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Opinion paper

The next generation of urban MACCs. Reassessing the cost-effectiveness of urban mitigation options by integrating a systemic approach and social costs

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HIGHLIGHTS

- Local climate policies lack scientific understanding for prioritizing mitigation actions.
- We develop a method to evaluate cost-effectiveness of urban transportation actions.
- This method combines urban modeling and MACCs to inform urban planning.
- Abatement costs from its application to a mid-sized city are presented.
- The impact of the inclusion of co-benefits is analyzed.

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ABSTRACT

Many cities are implementing policies and climate action plans. Yet local climate policies suffer from a lack of scientific understanding and evaluation methods able to support the definition of efficient mitigation strategies. The purpose of this paper is to build on classical approaches in the energy policy field that exist at the national and international level to propose an urban MACCs methodology able to fulfill this lack and inform local debates. The methodology is an extension of static "expert-based" MACCs; it combines a land use transport integrated model and an abatement cost methodology that integrates co-benefits, and takes into account the spatial and systemic dimensions of cities. The methodology is implemented for the transportation sector of a mid-sized European city (Grenoble, France). Our results present the cost-effectiveness and political feasibility of several proposed measures. We find that the inclusion of co-benefits can profoundly change the cost-benefit assessment of transport mitigation options. Moreover we underline the key parameters determining the cost-effectiveness ranking of mitigation options. These urban MACCs aim to serve as a bridge between urban planning and mitigation policies and can thus contribute to strengthen and align sustainable and climate change agendas at the local level.

1. Introduction

1.1. A lack of knowledge to support local climate action plans

Climate action at the local level is widely recognized as vital for effective emissions mitigation efforts (GCEC et al., 2014). However a review of existing literature reveals that although we have a good understanding of the scale of the challenge at the local level and plenty of literature on "what to do", we do not have enough literature on "how to do it" (Rosenzweig et al., 2010; Dhakal and Shrestha, 2010). One particular area with limited research is assessing mitigation costs and benefits at the local or city level. Indeed, existing climate and energy research has generally been focused on the national level (Keirstead and Schulz, 2010). Debates on policy making at the national and international level rely on evaluation methods which do not adequately represent local systems, include local sectoral analysis or incorporate the spatial dimension of cities, even when they use macro modeling (Kahn Ribeiro et al., 2007; Clarke et al., 2014, GCEC, 2014). In this context, the IPCC identifies in local mitigation policies a "lack of scientific

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Abbreviations: LUTI model, land use transport integrated model; BRT, Bus rapid transit

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understanding of how cities can prioritize climate change mitigation strategies, local actions, investments, and policy responses that are locally relevant" (Seto et al., 2014, p. 78).

This lack of understanding is clear for the transport sector, which accounts for 19% of global energy use and 23% of energy related CO_2 emissions (International Energy Agency, 2009), and is the sector with the fastest increase in energy consumption and CO_2 emissions (Ajanovic et al., 2012). Yet the cost benefit analysis for climate initiatives in the urban transport sector is generally focused on technological solutions and not the urban dimension (Smoker et al., 2009a, 2009b; Kahn Ribeiro et al., 2007; Kok et al., 2011; Sims et al., 2014).[1] This limits our understanding of effective local mitigation policies since the spatial organization of a city determines the level of GHG emissions and the optimal mitigation options (Newman and Kenworthy, 1998; Lefèvre, 2008). Several noteworthy abatement cost studies go further and try to consider the urban transport sector as a spatial system with different transport modes and interactions with land use (Wright and Fulton, 2005; Cambridge Systematics, 2009; Silva-Send et al., 2013; Yang et al., 2015). Nevertheless these studies mostly rely on exogenous hypotheses to evaluate the effect of the urban policies[2] and do not effectively simulate and test them. Thus to improve our understanding of effective mitigation policies for the urban transportation sector, energy analysis should be better linked to urban planning, notably through urban modeling. This is the goal of our study, along with other recent studies that also bridge urban policies and carbon pricing analysis through modeling (Avner et al., 2014; Grazi and Waisman, 2015).

1.2. Two specific challenges faced by climate action plans

Thousands of cities in both the developed and the developing world have announced their Climate Action Plans and have signed up to voluntary frameworks to develop their mitigation strategy (Seto et al. 2014, p. 8; Reckien et al., 2013; Millard-Ball, 2012). These plans are important to promote climate action, coordinate with other policies, and identify efficient strategies, but they also face several challenges.

First, these plans are not yet well connected to important urban planning policies such as land use planning or transport planning (Yalcin and Lefèvre, 2012), instead, they focus on individual actions and energy efficiency, ignoring the lasting changes that occur in a city because of land use policies or other cross-sectoral policies (Reckien et al., 2013; Seto et al., 2014). Consequently, the climate action plans generally exist in isolation as standalone documents and are seldom integrated into the larger urban planning framework. The challenge is to mainstream climate action plans into the rest of urban policy and planning (Viguié and Hallegatte, 2012).

However tools exist to overcome this difficulty and those identified in Section 1.1 and to take the urban spatial dimension into account. Indeed, examples show the interest of urban modeling tools to evaluate energy policies at the local level through land use transport integrated models (Lefèvre, 2008; Mitchell et al., 2011), complementary to energy models. LUTI models were developed to inform urban planning (Wegener, 1994; Batty, 2009). All LUTI models represent the evolution of different markets[3] but differ in terms of modeling theories and methods, e.g. aggregated or agent based, based on market equilibrium or dynamic processes (Jin and Wegener, 2013). Contrary to classical and widely used traffic models, which consider the urban structure as an exogenous input to simulate the mobility system, LUTI models are able to inform long term strategies because they simulate both the land use system and the transport system, as well as their interactions (Fig. 3).

Lefèvre (2008) uses the TRANUS model to analyze the long term energy consumption of urban transportation in Bangalore. Mitchell et al. (2011) use the Meplan model to assess the energy and climate impacts of several urban trajectories considering transportation, dwellings and commercial spaces in three regions of the UK.

A second obstacle relates to the lack of understanding of how cities can prioritize mitigation actions. As Lazarus et al. (2013) observe, although cities have ambitious long-term emissions reduction goals, "few have articulated how to reach them", moreover "targets are often arbitrary or aspirational, and reflect neither mitigation potential nor implementation" (Seto et al., 2014, p. 71). In the context of limited resources, which makes it necessary for cities to carefully select and sequence their actions to meet their emissions targets, a cost-effectiveness approach would be useful. However, while literature on national and international climate policies places a large emphasis on economic analysis, the literature on local climate action plans, as well as the plans themselves, say little about economic methodology or cost-benefit analysis, and instead emphasize other aspects (stakeholder support, communication) (Bertoldi et al., 2009; Wheeler, 2008[4]; Reckien et al., 2013). Currently the most common methodologies used to support Climate Action Plans are benchmarking, planning process guides and prospective analysis, which identify possible policies and their potential contribution to mitigation targets, but do not support the necessary prioritization of actions (Lazarus et al., 2013; Lechtenböhmer et al., 2009; Gomi et al., 2010).

The adaptation of the well-known Marginal Abatement Cost Curve (MACC) methodology at the local level responds to this gap. MACCs are widely used for the analysis of national and international mitigation policies because they are seen as a convenient and simple way to represent the cost effectiveness of different measures and to identify a cost-efficient strategy (Kesicki and Ekins, 2012; Wächter, 2013; Vogt-Schilb and Hallegatte, 2014). Nevertheless, few applications have been made at the city level (McKinsey, 2008; World Bank, 2013).

The McKinsey (2008) study of London's climate strategy was an interesting first local application of this method. With this methodology, the costs and mitigation potential of each measure are assessed individually and then ranked in order to create a cost-effective sequence of actions. However, this first generation reveals a few limitations of the MACCs methodology for urban analysis. Travel time and air pollution, two key characteristics of urban transport are not taken into account as co-benefits. The sum of the measures does not constitute a complete urban scenario to evaluate but rather a technical roadmap; the mitigation policies are not integrated with other urban policies, which limits the potential dialog with urban planners. Indeed, none of the measures considered in the McKinsey study have an impact on the urban system because the study only considers technical issues (Fig. 1), whereas cities have little power over technological issues as they mainly fall under national control. The World Bank (2012) observes that

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[1] For example in WG3, Chapter 8 Transport (8.6 Costs and potentials, p. 32), there is no mention of modal shift for cost assessment, and the authors observe that "The number of studies assessing potential future GHG reductions from energy intensity gains and use of low-carbon fuels is larger than those assessing mitigation potentials and cost from transport activity, structural change and modal shift, since they are highly variable by location and background conditions."

[2] For example, a study will make the assumption, based on literature or policies targets, that if land use policies or transit investment are implemented, the vehicle miles traveled will decrease of X%. With an urban modeling one can effectively simulate these policies and evaluate the effect on vehicle miles traveled.

[3] Land, housing, transport, labor.

[4] On the 64 states, large cities and small cities selected for his analysis of climate change plans in the US, only 15 have a comprehensive cost estimation of the measures included in their plans. Among the 18 large cities, none has a comprehensive estimation of costs, 2 on 17 for small cities plan.

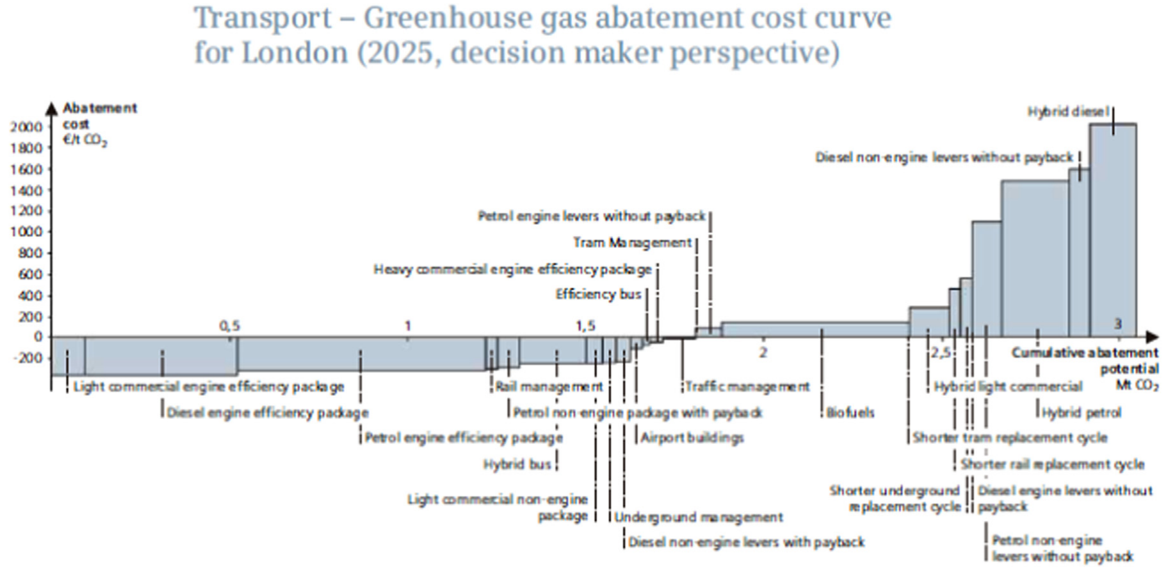

Fig. 1. The transport MACC for London (McKinsey, 2008).

the McKinsey methodology for MACCs leaves aside "other non-technology" GHG abatement options, such as urban form, public transport, and "household and citizen behavior changes", yet "such interventions can often be the most transformative ones a city can undertake." Moreover, interactions between various transportation measures and with the land use system are not taken into account despite their strong influence and lasting impact on urban structure. Evaluating these additional factors and interactions would require a methodology, such as an urban modeling tool, able to represent the urban system.

The World Bank study for the Changning district in Shanghai (2013), which also uses MACCs, is another example of the limitations of the MACCs methodology at the local level. The geographic scale of the district (3 km^2) is not significant enough to analyze transport and urban planning policies (transport is less than 1% of energy consumption in the study area). Additionally, the transportation strategies are limited in scope as much of the attention is directed at retrofitting policies.

The first generation of urban MACCs was a promising move towards economic analysis of local mitigation policies, making available tools formerly used exclusively at the national level. However, due to methodological limitations in terms of representation of the urban system, the approach used by McKinsey and the World Bank cannot provide a reliable assessment of local costs and potentials for the full range of urban policies, and fails to inform urban planning. It is therefore essential to develop and popularize a methodology that is adapted to local policy making needs.

1.3. *Objectives and methodology*

This paper attempts to contribute to overcome the two challenges presented previously from a methodological perspective, by presenting a new way to calculate MACCs curves, based on a LUTI model, and which is better adapted to the urban level. This paper[5] will focus on the transport and land use dimension of local action plans, which is, as stated in the literature review in Section 1.1, a critical sector for methodological improvement of abatement cost assessment. Moreover it is the urban transport sector that suffers the most from a static urban MACCs approach. Its application to a mid-sized European city provides results in terms of abatement costs and emissions savings for different policy mixes and urban scenarios.

We begin Section 2 with a more detailed analysis of MACCs principles and limitations; we then present our methodology and its application on one case study: Grenoble, France. In Section 3 we present and discuss the results of this application and the policy implications. We will conclude our paper in Section 4.

2. A new methodology for urban MACCs

2.1. *MACCs principles and limitations*

2.1.1. *Different types of MACCs*

MACCs are employed using two different approaches. The static "expert-based" approach assesses the measures individually based on several assumptions and an expert vision. The measures are ranked from least expensive to most expensive on the curve (Almihoub et al., 2013). This approach is easy to read and comprehend; it does not require understanding a complex model, moreover the "abatement potential of various measures can be linked to a single mitigation option without any ambiguity" (Almihoub et al., 2013). This simple way to present cost is particularly interesting in the framework of climate action plans to support discussion and debate between different stakeholders who may have a lower level of expertize in energy economics than at the national level. However, this approach neglects potential linkages with other parts of the economic system such as the impact of energy policy on the energy price. This makes it difficult to evaluate the interaction between different measures when they are assessed on an individual level, raising the risk of inconsistencies.

The second, dynamic "model derived" approach, is based either on a top-down model representing the whole economy or on an engineering-oriented bottom-up model with a precise representation of energy systems (Almihoub et al., 2013). With this approach, the MACCs are not identified via a portfolio of technical measures, but rather by the price of GHG emissions required to achieve a certain emissions trajectory (Kesicki, 2011). The strength of such an approach is to take into account interactions between measures and to maintain a consistent baseline between measures. Its weakness lies in the difficulty to isolate individual

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[5] This paper is based on a research project (AETIC), aimed at providing economic tools to support the elaboration of cost-effective climate action plans for transport, local energy system (heat network) and building sectors.

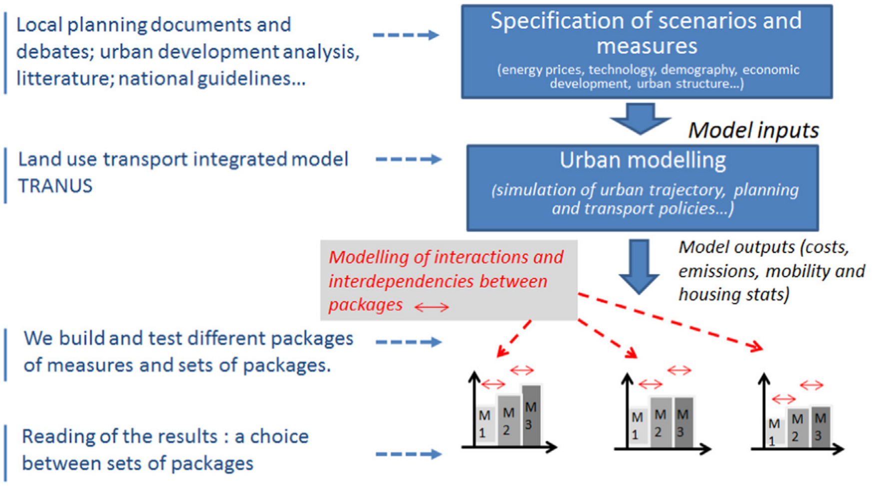

Fig. 2. Overview of our methodology (authors).

technical solutions employed to achieve an emissions reduction (Kesicki, 2011) and analyze their respective policy application.[6] This modeling approach would be interesting for urban planning, which has precisely to take into account interactions in the urban systems.

At the urban level, only the static "expert-based" approach is used (McKinsey, 2008, World Bank, 2013), with the objective to consider the perspective of local decision makers finding the suitable mitigation strategy to meet their abatement targets. The classical bottom-up and top-down model approaches for MACCs, by contrast, are exclusively available and applied at the national and international levels.

2.1.2. Limitations of MACCs

The visual simplicity of MACCs hides a high level of complexity. In order to sum up an entire trajectory and multiple impacts of a measure implementation into a single figure of abatement cost, MACCs require strong assumptions and simplifications, and as stated earlier, have several limitations. These limitations hold for MACCs at the national or international level, but they are also significant if we consider the application of MACCs to evaluate local climate action plans. They are described below: (a), (b), (c) and (d)[7] correspond to both dynamic model-derived and static expert-based MACCs; (e) and (f) correspond primarily to static MACCs since dynamic approaches via modeling can help overcome these issues.

a) *Cost perimeter:* there is a strong focus on technical costs (Kesicki and Ekins, 2012) and the approach neglects other costs such as distributional impacts (Vogt-Schilb and Hallegatte, 2011), the policy implementation cost and transaction costs for households or policy makers (Kesicki and Ekins, 2012). The exclusion of these costs explains the existence of negative abatement costs in many MACCs.
b) *Co-benefits:* MACCs often ignore co-benefits like energy security, air pollution reduction and fuel poverty (Kesicki and Ekins, 2012; Vogt-Schilb and Hallegatte, 2011). The correct estimation and inclusion of co-benefits can decrease the abatement cost as expressed by the MACCs.
c) *Transparency:* MACCs studies do not always clearly specify all of their assumptions and rarely perform sensitivity analysis to hypothesis variation (Ekins et al., 2011). These weaknesses can decrease the utility of MACCs as a policy assessment tool and thus their use in the decision making process.
d) *Lack of a spatial dimension:* due to their focus on socio-economic and energy systems, models used for long term energy planning at the national and international level poorly represent the spatial dimension of activities and the role of infrastructure in the spatial organization of economies. For example, in the IPCC fourth and fifth assessment reports, as well as for the French carbon price assessment, the studies to determine long term carbon values are based on tools that do not represent properly the local level (Kahn Ribeiro et al., 2007; Clarke et al., 2014; Crassous, 2009). Without any modeling, expert-based MACCs are even less able to take into account this dimension.
e) *Interactions:* for static expert-based MACCs, the results are based on the individual assessment of measures and not on the basis of a dynamic modeling system. Hence, there is a risk that MACCs do not capture intersectoral and intrasectoral interactions that occur as a result of abatement policies (Ekins et al., 2011; Vogt-Schilb and Hallegatte, 2011).
f) *Temporal dimension:* expert-based MACCs generally display the mitigation potential for only one year and this raises important intertemporal issues (Kesicki and Ekins, 2012; Vogt-Schilb and Hallegatte, 2011) show that path dependency and inertia are generally not taken into account whereas they can largely modify the ranking between measures. Discounting has a first order impact on the results and is recognized as an important issue that must be carefully examined.

2.2. LUTI modeling for urban MACCs

The limitations that we identified in previous sections led us to design a new MACC approach, which is an extension of the static expert-based MACC with a model-derived approach, based on a land use transport interaction modeling tool (see Fig. 2 for a presentation of the methodology). We use the Land-Use Transport Interaction (LUTI) model TRANUS to run three contrasting urban trajectories between 2010 and 2030 (urban concentration, urban sprawl and polycentric development), in which we test different mitigation strategies. We use the outputs of the model to build the MACCs. To simplify our analysis, these scenarios are based on the

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[6] In terms of decision making, the policymaker has not a choice between individual measures but rather between whole scenarios.

[7] These 4 limitations are equally valid for model based scenario analysis approaches.

same context (energy prices, demographic and economic evolutions)[8] and in each scenario we produce only one MACC.

We begin the presentation of our methodology with the model, since it will have implications on the construction of our MACCs, which is detailed in a later section.

2.2.1. LUTI model to support MACCs

Our analysis of the limitations of MACCs shows that there is a need for a modeling tool able to properly represent the urban system, and we showed in Section 1.2 that LUTI models can be interesting tools for energy assessment. With this tool we can represent the systemic dimension of mitigation policies in the urban transport sector in the MACCs and explore future urban development. Indeed, spatial dynamics[9] cannot be taken only as an input but should be explored with adequate methodology. Moreover in order to make the assessment of the different sectors coherent, they must be based on shared urban scenarios.

We briefly introduced the use of LUTI models for energy assessment in Section 1.2. To sum up, LUTI models can:

1. Represent both land use and the transport system in order to simulate urban pathways. The land use model simulates where households and economic activities locate according to accessibility, land and real estate prices, regulations and taxes. The transport model uses as an input the demand for mobility deduced from the urban structure simulated in the land use model, and then simulates the mode and path used by each type of agent, based on the quality of service of the different transport offers. A loop connects the accessibilities calculated in the transport model to the land use model.
2. Simulate a prospective scenario (generally between 10 and 30 years) with evolution of the context and under different policies for land use and transport (investment, tax, regulation policies).
3. Evaluate costs, emissions, urban system indicators (urban form evolution, housing needs, modal share, distance traveled, travel time…) as a consequence of the implementation of different measures and scenarios.
4. Evaluate energy performance through the well-known ASIF framework used to represent energy consumption and emissions in transport (Schipper et al., 2000) and decomposed in Fig. 3. A typical LUTI model can represent the evolution of A and S and give inputs for U (public transport capacity utilization) and O (level of road congestion), while E and F are exogenous inputs. This makes them complementary to energy models, which can inform the global energy situation (energy prices, penetration of biofuels…) and support the analysis at the local level (value of F).

2.2.2. The TRANUS model

Among the various LUTI models we have chosen TRANUS (De la Barra, 1989) because it fulfills both the theoretical relevance and operational requirements (Lefèvre, 2008). As with other LUTI models, it is based on the work of Alonso (1964) and Lowry (1964) on spatial microeconomics and gravity models. Moreover, it is one of the most widely used LUTI models (EPA, 2000) and it integrates a sophisticated transport model (Iacono et al., 2008). Thus this model can fulfill our need for a practical tool able to help cities for the definition of their climate policies. Fig. 4 presents a general architecture of the TRANUS model. Each sub-model is based on an iterative algorithm, that seeks an equilibrium for each sector and zone of the model in terms of price and production. The long and time-consuming process of calibration requires the adjustment of both the transport and land-use sub-models simultaneously. The discrete choice approach (McFadden, 1973) is used for both the land use and transport models. Our work is the first application of TRANUS[10] in France.

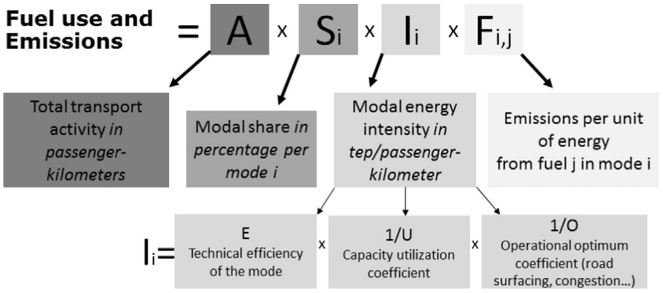

Fig. 3. ASIF decomposition (based on Schipper et al. (2000)).

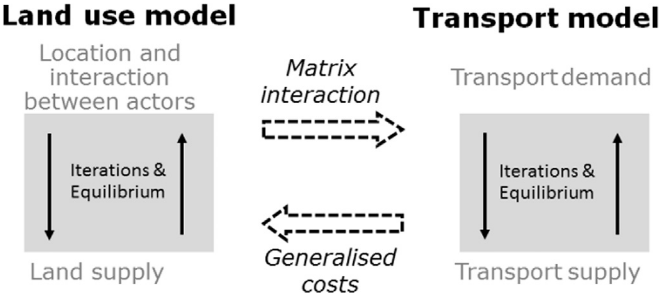

Fig. 4. TRANUS model architecture (Authors).

2.3. An extension of static “expert-based” MACCs for urban analysis

Our proposed methodology combines expert-based MACCs, in which we estimate cost and benefits of specific measures, with a LUTI model (TRANUS). Modeling helps to overcome some of the limitations of the first generation of urban MACCs (Section 1.2) and MACCs in general (Section 2.2) for the analysis of mitigation policies at the urban level, since it allows us to:

I. Widen the perimeter for costs and co-benefits with air pollution, travel time, travel costs for households, job attractiveness, distributional impacts, based on the simulation of the urban system.
II. Take into account the interaction between transport measures (for example between an urban toll and a new Bus Rapid Transit), and between land use and transport measures (limitation of urban sprawl and park-and-ride implementation).
III. Take into account part of the inertia of the urban system and the path dependency when an investment impacts the urban structure in the simulation period.
IV. Test a whole range of measures (urban planning, regulation, tax, investment in all modes) and not only technological ones.
V. Ensure a consistent baseline[11] for every measure.

As opposed to a traditional MACCs-derived model (bottom-up or top-down), the model does not automatically choose mitigation options based on the CO_2 price.[12] There is no optimization of the

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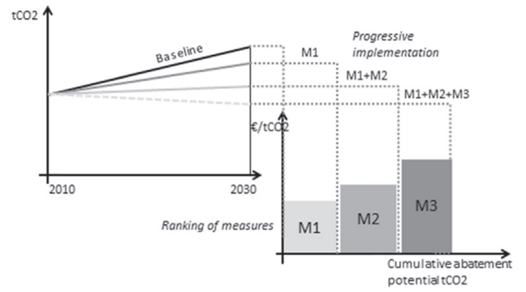
[8] Because decided at the national level, several mitigation policies are already integrated into the baseline scenario: indeed we consider that the business as usual scenario would see a certain diffusion of electric and plug in hybrid vehicle and an increase of ICE efficiency.

[9] i.e. Evolution of the urban shape.

[10] For more details on LUTI model and TRANUS see Lefèvre (2008) and Saujot (2013).

[11] Only for the urban dimension and not the global energy system, for which a computable general equilibrium model would be necessary.

[12] Evidently, the model is not able to create by itself a new tramway line for example.



Abatement cost (Measure 1) = $\left(\sum_n \mathit{Costs}_n/(1+r)^n\right) / \left(\sum_n \mathit{Emissions\ savings}_n/(1+r)^n\right)$ €/tCO_2

Costs$_n$*(Measure 1) equals the cost implied by the implementation of the measure in the year n, the potential co-benefits (local air pollution for example) and money savings (lower transport expense for household for example), by comparison with a scenario without this measure.*

Fig. 5. How to build a MACC with a bottom-up method (authors).

cost of climate policies in the model, as can be achieved in a bottom-up model. In our work, a set of relevant policies is defined ex ante with an expert-based approach and then tested with the model.

2.3.1. *Construction of MACCs and interactions between measures*

As explained in Fig. 5, building a MACC requires testing each measure to calculate its costs and benefits. Once the cost-benefit analysis is complete, different options can be ranked on the basis of their relative costs. However it is impossible to run the same analysis for urban transport because of the linkages between measures. For example, the abatement costs and benefits of a new bus rapid transit (BRT) line, shown as M1 in Fig. 5, will depend on alternative public transport supply, parking policies, and urban planning decisions. Therefore, not only does this prevent us from isolating an individual measure for analysis, but it also means that any analysis of a climate strategy in the urban transport sector as a simple sum of individual measures would ignore the essential interdependencies between measures and thus incorrectly evaluate total benefits and costs. This is all the more important given that real policies are often packages of measures.

To take into account the systemic dimension of cities, we use packages of measures (for example BRT and parking policies) and we estimate the incremental effect of additional packages of measures. By this manner, we can evaluate the interaction between multiple packages of mitigation actions (for example if we implement a tramway after an urban toll, its potential is likely to be higher). In other words, in the Fig. 5, the M3 box represents the abatement cost and potential of this package in a world where MI and M2 have already been implemented.

Finally we have to decide how we build the packages of measures we want to test. Mitigation policies in transport are part of larger urban policies, and we must therefore choose a coherent set of packages taking into account other constraints beyond abatement costs, such as political and financial feasibility or consistency between the measures and the urban development plan. In other words, we have to use several criteria in addition to the cost effectiveness criteria to build relevant set of packages (Table 3 provides an illustration of this approach). As a consequence, the possibility exists of non-growing cost curves as opposed to usual MACCs curves. This is also the consequence of the different cost perimeters: hierarchy can change depending on the type of cost and co-benefits considered in the calculus.

The way our methodology considers packages and interactions makes it possible to combine the assessment of technological interventions and urban policies within the same framework. Moreover, our methodology would make it possible to analyze and optimize policy mixes[13] (both construction of packages and of the set of packages), which is crucial in order to identify efficient and politically acceptable measures at the local level (Viguié and Hallegatte, 2012). Nevertheless, the interface between MACCs and LUTI should be improved to make this optimization easier to perform, and more useful for stakeholder discussions on policy mixes.

2.3.2. *Social costs and co-benefits*

At the local level, an effective should account for all the co-benefits of climate actions. In classical cost-benefit analysis for transport infrastructure, social costs and benefits (time, pollution, mobility cost for users) are determinant for the choice of the project. Thus it is important to take these costs and benefits into account when we consider mitigation measures in the mobility sector, since the political feasibility as well as local support for these kinds of measures will depend on them. Moreover, as the IPCC (Sims et al., 2014, p. 5)[14] observes, by including co-benefits, urban planning can offset a greater part of the mitigation costs and can thus strengthen climate policies at the local level.

In order to ensure that the model covers a breadth of costs and co-benefits, we take into account the total cost of transport for households both when using a car (fuel, purchase, maintenance, and insurance) or public transport. On the public side we consider the investment by the public authority as well as the public transport operational costs and revenues. We estimate the co-benefits using TRANUS, which includes the cost of travel and waiting time (time value based on official French guidelines (SETRA, 2010)), and the cost of air and noise pollution. We calculate the cost of local pollution and noise as a function of *vehicle x km* depending on the urban density, also based on French guidelines (Boiteux, 2001; SETRA, 2010). CO_2 emissions are evaluated with a polynomial function of speed since TRANUS gives the speed and number of vehicles for each link of the transport network. We use local data to describe the vehicle fleet characteristics in terms of pollution (EURO 1, 2 , 3, 4 and 5, diesel or gasoline) and emissions functions from French and European state-of-the-art studies (Joumard, et al., 2007; Ademe, 2007; Predit, 2007) to calculate emissions. In the baseline, we assume a progressive improvement of the whole fleet.

> Emissions CO_2 (g/veh km)$=a0+a1V+a2V^2+a3V3+a4V4+a5V5$, where ai are averages representing the Grenoble area car pool features.

In the case of an urban toll, we also calculate the welfare loss due to constraints on modal switching and evaluate the distributional impacts of the toll. In this first exploratory work we have not been able to integrate housing costs for households and businesses, nor urbanization costs for public authorities into the abatement cost.

2.3.3. *Abatement cost and discounting*

The choice of a proper discount rate is crucial since it has a first order impact on the abatement costs and could lead to incorrect

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[13] We partially performed this during the preparatory work to create the set of measures used in this article, with back and forth between modeling and definition of the measures. This work could not be presented in this article partially for lack of space but also because it was a preparatory step not fully documented to be presented precisely.

[14] "Infrastructure investments ($/$tCO_2$ avoided) may appear expensive at the margin, but sustainable urban planning and related policies can gain support when co-benefits, such as improved health and accessibility, can be shown to offset some or all of the mitigation costs. *(medium evidence, medium agreement)*".

estimation of the abatement cost. This is a major explanation of negative abatement cost (Kesicki and Ekins, 2012). In line with the existing MACCs used at the urban level, our point of departure to calculate abatement cost is the behavior of a company selling kWh or any local actor selling its emissions savings in a carbon market, i.e. we consider that the climate plan produces CO_2 abatements. Thus the abatement cost is defined as the sum of discounted costs of a measure (adjusting for its lifetime) divided by the sum of discounted benefits (i.e. emissions savings) during the same period.

We have chosen a 20-year period for our cost-benefit analysis (2010–2030), which is coherent with the climate mitigation policies horizon but also with the period considered by the transport plan and the regional plan in Grenoble. The 20 year horizon mismatches with some urban investments that have costs and benefits for a longer period. For example, the infrastructure for a tramway may last over 40 years. Therefore we calculated a residual value for long term infrastructure and included it in our calculations. In line with the nature of a local climate action plan, we evaluate from the perspective of policy makers and therefore use the official French discount rate used for public investments (4%) for our calculations. This discount rate provides a realistic basis on which to determine what should be done in climate action plans. Yet, there is evidence that suggests that households use subjective discount rates that vary widely and are unlikely to be equal to the public rate (Enzler et al., 2014; Greene, 2010).[15] Analyzing options with the public rate alone can thus underestimate the real cost for households.

Therefore, we run a sensitivity test with another discount rate, better adapted for household investment, as an illustration. This rate [20%] was selected on the basis of recent literature which estimates the subjective discount rate in the population (Enzler et al., 2014) specifically for fuel saving and automobiles (Greene, 2010; Buenestado, 2013). In transport, the discount rate impacts the cost for car use and not for public transport. Car buyers pay upfront for a future supply of mobility service, contrary to pay-per-use public transport service. Drivers thus invest in future kilometers and a higher discount rate will imply a higher cost per kilometer. Conversely public transport does not imply an investment from households.

2.3.4. *Key assumptions and baseline*

The following table contributes to the transparency of the analysis since it summarizes the key assumptions of the modeling exercise, i.e the assumptions that will have the most significant impact on the results and that should always be made transparent for the discussion to be productive (Table 1).

Table 1
Summary of the key assumptions for the simulation and the baseline scenario.

- **Demographic and economic growth**: [0.6% /year; 0.45% /year];
- **Deployment of electric and plug-in hybrid vehicle**: they will represent 18% of car.km in 2030 in the baseline.
- **Energy prices** are key parameters since higher energy prices will diminish abatement costs: our assumption (based on POLES modeling) is a *60% increase for fuel between 2010 and 2030. Price in 2010 in €/kWh with tax: 0.11 for diesel fuel and 0.14 for gasoline.*
- **Discount rate**: as discussed in Section 3.2. Our assumption is 4% and we do a sensitivity analysis for households at 20%.
- **Emissions perimeter**: We only consider functioning emissions in this article but additional life-cycle analyses have been made. For example, for electric vehicles in the French context, taking into account battery manufacturing would add around 20–30 gCO2/VKT and would increase abatement costs by around 15–20% over the 2010–2030 period.
- **Technological assumptions**: the main assumption concerns the decrease of battery costs: [760, 500, 400, 350 €/kWh] between 2015 and 2030.
- **Efficiency of internal combustion engin**e: based on evolutions in the French market, we assume an 11% consumption reduction between 2010 and 2030 for the car fleet.
- **Operating cost of public transport**: between 0.3% and 0.5% increase per year depending on the scenario.
- **Time value for 2010–2030:** generally time value increases over time with revenue. To avoid interfering with our mitigation policies analysis and add uncertainties concerning the whole economy evolution, we do not use such an assumption.
- **Car ownership rate**: to evaluate the monetary savings of modal shift, a hypothesis mustbe developed on the evolution of car ownership (what proportion of agents react to an increase in consumption of public transport by reducing car usage vs. selling their respective cars outright). We assume that the average reduction in car-related costs in the case of a modal shift is one third of the maximum potential savings (i.e. selling the car outright).
- **Waiting time**: the literature generally considers a penalty cost for waiting representing discomfort (a factor of between 1.5 and 2.5). As a result, a policy that increases the use of public transport will necessarily increase waiting time and thus costs even if the global travel time is unchanged. Yet conditions for waiting when commuting have improved thanks to investment in stations (including real time information) and smart phone diffusion; these innovations call the penalization of waiting time into question. To evaluate how results would change, we perform tests with and without a penalization of waiting time equal to a factor of 2. Our analysis joins other discussions in the literature on the contradictions and paradoxes of saving travel times in urban policies (Banister, 2008; Metz, 2008).

2.3.5. *Action plan and scenarios*

We tested a whole range of measures: investment in public transport, regulation (urban tolls), investment by households (fuel efficient electric vehicle), and behavioral evolutions (carpooling). A description of the measures tested in the three scenarios is provided in Table 2. Table 3 describes the rationale for the choice of the set of measures for the first scenario, the assumptions and inputs for the model, and the main results. It is an illustration of the value added of the methodology for understanding the urban system and the impacts of each package.

2.3.6. *The case study: Grenoble, France*

Grenoble is a typical mid-sized city in Europe, ranking 70th of the 99 major European metropolitan areas[16]. Our interest in Grenoble is based on a number of factors: urban planning in Grenoble is very ambitious with respect to environmental issues and the city has been a pioneer in adopting climate action; heavy public transport investments have been made in the last decades to support sustainable transportation. The Grenoble case is also characterized by significant constraints: the city faces a critical level of local pollution due to its geographic situation, high levels of local public debt (thus a strong need for cost efficient investment in transport) and significant urban sprawl. Grenoble is therefore a pertinent case study to test our methodology.

The study considers the urban region, which covers 3700 km², which includes the Grenoble agglomeration of 310 km², which itself represents 54% of the 730,000 inhabitants and 65% of total jobs. The rest of the study area includes suburban and rural areas with lower densities, as we can see in Fig. 6. In practice, we consider two subsets of the study area: one corresponding to the climate action plan (Grenoble agglomeration authority, 310 km²), the other corresponding to the urban region falling under the urban planning document (3700 km²).

We use TRANUS to run three urban scenarios based on the local urban planning document (2010–2030). We analyzed the planning

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[15] Higher discount rate explains why « low hanging fruits » - measures with negative abatement cost -, are not implemented by households (for example concerning housing refurbishment). It represents market failure, but also access to credit and risk perception.

[16] http://demographia.com/db-eurmetro.pdf (last access 21.01.15).

Table 2
Sets of measures for our 3 scenarios (more detailed are available in Saujot (2013)).

	Main measure of the Package 1	Main measure of the Package 2	Main measure of the Package 3	Main measure of the Package 4	Main measure of the Package 5
Set for S1 Urban Concentration	BRT	Urban toll	Tramway network expansion	Electric and plug-in hybrid vehicle	Car sharing
Set for S2 Urban sprawl	Urban toll	Electric and plug-in hybrid vehicle	Tramway network expansion	Inter-urban public transport	Car sharing
Set for S3 Polycentric development	Urban toll	Tramway network expansion	Electric and plug-in hybrid vehicle	Inter-urban public transport	Car sharing

Table 3
Set and packages of measures description for the scenario Urban Concentration.

Urban Concentration Scenario		
Why this ranking?	**Assumptions**	**Results, with additional impact of each measure**
M1: Bus Rapid Transit (dedicated lanes), Parking Policies and Non-Motorized Modes Planning		
Improvement of bus already worked well.	*Modeling*: improvement of bus perception (between bus and tramway).	*Mobility*: increased bus speed by 2 km/h, Lower congestion for cars;
To reinforce public transport is coherent with the densification scenario. Lower investment than tramway. High potential to make bus more attractive	*Costs*: investment of 85M€: 5M€/km for bus lanes (18.5 km) ; new buses.	Bus supply: +16% veh.km, bus demand +37% pass.km *Urban development*: 1,300 jobs and 2,000 more households in the agglomeration
M1+**M2**: Urban Toll and Parking Policies		
Cons: low acceptability, M1 improves it. *Pros:* high reduction potential for CO2 and local pollutants (key issue in Grenoble).	*Modeling*: zone inside the beltway; 4 €/day to use a car for all users	*Mobility*: decrease of cars in the zone from 105,000 to 57,000. Global increase of travels time. No transfer of traffic on the belt-way. Speed: +3 km/h in the agglomeration.
To provide financing for further investment in public transport. To reduce congestion.	*Costs*: operating and investment (15 years return)= 25 M€/year	Revenue per year: 100 M€ *Urban development*: reorganization of jobs and households but globally positive for the agglomeration in terms of attractiveness.
M1+*M2*+**M3**: Tramway Network Extension and Transit Oriented Development (TOD)		
Cons: finance limits.	*Modeling*: 13 km of new tramway (initial network of 43 km). Special planning instrument for TOD: dense development along tramway lines. Higher speed (2 km/h)	*Mobility*: offer+32% veh.km, demand+60 pass.km
Pros: coherent with the densification scenario and the growth of the first belt not yet served by tramway. It follows the trend of extension of the tramway network. Commitment to use the revenue of the urban toll for public transport.	*Costs*: investment of 144 M€ in 2015 and 135 M€ en 2020	Competition with bus. Not enough to compensate the impact of urban toll. *Urban development*: more jobs in the agglomeration (1800).
M1+*M2*+*M3*+**M4:** Electric and Hybrid Plug-In Vehicle, Charging Infrastructure and Urban Toll/Parking Incentives		
Cons: Context of decreasing space for cars on the territory; makes more complex the integration of charging points and less efficient the incentives to households. Cost of the subsidy for low revenue households.	*Costs:* €10M for infrastructure and charging management.	*Mobility*: 6,000 low carbon vehicle on a total fleet of 160,000 cars.
Pros: tool important for suburbs. Promising technology.	*Hypothesis:* decrease of battery cost [760, 500, 400, 350 €/kWh] between 2015 and 2030; optimized car (e.g.: Prius); 35.5 gCO2/km.	*Urban development*: no significant effect because of substitution with ICE car.
M1+*M2*+*M3*+*M4*+**M5**: Carpooling		
Cons: high uncertainty on the ability of public investment to trigger a collective dynamic of car-sharing. Behavioral obstacle. Public expertize still to develop.	*Modeling:* increase from 1.3 to 1.5 pers/car between 2010 and 2030.	*Mobility*: 18 000 car-sharing users, i.e around 5% of total car user.
Pro: high potential, low cost	*Costs*: 50 car-sharing zones for 1000 spaces, Studies, subsidies to incentive car-sharing, advertising campaign. Total €3.5 M.	Speed: +2 km/h in agglomeration. Decrease of public transport frequentation (−5%) *Urban development*: no significant effects on population but helps growth of jobs outside the agglomeration.

debates and the different local policies (housing, land, transportation, business) to identify sets of assumptions and to define our three scenarios which were discussed with the local authorities. In the first scenario (S1), *Urban concentration*, population and job growth mainly happens in the densest area, i.e. the agglomeration. In the second scenario (S2), *Urban sprawl*, population growth is the largest in peripheral areas, whereas jobs growth is shared between the agglomeration and the rest of the area. In a third scenario (S3),

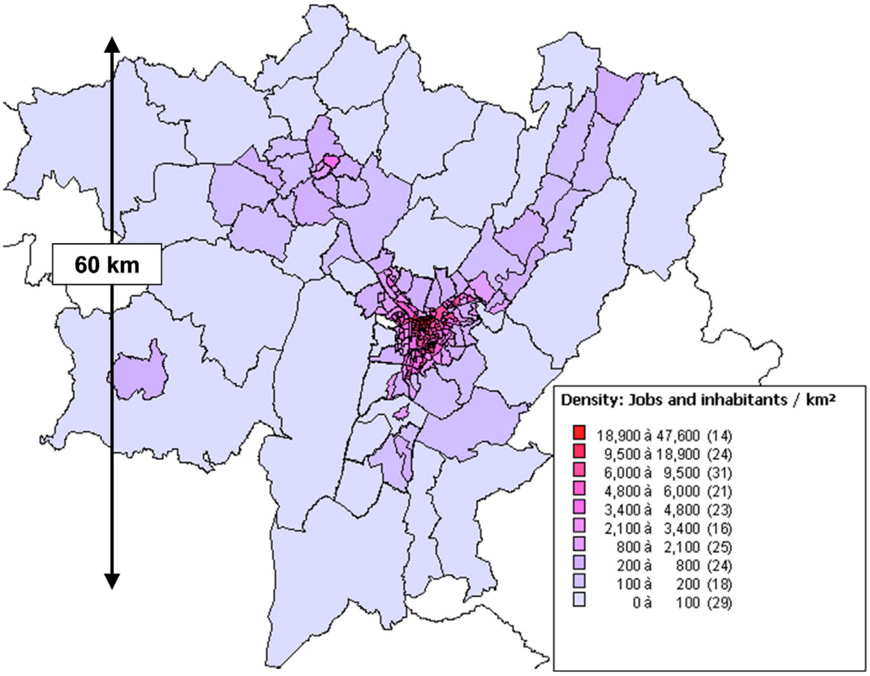

Fig. 6. the Grenoble area represented in TRANUS with progressive meshing (Authors) Density of jobs and inhabitants/km^2, (number of zones).

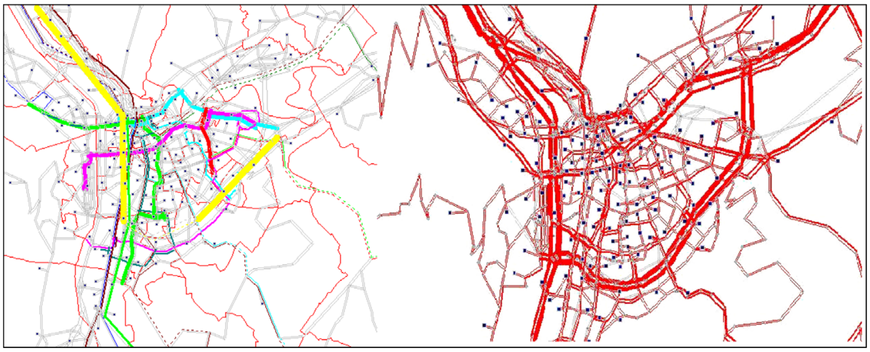

Fig. 7. the transport network in TRANUS, on the left the tramway lines, where each point is a zone of the model (where jobs and household by types are described); on the left the road network with a width proportional to capacity (authors).

Polycentric development, smaller cities around the agglomeration share population and job growth with the agglomeration.

Our TRANUS application was implemented based on national (mainly housing survey, fiscal survey, jobs survey) and local data (transport survey, land and housing price data), and also on existing transport modeling in Grenoble. A LUTI is particularly demanding in terms of data since each sector has to be described for each zone. The application required combining different partial sets of data due to weaknesses in the official statistics (land price, housing price). We include seven types of households in the model; these groups are students, low income seniors (65 and above), high income seniors (65 and above), and four levels of income for the remaining households. We include six types of economic activities in the model that include industry, offices, retail, supermarket, education, and public services and five types of floorspace that include detached dwellings, apartments, social housing, industrial floorspace, mixed use floorspace and retail floorspace. We also include a comprehensive representation of the transport system in the model with 224 transit zones and 5000 links representing almost the entire road network (see Fig. 7). We also include all other modes of ground transport – trains, cars, tramways, buses, bikes and walking – in the model.

3. Results and discussion

3.1. A sample of MACCs for the transport sector

The full results of the application, including the emissions trajectory, comparison of urban forms and other MACCs can be found in Saujot (2013). However, given the methodological scope of this article and its limited size, we will focus here on MACCs for a single scenario (S1 urban concentration). We use five different MACCs, each of which relies on a different set of assumptions to evaluate costs. Table 4 sums up the different MACCs provided in the figures of this section.

This first MACC (Fig. 8) represents the potential of five abatement measures and the economic cost borne by households and public authorities; we use a 4% discount rate for this MACC. The results reveal that public transport and technological solutions have similar costs, while an urban toll is comparatively cheaper and has a more significant mitigation impact. Logically, carpooling has a negative abatement cost since implementation costs are very low and car distance costs are shared between multiple riders. In terms of mitigation potential, urban toll can reduce emissions by 40,000t CO_2 in 2030, all other measures have a lower abatement potential ranging from 9000t to 14,000t.

Table 4
The different MACCs.

MACCs	Fig. 7	Fig. 8	Fig. 9	Fig. 10	Fig. 11
Type of cost	Economic costs	Economic costs	Economic cost + pollution and noise	Economic cost +pollution and noise+ time	Economic cost +pollution and noise+ time
Discount rate	4%	20%	4%	4%	4%
Waiting time value	–	–	–	2 times the value of travel time	Value of travel time

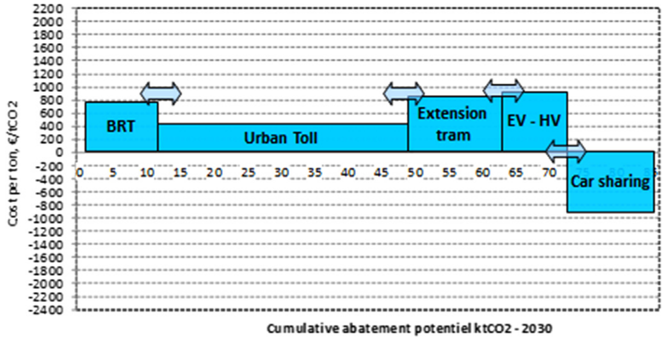

Fig. 8. MACCs in transport sector, economic costs, 4% discount rate, Perimeter of the climate action plan (authors).

It is important to keep in mind that interdependencies are taken into account for this MACC. For example, the potential of *Measure 3 Tramway* is larger because of the previous implementation of an urban toll. This is because the implementation of the urban toll favors the use of the tramway over cars in an economic trade-off context. Another example is the incentivization of electric/hybrid vehicles and its integration with the urban toll; we assume in Measure 4 that electric/hybrid cars will pay a lower toll as an additional incentive.

In Fig. 9, we change the discount rate from 4% to 20%, to represent costs for low and middle income households more realistically (these households presumably have a higher discount rate as a result of budget constraints). We notice that the results are very different from the 4% discount rate case. The abatement cost for electric and plug-in hybrid vehicles, which requires a capital expenditure, increases sharply in this scenario since we assume that households place a greater value on initial investment. Conversely, abatement costs for public transport solutions decline.

A higher discount rate makes car use more expensive and the modal switch implied by measures 1, 2 and 3 leads to higher savings for households.[17] Another way to interpret this effect is that as it becomes increasingly burdensome for households to purchase a car, policies favoring modal switch become more profitable.

This sensitivity test illustrates the importance of accurately evaluating discount rates for effective mitigation policies. For example, a carbon tax (which, in part, increases variable costs in the hopes of encouraging households to invest in more efficient technologies, e.g. hybrid/electric cars), could potentially have a lower impact on household investment, and thus emissions mitigation, than would be suggested by analysis based on the standard 4% discount rate.

Returning to the original 4% discount rate case and adding co-benefits (local air pollution, noise), we see in Fig. 10 that all abatement costs decrease with the addition of co-benefits. In addition, all of the mitigation measures tested have co-benefits.

We do not present the corresponding MACC that combines co-benefits and 20% discount rate, but it shows negative abatement costs for the three first measures (see Table 5). Put simply, this shows that an effective transport policy can also be a social policy. When local authorities invest in modal switch, a higher discount rate is positively correlated with welfare gain, indicating that such investments, which benefit the most economically constrained households, are also beneficial for the community at large.

Finally, the introduction of time valuation changes affects the results of the MACC as seen in Figs. 11 and 12. Taking time into account improves the evaluation of mitigation, but requires caution as the results are highly sensitive to modeled travel time uncertainties. In Fig. 11 we add co-benefits and time with a factor of 2 for the value of waiting time. We can see that solutions based on modal switch, which imply waiting time, are logically penalized in this case, even if measures 1 and 3 do not change the sum of travel and waiting times before and after the modal switch.

In Fig. 12, we reduce the waiting time value hypothesis and consequently the cost for public transport solutions also decreases. The case of urban toll is different because it deteriorates the overall mobility situation, resulting in a 5% increase of travel and waiting times during the morning peak hours. By contrast, we see that carpooling is a very efficient measure because it decreases mobility costs, congestion and local air pollution. However the implementation of this measure is challenging because it calls for a change in behavior and lifestyle; therefore, the transaction costs associated with this measure could be underestimated.

3.2. Key results and implications

- With the five measures, emissions levels in 2030 are expected to be 30% lower than the baseline in 2030 and 49% less than the 2010 level. This decarbonization level would not be sufficient to meet the French national target (a division by 4 between 1990 and 2050),[18] and would thus need to be accelerated between 2030 and 2050.
- Urban toll has a large potential and appear to be cost-effective, except if we take travel times into account. To increase cost effectiveness, the transport network will have to be optimized to limit time losses.
- Abatement costs for public transport are high but if we consider the co-benefits the cost decreases by a factor of 2. Additionally, if we consider a higher discount rate for household car purchases, the abatement cost for public transport turns negative.
- Abatement costs for electric and plug-in hybrid vehicles are even higher than those for public transport. Consequently, as observed by Prud'homme and Koning (2012), supporting these solutions with public money could be a hazardous bet on their future cost decrease. Nevertheless, as Vogt-Schilb and Hallegatte (2011) note, it can make sense to implement this kind of

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[17] In other words, when a BRT is implemented, the modal switch toward public transport implies savings for former car users. The more expensive it was to use a car initially, the larger the savings from the modal switch will be. In the methodology used in this paper, a higher discount rate corresponds to an increase in the cost of car use.

[18] This target is a basis for analyzing results but not the official one for transport sector since only a multi sector analysis could allocate the right target to each sector based on their relative costs and potentials.

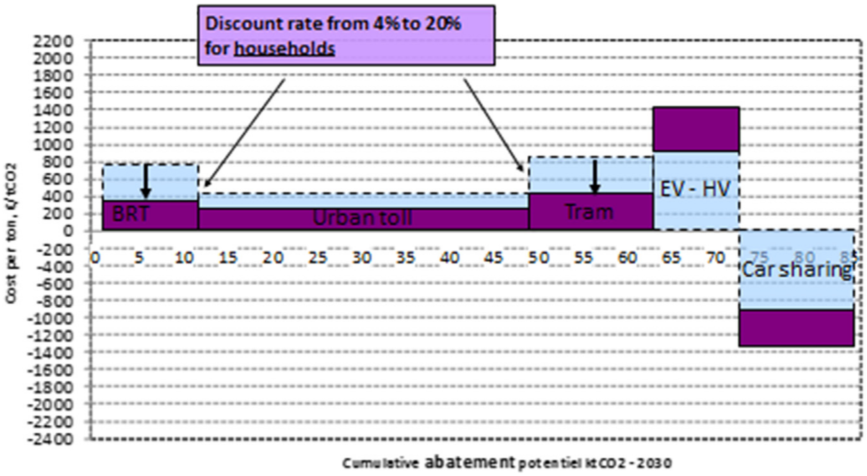

Fig. 9. MACCs in transport sector, 20% discount rate and economic costs only, climate action plan perimeter (authors).

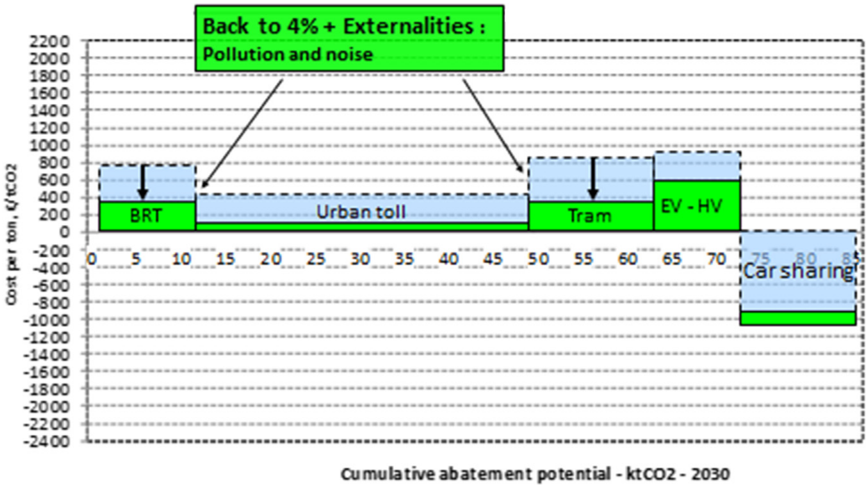

Fig. 10. MACCs in transport, co-benefits included, 4% discount rate, climate action plan perimeter (Authors).

Table 5
8 ways to calculate abatement costs.

Abatement costs-Scenario Urban Concentration				
			Waiting time value 20€	*Waiting time value 9€*
Package	**Economic costs**	**+Externalities**	**+Externalities+Time**	
€/t CO_2 Discount Rate 4%				
BRT	766	371	*1130*	*363*
Urban Toll	424	66	*1734*	*700*
Tramway	777	330	*1032*	*216*
EV-HV	840	585	*584*	*584*
Car sharing	−867	−1017	*−2316*	*−1991*
€/t CO_2 Discount Rate 20%				
BRT	302	−93	*665*	*−102*
Urban Toll	210	−147	*1530*	*489*
Tramway	412	−34	*668*	*−148*
EV-HV	1302	1037	*1037*	*1037*
Car sharing	−1293	−1444	*−2742*	*−2417*

policy early since its abatement potential could be decisive for the 2030–2050 period and since it has a certain inertia (behavior change, technological improvement, fleet renewal).

- Carpooling is very cost-effective. More public policies should be implemented to support this mode of transport, given its potential and the challenges it faces in terms of transaction costs and behavioral and social change.

Table 5 sums up the results for the 8 ways to calculate abatement costs in our methodology.

3.3. *Using these MACCs as a decision making tool*

We developed our methodology in the perspective of informing policy making for local climate action plans. This is why we chose MACCs: they are an easy to read tool for cost-effectiveness evaluation that could be useful to engage a discussion on local climate policies with urban planners. Nevertheless, the first generation of urban MACCs had limitations, which our methodology is designed to address.

Our improvements, while ameliorating the application of MACCs at the local level, have implications in terms of reading and interpretation, as we have seen in the literature on the relative advantages and disadvantages of model-based MACCs. As a consequence of the integration of the systemic aspect of a local mitigation strategy, we consider packages of policies rather than individual policies, and abatement costs depend on the implementation of previous packages. Thus, one needs to analyze multiple sets of packages for each urban scenario to understand the cost-effectiveness of the different strategies rather than simply choosing between packages.

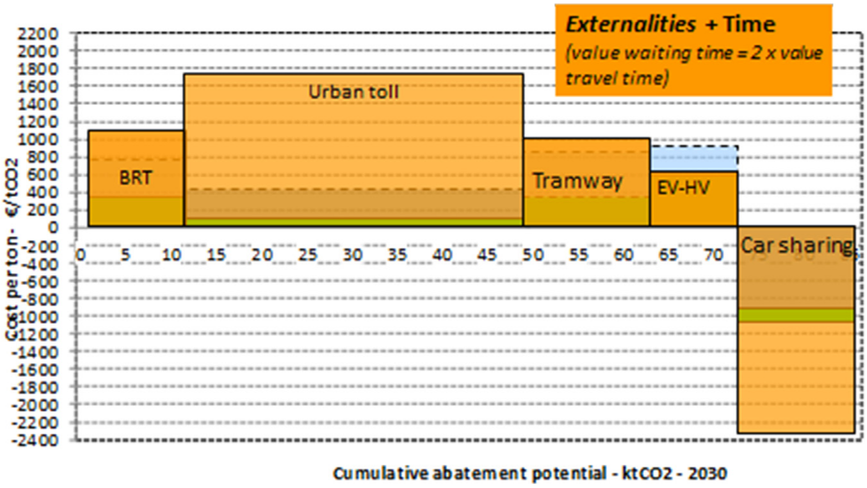

Fig. 11. MACCs in transport, 4% discount rate, co-benefits and time (double value for waiting time), climate action plan perimeter (authors).

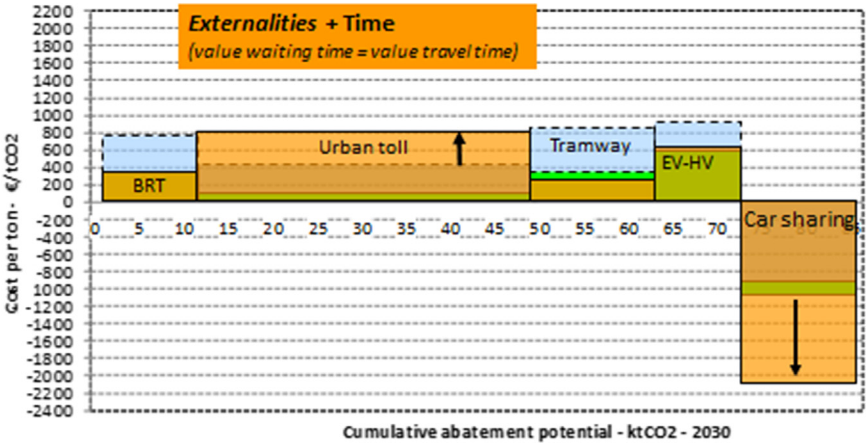

Fig. 12. MACCs in transport, 4% discount rate, co-benefits and time (no double value for waiting time), climate action plan perimeter (authors).

Our methodology chooses to translate the results of a scenario analysis approach into MACCs, i.e. into a single dimension of cost-effectiveness. This makes them more realistic than first-generation of urban MACCs, but also harder to read. In return, the value-added of our MACCs methodology is to integrate the value of a scenario approach modelled by a LUTI and turn it into a simple chart, useful for discussing local climate plan ambitions and also coherent with a large part of the literature on energy analysis which is based on MACCs to discuss cost-effectiveness.

Finally, these MACCs have been designed to integrate cost-effectiveness into the decision making process of climate action plans but not directly to provide an optimal ranking, which we feel can only be the result of a planning process at the local level. We are cognizant of the several assumptions and simplifications that drive the MACCs. Moreover, we show that there is neither a unique cost for each measure nor an unequivocal hierarchy and thus we agree with Kesicki and Ekins (2012) that a “MAC curve is not, and should not be used as, a one-stop shop for ranking abatement policies”.

3.4. Analysis of the urban scenario with social costs

The effect of including social costs is not straightforward. It is clear that mitigation policies often bring co-benefits like reduced air pollution or noise, and a better understanding of this impact is interesting in order to support mitigation policies at the local level, since it can partially offset costs and increase the political acceptability of the measures. In our results there is often a factor of 2 on abatement costs when social costs are included. However, social costs also interact with urban form, which adds an additional dimension to policy choice. Our analysis shows that over the 2010–2030 period, a compact scenario (S1) concentrates population in the most polluted part of the whole territory more than a sprawl scenario (S3). Consequently, even if mitigation policies lead to a bigger pollution decrease in S1 than in S3 over the period, the total cost of pollution could be higher.[19]

Concerning congestion and travel time, there are no simple rules, since policies to support public transport can also increase travel time. This is a trade-off that every city willing to support walking, cycling and public transport faces: limiting the space for cars or increasing its cost (urban toll, parking fees) can lead to increased congestion or an increase in travel time due to modal shift. A comparison between urban scenarios underlines these effects. Looking at the results based solely on economic costs and CO_2 reduction would certainly give preference to a compact scenario. Indeed, in 2030 the emissions level of this scenario is 8–10% lower than the sprawl and polycentric scenarios and the total discounted cost of the mitigation policies is more than 50% lower (see Table 6). Nevertheless, including social costs shows that the

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[19] Our methodology allows us to identify this effect but, as we note in the conclusion, we would need a more disaggregated method for modeling pollution to analyze the effect in detail.

Table 6
A comparison of costs and reduction levels between urban scenarios.

	Global discounted cost of the implementation of the 5 packages, € millions, discount rate 4%, waiting time value 9€			
	Economics costs	+Externalities	+Externalities+Time	*Reduction of emissions between 2030 and 2010 with all packages*
S1 Urban concentration	238	−118	−84	*−47%*
S2 Polycentric development	574	295	−60	*−41%*
S3 Urban sprawl	574	286	−198	*−41%*

Notes: Costs for the three scenarios are calculated with their respective baseline

situation is more complicated. For example, we observe that mitigation policies induce higher congestion in S1, contrary to the two other scenarios where mitigation policies improve travel time (see the increase in costs for S1 in Table 6). The analysis of travel time in S1 highlights potential competition between two measures in a scenario in which we attempt to increase the offering of public transportation in a dense urban environment, and underlines the need to optimize the public transport network to ensure the complementarity of bus lines and tramway extensions.

Including social cost clearly improves our understanding of potential mitigation strategies at the city level. Our work demonstrates that mitigation indicators cannot be considered in isolation, and that the impact mitigation policies have on the way people live and travel in a city, and their interactions with urban form, must also be investigated. Ultimately, from a policy perspective, the analysis highlights the tradeoffs present in each if the scenarios. In S1, densification brings important mitigation benefits. The challenge in this case is to minimize negative effect of mitigation policies on congestion and travel time, but also to minimize increases in housing costs.[20] In S2 and S3, the urban form gives fewer opportunities to reduce emissions with a modal shift to public transport. Consequently, the policy challenge is more about incentivizing technological improvement and carpooling.

4. Conclusions and policy implications

This paper has attempted to extend the MACC methodology with a land use transport integrated model, in order to inform local policy making for emissions mitigation. These methodological improvements could help to mainstream climates policies into the urban planning framework: our methodology produces results that are coherent with urban planning analysis, and consequently makes a discussion on climate action possible with urban planners. Moreover, LUTI modeling could constitute a tool common to both climate policy makers and urban planners.

Our results show that, compared to the first generation of urban MACCs, our method can provide a more comprehensive and realistic analysis of mitigation policies. With the different levels of cost analysis and the diversity of model outputs, key assumptions and best policy mixes can be discussed and the political feasibility of the measures can be analyzed. Most notably, we show that including social costs can profoundly change the cost-benefit assessment of urban mitigation options. This has policy implications in terms of prioritization between sectors. Indeed, if we reassess abatement cost considering the whole range of co-benefits and sensitivity to key parameters (notably the discount rate), the transport sector can be as cost-effective as housing sector,[21] which would seem unlikely with a standard assessment.

However this methodology also makes it more complex to build and analyze, which could impact its feasibility as an actual planning tool for cities, notably with limited resources. Moreover LUTI models are more complicated to manipulate than transport models and are not yet operational tools (Saujot et al., 2015).[22] Thus, as a first approach, cities could use a simplified methodology, according to their competencies and tools, which conserves the ability to investigate cost effectiveness of urban policies with particular attention to interactions between policies and urban development scenarios. This is for example what the French energy agency is currently doing: a guide to popularize a simple cost-effectiveness evaluation of climate action plans is being distributed to French cities.[23] Although cost-effectiveness is not currently at the center of the local climate policies agenda, we think that this aspect of policy making will progressively gain in importance, notably with pressure from the national and international levels.

Our study is limited by the fact that we were not able to include several co-benefits such as market attractiveness, safety, and urban renewal effects. It is, for example, worth noting that co-benefits for urban renewal have been decisive for investment in tramways in France in the last decade, but could not be integrated into this study. Future research could reinforce these aspects and add a new dimension to local policy analysis. Moreover, the expansion of the simulation period could have improved our cost-benefits analysis, since the change in the urban structure could create more benefits and potentially reduce costs in the very long term.

We hope that our work serves as a reminder that abatement cost, like every cost, is a social construction, relying on multiples norms and hypotheses that should be discussed transparently; different ways to calculate costs coexist according to the diversity of legitimate issues faced by urban planners and policy makers.

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[20] These are not included in our analysis, but are generally a negative consequence of densification.

[21] This result comes from the whole Aetic project and could not be presented in details in this article. See Criqui et al. (2013)

[22] LUTI models, even if developed and used for decades, are still on the research agenda and raise questions about their daily use for urban planning.

[23] The authors contributed to this guide.

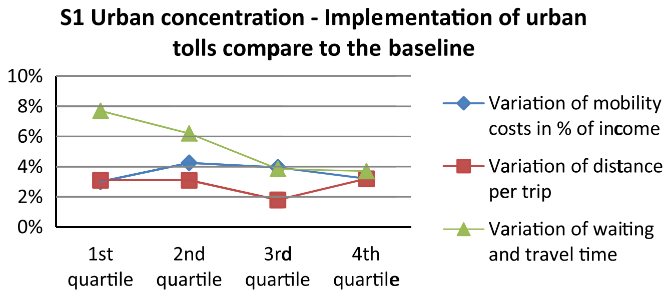

Fig. 13. Urban toll impact on households (authors).

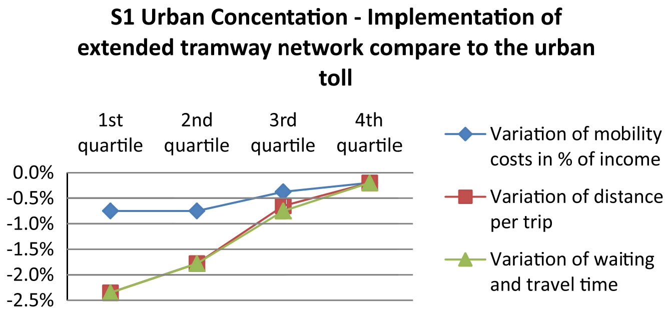

Fig. 14. Tramway impact on households (authors).

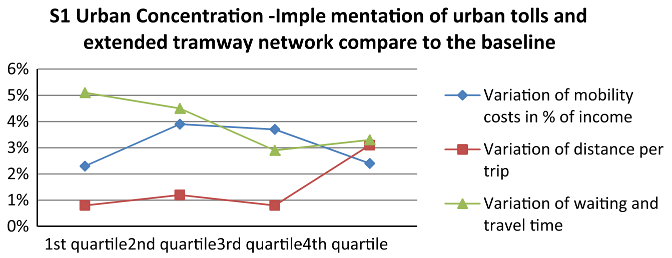

Fig. 15. Urban toll and tramway impacts on households (authors).

Appendix A. An illustration of results in terms of distributional impacts

By using TRANUS, we are able to show that urban toll has a regressive effect and the low income population loses more than high income households: we see in Fig. 13 that mobility cost, distance per trip and waiting and travel time increase more for the 1st and 2nd quartile than for the 3rd and the 4th. On the other hand, after the implementation of the urban toll, an extension of the tramway will have a progressive effect: we see on Fig. 14 that the situation improves more for the 1st and the 2nd quartile. Yet the tramway does not fully counterbalance the effect of the urban toll: as we can see in Fig. 15, the whole effect of the urban toll and the tramway on mobility cost and travel time is bigger for the 1st and the 2nd quartile. This result is confirmed by the assessment of the global cost evolution (mobility cost and monetization of waiting and travel times): this cost increases more for the 1st and 2nd quartile than for the 3rd and 4th.

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