

[13] Lamsal, L. N., Martin, R. V., Parrish, D. D., et al., N. A. 2013. Scaling Relationship for NO2 Pollution and Urban Population Size: A Satellite Perspective. Environmental Science & Technology, 47(14): 7855–7861.

[14] Nieuwenhuijsen, M. J. 2020. Urban and transport planning pathways to carbon neutral, liveable and healthy cities; A review of the current evidence. Environment International, 140: 105661.

[15] Rauzier E., Verzat B., Letz T., et al., 2020. Transition industrielle - Prospective énergie matière : vers un outil de modélisation des niveaux de production. https://librairie.ademe.fr/changement-climatique-et-energie/340-transition-industrielle-prospective-energie-matiere-vers-un-outil-de-modelisation-des-niveaux-de-production.html (accessed August 15, 2021)

[16] Seckler, D., Barker, R., and Amarasinghe, U. 1999. Water Scarcity in the Twenty-first Century. *International Journal of Water Resources Development*, 15(1–2): 29–42.

[17] Serrenho, A. C., Norman, J. B., and Allwood, J. M. 2017. The impact of reducing car weight on global emissions: The future fleet in Great Britain. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 375(2095): 20160364

[18] Zawieska, J., and Pieriegud, J. 2018. Smart city as a tool for sustainable mobility and transport decarbonisation. *Transport Policy*, 63: 39–50.

[i] The model can be downloaded via this link: http://team.inria.fr/steep/software/Urban_mobility_model_for_Lyon.ods