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Effectiveness and political economy of climate change mitigation policies at the urban scale.

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RESUMÉ ET MOTS CLÉS

L'urbanisation est un des faits majeurs du 21eme siècle, avec des migrations massives vers les villes des pays en développement. Étant donné l'inertie et la dépendance au sentier qui caractérisent les formes urbaines, il y a un besoin pressant de mettre en place les fondations d'une urbanisation réussie dès aujourd'hui. Un aspect important est de permettre des trajectoires urbaines bas carbone et soutenables et d'éviter des « lock-ins » intensif en carbone, en particulier pour les émissions provenant du transport urbain. Les progrès technologiques sous la forme de véhicules plus efficaces et de carburants alternatifs ne semblent, aujourd'hui, pas en mesure d'atteindre cet objectif seuls. Et les émissions de CO_2 issues du transport urbain étant partiellement un co-produit des formes urbaines, les politiques foncières, de logement et de transport sont de manière croissante reconnues comme des leviers importants pour freiner la demande de transport et promouvoir des modes de transport doux et collectifs qui contribuent à la réduction des émissions. Bien qu'importante, la réduction des émissions de CO_2 n'est qu'un objectif parmi d'autres pour les décideurs locaux : agir sur la pauvreté, la fourniture de services publiques de base et l'accès à un logement abordable sont d'autres exemples d'objectifs importants. Des politiques visant à réduire les émissions qui mettraient en péril d'autres buts ou qui se traduiraient par des niveaux de bien-être des populations réduits (principalement à travers des couts du logement plus élevés) auraient peu de chances d'être acceptées et mises en œuvre. Des politiques climat portant sur le transport urbain se doivent donc d'être à la fois efficaces et politiquement acceptables. Partant de constat, cette thèse examine comment un groupe de politiques et d'investissements urbain, foncier et transport peuvent contribuer à freiner les émissions de CO_2 liées au transport urbain et quelles sont les conséquences pour les ménages en termes de bien-être dans les aires urbaines. Cette analyse est conduite à travers le développement, la calibration et l'application à des villes réelles d'un modèle Transports – Usages des sols fondé micro-économiquement (NEDUM-2D).

Mots-clés: Forme urbaine, Abattement d'émissions de CO_2, Transport urbain, Modélisation Transports – Usages des Sols, Économie urbaine, Foncier, Logement, Étalement urbain

ABSTRACT AND KEYWORDS

Urbanization is one of the most defining traits of the 21st century with people flocking to cities in massive numbers in developing countries. Given the inertia and path dependence that urban forms display, there is a strong need to get urbanization right today. One key aspect is to ensure low-carbon and sustainable urban futures and avoid carbon-intensive lock-ins, in particular for emissions stemming from urban transport. Technology in the form of more efficient vehicles and alternative fuels currently does not seem to be able to achieve this goal alone. And as urban transport CO_2 emissions are partially a by-product of urban forms; land-use, housing and transport policies are increasingly recognized as important levers to curb transport demand and promote soft and collective transport modes which contribute to emission mitigation. However important, reducing CO_2 emissions is but one of city policy makers' objectives: acting on poverty, providing basic services and access to affordable housing to name a few are equally important. So that policies aiming to reduce emissions, that would jeopardize other goals or result in lower welfare levels (mainly through higher housing costs) have low chances of being accepted and implemented. Successful urban-transport climate policies need to be both effective and politically acceptable. Starting from this assessment, this dissertation investigates how a subset of urban, land and transport policies and investments can contribute to curb transport-related CO_2 emissions and what are the welfare consequences for households in urban areas. This is done through the development, calibration and application of a micro-economically founded land use – transport model (NEDUM-2D) to real-world urban areas.

Keywords: Urban form, CO_2 emission mitigation, Urban transport, Land Use Transport modelling, Urban economics, Land, Housing, Urban sprawl

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INTRODUCTION TO THE PHD

"from now on
cities
will be built
on one side
of the street
so that soothsayers
will have wilderness to wander
and lovers space enough
to contemplate
a kiss"

Williams, Saul. 2003. *Said the Shotgun to the Head: A Poem.* New York, NY: Pocket Books.

1 THE URBAN LANDSCAPE: FORCES OF AGGLOMERATION VS DISPERSION AND FORCES OF HORIZONTALITY VS VERTICALITY

Ironically, transport, the very service that allows human beings to remain connected while living in distinct locations is the key shaper of cities which could be described as the ultimate distance reducers. But transport interacts with other forces in determining the distribution of people and economic activity at various scales: worldwide, over continents, at the national and regional levels and within urban areas.

The reduction in transport costs brought about by technological innovations such as the railway revolution and later the emergence of the automobile means that it became easier to sell products in distant locations. Agricultural products which would once have rotten on the one week horse powered trip from Rennes to Paris can now reach their destination in a few hours. A near immediate consequence of this possibility of supplying (and being supplied) over greater distances is that many towns and cities that existed as local markets and job centers became redundant and declined in population and attractiveness. Because of the existence of agglomeration economies, extensively documented in the literature, it is less costly to produce in a given location than in multiple ones. A corollary to the statement above is the increased concentration of people in a system of a limited number of cities and the emergence of increasingly large cities. These agglomeration economies also explain that urban agglomerations were able to specialize in what they did best leading to a new division of labor over large geographic distances (Huriot and Bourdeau-Lepage, 2009).

More central to this dissertation, is the strong relationship that urban transportation systems and building construction technologies entertain in determining the structure of urban areas. Cities built in the nineteenth century and earlier, such as Paris and London, were scaled for pedestrian and horse back transport and were built in a compact way so that most areas were reachable in a limited amount of time. By comparison, the emergence of steam trains at first, then street cars followed by buses and metros and eventually individual cars as an affordable transport option for many in cities of developed countries associated with massive investments in

highways (Baum-Snow, 2007) considerably reduced travel times and led to the decentralization of population and the increase in urban extents. Because these technologies made it possible to reach jobs and urban services often located in the center of cities more easily, they allowed people to live further away in more spacious homes that could also often display a lawn. The well-known American suburb was born and the intensity in the use of land declined as a result.

But, opposite trends also appeared, the iconic Manhattan skyline which draws millions of tourists to the American city only became possible because of two separate but highly complementary innovations. The first is the discovery of metal frames that could sustain the weight of high rises. However, by itself this innovation would not have been sufficient for skyscrapers to be built on a massive scale. Imagine for one second having to walk up and down the 30+ flights of stairs on a daily basis this would have implied for many tenants. The key second innovation was the invention of elevators as a transport technology which made verticality livable. Building these skyscrapers was partly motivated by reputation effects as the building displayed the names of their main financers but it also obeyed to a fundamental economic rationale: where land is most valuable, as in city centers, it will be used more intensively (Ahlfeldt and McMillen, 2015; Helsley and Strange, 2008). This (slightly) anecdotal yet powerful image of Manhattan and its skyline has the merit of showing the fundamental relationship that links urban landscapes and structures with transportation and construction costs. When the prior goes down, the urban world becomes more horizontal, when the latter goes down, it becomes more vertical. Over the last two centuries, the forces of horizontality have coexisted with but dominated the forces of verticality.

Land use regulations (or lack thereof) also have a very strong effect on the forms and structures that urban areas take. In many developing countries, lack of clear property rights for land parcels will mean that households, and construction companies even more so, will not have an incentive to build upon land in a way that reflects its highest use. Because of conflicting claims on land property there is a strong risk that any improvement to housing structures will not benefit the owners or tenants as these run the risk of either being expelled or not being able to resale their property. Kibera, an area in Nairobi, Kenya and one of the world's largest slums (1000 acres) is a case in point. Once upon a time a peripheral area to Nairobi, Kibera, is now a central part of the uprising Kenya's capital city. While a traditional urban economics model would predict the gradual conversion of slums into formal housing[2] and the increase in building heights as the demand for land in the proximity to main job centers increases, the existence of large transaction costs can explain the persistence of very basic housing conditions. A study assesses that Kibera hosts less than half the housing space it should and foregoes the equivalent of 1billion US$ in land values as a consequence of unclear institutions governing land ownership (Henderson et al., 2016). Conversely, stringent land use regulations can also negatively impact the form of urban areas and burden its residents with high costs. Mumbai, India is a prime example of such costly regulations. The Floor Area Ratio regulations (FAR), determining the heights of buildings that can be constructed on land plots, are set low and in a coarse way. Outside the city center, they are essentially set to or below 1.5 roughly translating into buildings that are capped at 1.5 floors. This regulation, when respected, reduces the supply of space for housing or businesses, driving rents up, lowering the size of individual units

[2] Just as 19th century shacks and housing were demolished and rebuilt in New York and London.

and pushing outward and imposing extra commuting costs to those that cannot afford locations in the vicinity to the city center. If landowners choose not to respect this FAR regulation, they will build larger structures which can house more households or businesses and lead to higher profits but they will be informal and under the threat of destruction from local and central governments (Lall, 2013).

Finally, decreases in transport costs have not simply led to increased concentration in a limited number of urban areas and caused urban population decentralization. They have also affected the distribution of economic activities within urban areas. Two countervailing forces are at play here. On one side the agglomeration economies that stem from reduced distance and increased densities will tend to favor the clustering of firms and plants in the most accessible parts of the city, often the center. On the other hand, costs of congestion in the form of traffic jams for the delivery of production inputs and higher land values will favor the decentralization of activities that are less prone to agglomeration economies or for whom the costs of congestion outweigh the benefits of agglomeration. Typically these activities are either more demanding in floor space, a large production chain for example, are mature activities such that their potential productivity gains have already been exploited, or are local in nature with the purpose of serving local customers – think of a French bakery for example. All the activities coexist in modern cities and transportation costs determine in a large part how they are distributed across space.

2 THE ELEPHANT IN THE ROOM: THE WORLD IS URBANIZING ... AND SO ARE CO_2 EMISSIONS

Today more than half the world population is urban, 54% in 2014 (UN DESA, 2015b) and the shift from rural to urban societies is a global trend that is accelerating with massive urbanization taking place in developing countries. While urbanization is mature in most industrialized and emerging countries with shares of urban population as high as 80% in North America and Latin America and 73% in Europe[3], they are 40% and 48% respectively in Africa and Asia. But populations in Africa and Asia and their urbanization growth rates are so large that these continents are experiencing unprecedented absolute increases in urban dwellers. Standing at 472 million people today, Africa's urban population is expected to reach 659 million by 2025 – equivalent to adding the whole of Nigeria's population – and to double by 2040 to close to 1 billion. It is the continent with the fastest growing population (+2.55% over the 2010 – 2015 period). Asia today hosts 60% of the World's population (UN DESA, 2015a) and despite slowing population growth rates is urbanizing as quickly as Africa. By 2050, UN projections indicate that 6.34 billion people will be urban (two-thirds of global population), only 1,11billion of these in North America, Europe, Japan, Australia or New Zealand. Together, Africa and Asia are expected to host 90% of the increase in urban population by 2050. Urbanization in developing countries will maybe be the most defining trait of the 21st century (Figure 1.1).

Urban areas generate an overwhelming share of global wealth. While precise figures are not available, as GDP is rarely reported at the infra-

[3] The UN reports that the share of urban population in Europe, North America, Japan, Australia and New Zealand was 54.6% in 1950, i.e. slightly higher that the urban percentage on a global scale in 2014: United Nations, Department of Economic and Social Affairs, Population Division (2015). World Urbanization Prospects: The 2014 Revision, custom data acquired via website.

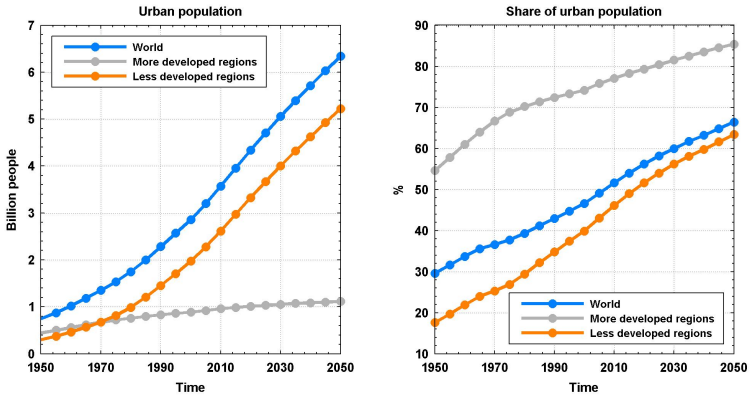

Figure 1.1: Dynamics of urbanization of people disaggregated by income group (source: UN DESA, World Urbanization Prospects, 2015)

national level, best available estimates indicate that about 80% of GDP is produced in urban areas (GEA, 2012; Seto et al., 2014). A corollary to the role of cities as major production centers is that they are also major CO_2 emitters. Here again supporting evidence of this claim is scarce as measuring emissions at the infra-national level and attributing them to urban areas is uneasy. The difficulties are two-fold: 1/ measuring CO_2 emissions at the infra-national level where accounting systems are absent and 2/ attributing these local estimates to urban areas, when the limits of urban areas are notoriously difficult to ascertain as administrative boundaries are unable to capture their extent (Dijkstra and Poelman, 2014; Roberts et al., 2017). The 5th Assessment Report of the IPCC reports that best estimates for urban shares of CO_2 emissions from global final energy use are between 71% and 76% for years 2005-2006[4]. When one accounts for all greenhouse gases, the contribution of urban areas is much lower "as the large majority of CO_2 emissions from land use change, N_2O emissions, and CH_4 emissions take place outside urban areas" (Seto et al., 2014). Given the demographic shift toward an urban world in the coming decades, the share of urban GDP and contribution to GHG emissions is likely to rise dramatically.

3 WHY FOCUS ON URBAN TRANSPORT-RELATED EMISSIONS?

Figures from the 5th IPCC Assessment report indicate that transport represents 14% of all GHG emissions when accounting for non-energy related sources such as Agriculture, Forestry and Other Land Use – AFOLU (Figure 1.2).

The International Energy Agency reports that in 2014 transport represented 23% of worldwide CO_2 emissions from fuel combustion, with road transport accounting for three quarters of these. Moreover, the IEA also indicates that transport CO_2 emissions from fuel combustion have increased by 71% from 1990 to 2014 (IEA, 2016a). And the IEA also forecasts that transportation emissions will increase faster than other sources to represent 33% of energy-related emissions by 2030 (IEA, 2011). These figures and the upward trend in transport emissions are significant and warrant robust re-

[4] There are large variations between estimates and some efforts have employed ranges rather than single figures, either to account for uncertainties in data, emission factors and definitions of urban areas or to reflect different methodologies for attributing emissions to specific areas (consumption vs production based for example).

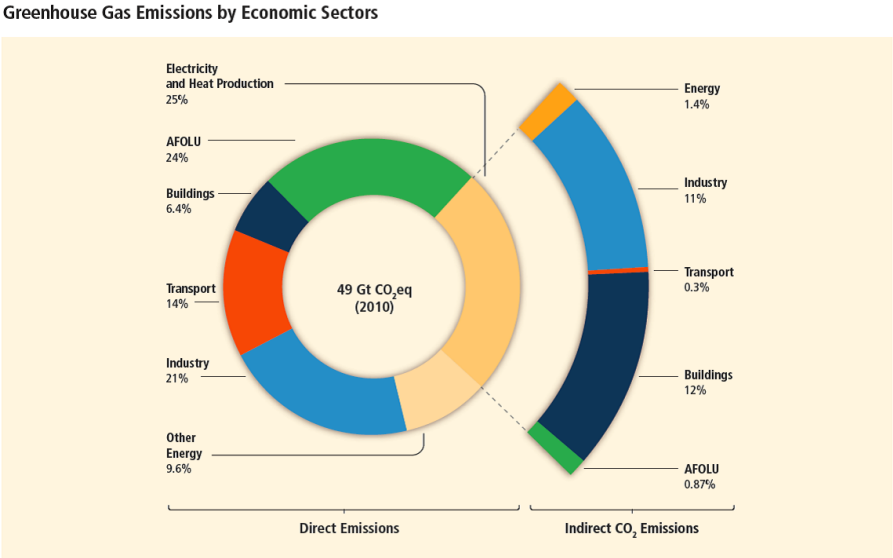

Figure 1.2: Total anthropogenic GHG emissions ($GtCO_2eq$ / yr) by economic sectors (IPCC, 2014). Source: IPCC, 2014, Synthesis Report, Figure 1.7 p47

search and policy action in order to avoid dangerous climate change impacts. But these figures would appear much lower when discounting for goods travel, for rural households' travel and for leisure travel which are not at all or not specifically urban. For example, urban transport is estimated to represent 40% of the transport's sectoral emissions (IEA, 2016b), or 6% (2.8 $GtCO_2e$)[5] of annual anthropogenic GHG emissions (Creutzig et al., 2016). So why should one focus on urban households' transport-related emissions and among these on their commuting related emissions?

The first reason is that the World is urbanizing and that while current urban population shares remain below 50% for Asia and Africa, these two regions will be 64.2% and 56% urban by 2050 indicating large influxes of populations into urban areas, adopting an urban lifestyle and setting into urban patterns of commuting. The second reason is that vehicle ownership rates in developing countries are still very low but are likely to rise substantially in the future as incomes increase (see Figure 1.4 and Dargay, Gately, and Sommer (2007)). Deloitte for example indicates that car ownerships are 2, 28 and 20 per 1000 inhabitants in Ethiopia, Kenya and Nigeria respectively in 2014 (Deloitte, 2016). This is far below the World average of 182/1000 inhabitants in 2015 and pales into insignificance when compared to the 581 or the 821 vehicles/1000 inhabitants in EU28 and the USA respectively[6]. So what would happen if and when urban commuters in developing countries catch up to the urban lifestyle of their Westerners' counterpart? A deep-dive into some specific cities can provide some answers.

Creutzig et al. report that annual emissions from urban transport are often in the range of $2tCO_2e$/capita (Creutzig, Mühlhoff, and Römer, 2012). They find these figures for the cities of Barcelona, Freiburg, Malmö and Sofia that all benefit from reasonably good public transit systems, likely to lower urban transport emissions. And yet these figures for urban transport

[5] This is less than half the emissions from urban buildings (43%). Together urban transport and urban buildings account for 20% of annual anthropogenic GHG emissions (Creutzig et al., 2016).

[6] http://www.oica.net/category/vehicles-in-use/. Consulted on September 3rd 2017 for 2015 statistics.

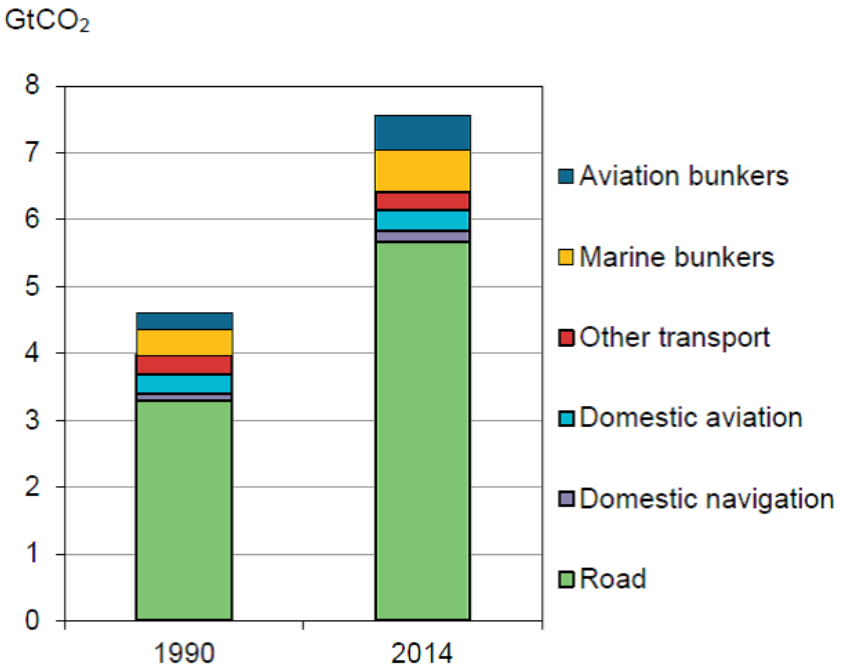

Figure 1.3: Worldwide transport-related CO_2 emissions from fuel combustion (IEA, 2016a). Source: IEA (2016) CO2 Emissions from Fuel Combustion - 2016 edition - Key CO2 Emissions Trends. All rights reserved

Figure 1.4: The relationship between Motorization rates and GDP per capita broken down by region. Figure removed in the diffusion version of the dissertation. It is consultable at source: (Jacquet et al., 2010) p257.

alone are already twice the per capita carbon dioxide budgets that were considered compatible with safe GHG atmospheric concentrations in 2000 (Baer et al., 2000). In Paris, Ademe estimates that urban transport emissions represent 54% of the city's total GHG emissions (Viguié, 2012). Fujii et al., using an OECD database covering 281 metropolitan areas larger than 500,000 people in the OECD, find that on average transport represents 29% of total urban emissions which would translate into a little over 3 tCO_2e per capita annually in 2008 (Fujii, Iwata, and Managi, 2017). These figures, while very high remain well below similar figures reported for U.S. cities. Glaeser and Kahn using 2001 census information for 68 U.S. metropolitan areas show than on average a household would emit 12.74 tCO_2e from driving and using public transport each year (Glaeser and Kahn, 2010). These figures are not directly comparable to the previous ones as they are reported at the household level. But making the same assumption as the authors that the average household size is 2.62, we would find emission levels from transport for urban households to be close to $4.9tCO_2$ annually.

Other reasons to focus on urban transport emissions are linked to the strong inertia displayed by urban forms, likely to lock cities into non-sustainable development pathways if early action is not taken. The structure of urban areas, how jobs and people are spatially distributed, indeed conditions travel patterns. These crucial elements are discussed in detail in sections 6 and 7.

To summarize, transport emissions are large and growing faster than emissions from other sectors. While emissions attributed to urban transport currently represent a relatively low share of the total, these will likely increase dramatically as the world urbanizes and developing country urbanites reach higher levels of incomes. These will also represent a larger share of the total emissions if cheap emission abatement options are implemented first (electricity, manufacturing,...). Finally urban forms and transport emissions entertain a strong relation and failure to promote urban forms which would lessen the need for carbon intensive transport would lock cities into non-sustainable pathways. As a result of these trends, there is a strong need to focus on the mitigation of emissions that stem from transport in cities. This should be done in developed country cities where these emissions are very large but proactive measures should also be taken in developing country cities to avoid a similar development pathway.

4 A SECTORIAL OR A SYSTEM'S LENS FOR URBAN TRANSPORT EMISSIONS?

Urban energy-related CO_2 emissions are very similar to national and rural emissions. They emanate massively from a limited number of uses such as transport (fuel consumption), residential (heating/cooling, lighting, cooking...), commercial (heating/cooling, lighting) and industrial (production linked energy use, heating/cooling, lighting) and energy production/conversion (electricity). So, why would urban energy-related CO_2 emissions warrant a specific focus? Why would sectorial policies not be better suited to tackle these emissions and their contribution to climate change? In a nutshell, the reason is that urban emissions, in particular urban transport emissions, are partially a by-product of the form that cities take. The following sections aim at discussing the channels available to reduce or avoid emissions, pointing out that relying solely on technological solutions

will likely fall short of the necessary emission abatement: structural aspects are key.

Urban transport emissions can be conveniently decomposed into a finite number of block determinants using the ASIF equation (Schipper, Marie-Lilliu, and Gorham, 2000). The ASIF equation reads as follows:

$$G = A \cdot S_i \cdot I_i \cdot F_{i,j}$$

With G being the sum of urban transport CO_2 emissions (tCO_2), A is the travel ***A***ctivity measured in passenger-kilometers and ton-kilometers for goods travel (pkm, tkm), ***S*** is the mode ***S***hare of various travel means such as individual cars, public transport, cycling or walking (%), ***I*** is the energy ***I***ntensity of travel by each mode (Joule/pkm or Joule/tkm) and ***F*** is the carbon content of each ***F***uel (tCO_2/Joule). Subscripts ***i*** and ***j*** refer to the mode ***i*** and fuel ***j*** respectively.

The reason for the popularity of the ASIF equation is that it allows to break-down urban transport CO_2 emissions in a way that closely matches the levers that exist to curb them. In fact, in more recent years, there has been a shift from discussing the ASIF to the ASI equation, the latter standing for Avoid – Shift – Improve, which is even more immediately policy oriented and less descriptive[7].

- ***A*** stands for **Activity** and measures the physical distances that are travelled by people (passenger·km) or goods (ton·km) for example during a year. When considering urban commuting, a good way of capturing Activity is by measuring the average distance travelled to work. For a given population size GHG emission abatement strategies targeting the Activity component will consist in reducing the distance to work (or other non-work related regular destinations). How this reduction in average distance manifests itself will be the subject of a following section.

- ***S*** stands for modal **Share** and measures the share of travel that is ensured by various modes (%). In urban settings for passenger transport, modes can encompass walking, cycling, cars, two-wheelers and public transport. Public transport, in turn, can take many forms from metros and buses to Bus Rapid Transit and, in many developing country cities, moto-taxis (Boda-bodas in Uganda) and often colorful minibuses (Tap-Taps in Haïti, Matatus in Kenya, Maghbanas in Guinea, Sotramas in Mali or Tro-Tros in Ghana). As fuel efficiency of vehicles increases with the number of occupants, collective transport modes typically require less energy per passenger when they are full than smaller transport modes. So, reducing fuel consumption for transport and related CO_2 emissions, implies a shift from personal to collective motorized transport, an increase in vehicle occupancy rates when these are below their carrying capacity and the promotion of soft modes of travel such as walking or cycling.

- ***I*** stands for energy **Intensity** of travel modes. It measures the amount of energy required for one unit of travel, for example a passenger·km (J/p·km). For each travel mode discussed above, technological progress can achieve substantial fuel savings. Improvements can take many forms from increasing motor efficiency (reducing the share of energy

[7] http://www.wrirosscities.org/media/shifting-gear-new-paradigm-tomorrows-cities.

which is lost in the form of heat in the combustion process for example – currently around two-thirds of the energy (Sims et al., 2014, p. 609)), to reducing the weight of vehicles, tire designs to reduce road friction or automatic energy use optimization such as stop-and-start systems that reduce the amount of time an Internal Combustion Engine spends idling. For each transport mode, ***i***, increasing fuel efficiency or reducing energy intensity of motorized vehicles implies technological progress. It should be noted that Internal Combustion Engines (ICE), as the oldest type of vehicle engine have benefited from well over a century of technological progresses, such that the differential between the present state and the theoretical maximum yield is narrow. While there are plenty of opportunities to increase fuel efficiency of vehicles as a whole, especially for newer hybrid, electric or hydrogen fueled vehicles, opportunities are not infinite and progress at some point has decreasing returns.

- ***F*** stands for carbon content of **Fuels**. It is measured in gC/J. The fuels that can be used for motorized transport encompass petroleum products (petrol, diesel, Liquefied Natural Gas (LNG),...), electricity and hydrogen or a combination of some of the prior in hybrid vehicles. Reducing CO_2 emissions from motorized transport using the fuel lever would imply a shift away from the most carbon intensive fuels such as petrol or diesel. However, whereas electricity and hydrogen have a zero end use carbon content (Tank-to-Wheel), their production can entail significant emissions depending on the process (Well-to-Tank).

When looking at the practical breakdown of emissions using the **ASIF** decomposition it is important to keep in mind that the different levers for emission reduction are 1/ inter-related and that 2/ maximizing the potential of all requires action sequencing. Take for example investments in a public transport network to promote collective mode ***S***hares. If these take place in a very sprawled and car-centric city with low population densities, the investments needed to provide households with an acceptable level of service will be huge and for large parts of the network, ridership will be very low. So that the economic cost of public transport is dependent on urban form. Public transport is indeed only efficient when there is concentration of demand. In this specific case, once the urban area has sprawled massively, investing meaningfully in public transport becomes near impossible. Levers ***A*** and ***S*** are related and both depend on the prior ability to limit low density urban growth. Similarly, sprawling urban areas are less favorable to soft transport modes as travelled distances are on average longer and the urban environment usually geared towards car travel, less secure for cyclists and pedestrians.

Another example of the inter-relatedness of emission reduction options is that of investing heavily in electric vehicles. It will only make sense to do so if the electricity itself is decarbonized. There is a key sequencing issue here. For example, if electricity is produced entirely from coal then its carbon content can even be higher than that of petrol. If however, it is produced though renewable sources or even nuclear plants, its carbon content can be close to zero. As a consequence advocating for fuel switching in motorized vehicles only makes sense if the production of alternative fuel is decarbonized in parallel.

5 CAN TECHNOLOGY DO IT ALL? (PROBABLY NOT)

5.1 *What to expect from Energy efficiency (**I**) with current technologies?*

Unitary fuel consumption in cars has decreased spectacularly since Internal Combustion Engines (ICE) and cars were popularized. Standing at 18 Litres/100km for the Ford T models in the early 1900s, that had on average a quarter of today's vehicle power (15kW) and could only reach 40 to 80 km/h, average fuel consumption in France is now closer to 6.5 Litres/100km.

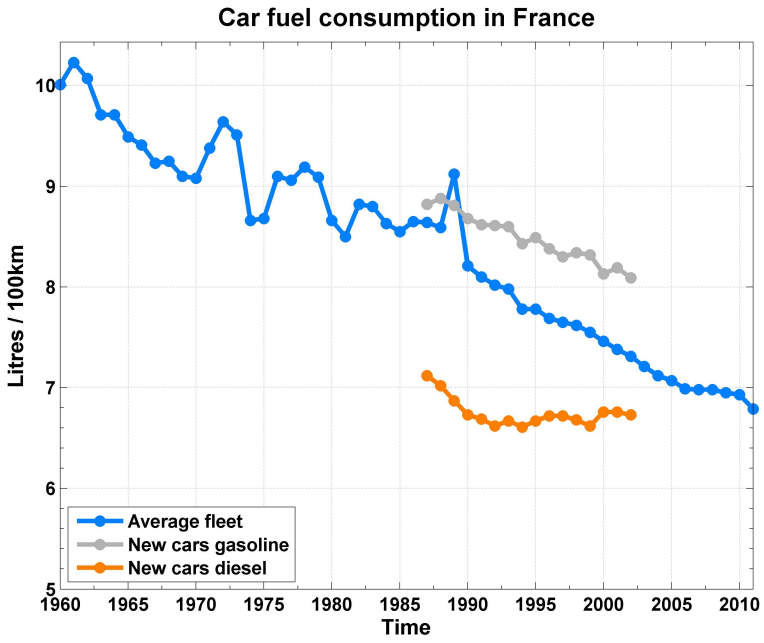

Figure 1.5: Fuel consumption by cars in France over the 1960 – 2011 period (data: SoES – CGDD)

While conventional measures indicated that new cars consumed on average 6.7 litres/100km in OECD Europe in 2005, the figures in North America, Africa and China were much higher at 9.5, 10 and 9.1 litres/100km (IEA and WBCSD, 2004). There are therefore theoretically large gains to be expected in terms of emission abatement from fuel efficiency (***I***) in the future. However three sets of dynamics should caution against excessive optimism. First, as discussed above, the increase in motorization rates and motorized travel in developing and emerging countries is likely to offset any gains on the intensive margin. Second, a 'rebound effect' can kick in, whereby marginal monetary savings due to higher fuel efficiency are partially reinvested in more travel leading to increased mobility and lower fuel savings. When deciding how much to travel or where to settle in an urban area (which in turn determines how much travel is needed), transport costs are indeed a key determinant and if these are lowered because of lower fuel consumption, it can result in more travel. This effect is consistent both with urban economics (Fujita, 1989) and the theory of constant monetary travel budget (Zahavi and Talvitie, 1980). There are no definite answers on the magnitude of the rebound effect with Wang, Zhou, and Zhou (2012) reporting that it is as high as 96% for urban passenger transport in China but other studies showing it can be as low as 10% according to a recent study in the U.S. (Gillingham,

Jenn, and Azevedo, 2015). Third, there are asymptotic limits to how much fuel efficiency can be achieved with ICE engines. The IEA (2009) for example reports that progress in spark and compression ignition engines could deliver long term (2050) fuel savings in the range of 28 – 33% compared to 2005 but probably not more unless partial hybridization is implemented.

5.2 *What to expect from fuel switching (**F**)?*

Fuel switching means replacing or combining fossil fuel products with less carbon intensive fuels. There are three main types of fuels that have the theoretical potential to be combined with or replace gasoline and diesel: biofuels, electricity and hydrogen. The appeal of biofuels, after a short period of euphoria, declined in the late 2000s. There are several reasons for this. First, the production of first (and in part second) generation biofuels entailed direct competition for land and water with food products, timber or other agricultural uses. As such they are supposed to have contributed to the rise in price of food products in 2008 that negatively impacted developing country populations and have become less politically acceptable. Second, their carbon content, when assessed over the life cycle of the crop, may be much less low than initially expected and in some cases compares unfavorably to gasoline and diesel (Waisman, Guivarch, and Lecocq, 2013). However, third generation biofuels, derived mostly from algae, would not compete with food products for arable land and potentially present interesting yields. The production of algae for fuel purposes has however not been undertaken on a commercial as yet.

Hydrogen and electricity have theoretically larger potential to curb CO_2 emissions. Electricity in particular is currently considered as the substitute to liquid fossil fuel with the most potential. First, electric vehicle propulsion systems are well known and do not represent major technological difficulties. Second, electricity distribution networks already exists throughout the world and their extension to service fuel electric cars and other vehicles, while challenging, is not insurmountable. Fuel cell vehicles also rely on an electric motor. Hydrogen is converted to electricity on-board by electrochemical conversion. But hydrogen, unlike fossil fuels, is not easy to transport, distribute and store, especially in vehicles where space is limited. Hydrogen, as a highly inflammable gas, also requires specific safety measures. Finally fuel cells are currently costly to produce and certain barriers still exist that would prevent mass deployment. So, in the current state of affairs, that could very well change quickly, electric vehicles seem to have an advantage over fuel cell vehicles. Three challenges do however still exist for fully electric vehicles to take over ICE: i) vehicle autonomy is currently limited by the capacity of batteries to stock enough energy, creating challenges for trips longer than 150 to 200km (Sims et al., 2014), requiring either fast charge systems or a battery exchange network, ii) the costs of batteries, although declining rapidly, are still prohibitive and iii) electricity production will have to be scaled up so as to meet demand if electric vehicles represent a significant share of on-road vehicles in the future[8]. For these reasons, it is expected than in the short to

[8] Some authors have argued that electric vehicles could offer an interesting solution to the intermittence of renewable power sources such as wind or solar (Chateau et al., 2011). By stocking electricity, electric vehicles could even feed the grid when they are not in use and connected through a plug. The WETO-T report imagines a scenario where 2 million electric vehicles are plugged in to the grid at any given time. When each car has a power of 50kW, the combined instantly available electricity would be 100GW.

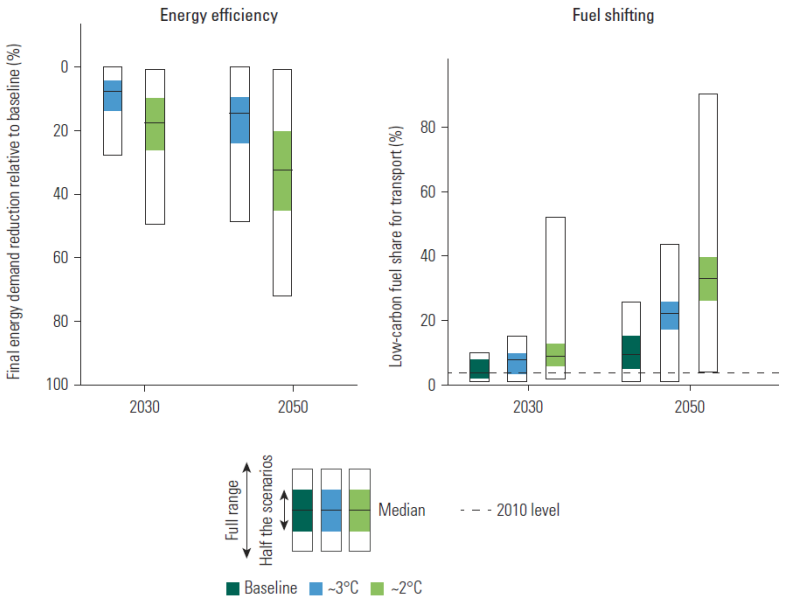

Figure 1.6: Actions required in the transportation sector to limit temperature rises compared to pre-industrial levels below 2°C or 3°C. Figure from Fay et al. (2015) adapted from IPCC (2014). License: Creative Commons Attribution CC BY 3.0 IGO

medium term, hybrid vehicles running on a combination of fossil fuel and electricity will be more competitive.

The contribution of electric (and Fuel Cell) vehicles to GHG abatement crucially depends on the production mode of electricity (and hydrogen). Only if the electric mix is sufficiently decarbonized will electricity and hydrogen provide CO_2 emission gains. In places where electricity is for example generated overwhelmingly from coal (with a higher carbon content than liquid fossil fuels), using electricity to fuel passenger vehicles instead of gasoline or diesel could result in an increase rather than a decrease in CO_2 emissions, despite the higher efficiency of the electric motor compared to ICE (90% vs 20-25%). While vehicle electrification comes with its challenges, as detailed above, the most important step is to first decarbonize electricity (Fay et al., 2015). A World Bank report building on findings from the IPCC shows that the share of low-carbon, neutral and even negative-carbon energy supply must rise from less than 20 percent in 2010 to about 60 percent in 2050 to be able to reach the 2 Celsius degree temperature increase (Fay et al., 2015). In this case, electricity must be produced from 1/ renewable energy such as solar, wind and hydropower, 2/ bioenergy and bioenergy coupled with carbon capture and sequestration (CCS) and 3/ nuclear power. Bioenergy coupled with CCS produces negative emissions which can offset the positive emissions from the remaining 40% of electricity production. In the case where CCS and nuclear power are not available in the future, it is still possible to reach the 2 Celsius degree target but these scenarios will require higher penetration of zero carbon electricity production technologies. The same conclusion holds if the potential for biomass, solar and wind based electricity production is constrained (Audoly, Vogt-Schilb, and Guivarch, 2014).

Many of the technologies needed to produce low or zero-carbon electricity – such as wind and solar – have progressed in recent times and their costs have decreased significantly, becoming competitive with more traditional and carbon intensive electricity production methods. The deployment of

other technologies such as CCS face larger uncertainties in terms of political acceptability and costs.

Overall, in the transportation sector – but without focusing specifically on urban emissions – the findings from the 5th IPCC report, building on conclusions from over 30 Integrated Assessment Models, point to a mix between fuel switching and final energy demand reduction to achieve the targets of 2°C or 3°C. To avoid higher temperature rises than 2°C, final energy demand in the transportation sector should go down by 20% in 2020 and 30% in 2050 and the use of low-carbon fuels, mainly low carbon-content electricity should go up by 30% in 2050 (see Figure 1.6) compared to a baseline. Assuming that urban transport emissions behave in a similar way to transport emissions in general, it appears that relying on fuel switching alone will result in insufficient CO_2 emission reductions. There is parallel need to reduce the demand for energy for transportation which involves both reductions in 1/ the energy intensity of travel and 2/ in the demand for transport. A strong case could be made that reduction in transportation demand is easier in cities for intra-urban travels than in between cities.

6 THE URBAN FORM AS A DETERMINANT OF URBAN TRANSPORT CO_2 EMISSIONS

Perhaps one of the most striking illustrations of the relationship that urban form and travel requirements entertain is provided by Bertaud (2002) while documenting from space the footprints of the built-up areas of Atlanta and Barcelona at the same scale (Figure 1.7). In 1990, both cities were home to approximately the same population, 2.5 and 2.8 million people respectively, for vastly different urban forms. Whereas, Atlanta's built-up area occupied close to 4.3 thousands square kilometers of land, Barcelona's stood at just 162km^2, i.e. 26 times smaller. It is easy to understand visually that trip length within Atlanta will on average be longer than in Barcelona, increasing transport demand. In fact, Bertaud reports that the longest possible trip in Atlanta is 137 km while it is only 37 km in Barcelona. And Atlanta and Barcelona do not only differ by their trip distances but also by how they can be served by public transport: Barcelona's metro network was 99 km^2 long in 1990 and ensured that 60% of its population lived within 600 meters of a station. To achieve the same accessibility figures, Atlanta would have to build a metro system covering 3,400 kilometers (vs a 74 km actual network) – an extremely expensive endeavor, near impossible to implement. Not surprisingly, users of Atlanta's metro network are few, 4.5% while they stand at 30% in Barcelona. So that, the form of urban areas, not only determines the average trip distances but also the transportation options available and mode shares.

Going back to the $ASIF$ equation discussed earlier, the comparison between the urban footprints of Atlanta and Barcelona is telling us that urban form has consequences on A – Activity and on S – Mode Shares. The lower demand for transport (A) associated with lower average traveled distances in Barcelona as well as the possibility of meeting that demand with collective transport options (S), which are less energy intensive than individual transport modes, indicate that the Spanish city through its urban structure alone will lead to lower CO_2 emissions per capita from urban transport.

This relationship between urban form and energy consumption for transport (and thus emissions) has been famously captured by Newman and Kenworthy (Newman and Kenworthy, 1989a,b). The authors established an inverse relationship between average population density and fuel consump-

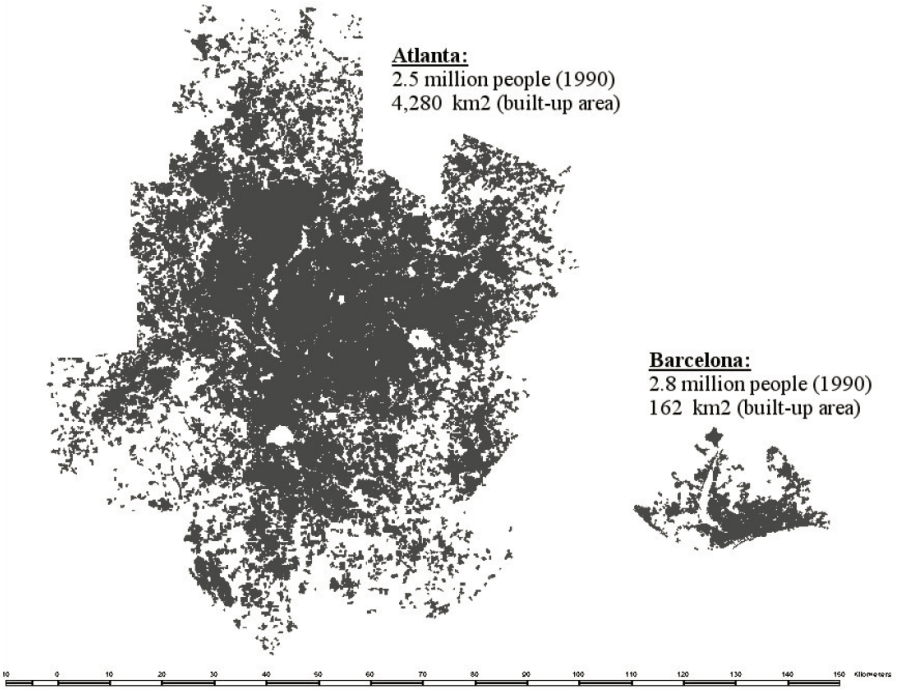

Figure 1.7: A comparison of the spatial footprints of the built-up areas of Atlanta, US (left) and Barcelona, Spain (right) in 1990 represented at the same scale (Bertaud, 2002)

Figure 1.8: The relationship between average population density in cities and energy consumption for transport. Figure removed in the diffusion version of the dissertation. It is consultable at source: Jacquet et al. (2010) p256 which rebuilt the relationship first publicized by Newman and Kenworthy (1989) using The Millenium Cities database (UITP).

tion for transport in a sample of 32 cities around the World. They found the following regional differences: gasoline consumption in U.S. cities was i) twice as high as in Australian cities, ii) four times higher than in European cities and iii) ten times higher than in Asian cities. Importantly, the authors found that differences in income, gasoline prices and vehicle efficiency could only explain half of the differences in gasoline consumption and attributed the remainder to land use and urban form variables summarized by average population density. Their main conclusion is that city leaders should focus on planning as a major instrument in order to reduce fuel consumption and CO_2 emissions from urban transport.

These publications triggered a vast literature focusing on the link between urban form, travel patterns and fuel consumption. And the findings and recommendations of the authors were challenged on several counts with much back and forth between proponents and challengers of the compact urban form. These critics can be broadly categorized into three buckets: i) those that question the link (or its magnitude) between urban form and travel patterns (and thus CO_2 emissions), ii) those that deem the cost of acting on urban form to be too high or unjustified and iii) those that contend that striving for compact cities would come with unexpected environmental costs in the form of compensatory travel.

6.1 *Objection 1: Questioning the link between urban form and travel patterns*

First, Newman & Kenworthy's study was tackled on the grounds of its methodological soundness. Gordon and Richardson (1989) and Gordon (1997) in particular challenged the study and put forward several limitations that they believed to skew the results. They mention specifically the fact that when 3 "odd" cities out of the 32 (Hong Kong, Singapore and Moscow) are removed from the sample and the difference in gasoline prices are properly accounted for, a doubling of population density would be required to achieve a 15% reduction in energy use. So a much larger densification would be needed to achieve a much smaller reduction in gasoline use. Secondly these authors argue that gasoline price variations have much larger impacts on gasoline consumption than population density and this is misrepresented in the initial study. An updated version of the initial database published in 2003 added 51 cities to the dataset which addressed the city selection bias.

Second, a very large number of studies investigating the relationship between the built environment and travel patterns found different and often contradictory results. These were surveyed by Crane (2000) and part of the confusion can be attributed to the diversity of methods used, outcomes measured and built-environment variables retained for the studies. For example, a more mixed-use (residential and commercial activities) neighborhood can be associated with higher trip frequencies and yet lower miles travelled. Crane's conclusion is that given these uncertainties and the low magnitude of the impact of the built environment found on travel behavior, caution should be exerted before using planning as a means to reduce travel outcomes. When putting these contradictory results together, it is tempting to conclude that urban form has limited impact on travel patterns but that pushing for compact forms would be tied to large costs – this has led some scholars to call the compact city a fallacy (Neuman, 2005).

But more recent research has i) found more positive links between urban form and reduced travel or gasoline consumption and ii) been more successful at explaining the apparently contradictory results. Papers by

Karathodorou, Graham, and Noland (2010) Brownstone and Golob (2009) Bento et al. (2005) Næss (2012) and the meta-analysis by Ewing and Cervero (2010) have found much clearer and positive links between either Vehicles Miles Travelled (VMT) or fuel use in relation to built environment variables including population densities. Secondly, the reasons for contradictory (or seemingly so) results between studies can be explained by the geographic scale at which the impact is measured. Næss (2012) based on 30 similar studies conducted in Nordic countries indeed finds positive but weak relationship between neighborhood characteristics, including population densities, and travel patterns of their residents. The weakness of the relationship at the neighborhood level can be explained by the fact that people value diversity. So that the proximity to some activity at the neighborhood level does not imply that people will systematically shop nearby or find work in close proximity to home. Therefore, differences between neighborhoods of the same city will not be that strong irrespective of the local density. Naess does however find higher neighborhood effects when the distance to the main center of activity is accounted for and he questions whether this variable was systematically introduced in previous studies mainly focusing on US cities and at the neighborhood level. But most importantly, at the scale of the urban area the effects are much larger. At the level of the urban area, the average population density effect has a much stronger role as it reduces the average distances travelled irrespective of whether residents commute close or far from home. Gudipudi et al. (2016) using consistent definitions and datasets for urban area extents for all US cities, found that a doubling of density was associated with a 42% reduction in CO_2 emissions from buildings (residential and commercial) and on-road sectors, with the transport sector exerting the highest changes.

In total, while Newman and Kenworthy's initial study did suffer from some flaws, their main conclusion that average population density is strongly and negatively associated with fuel use for transport and thus CO_2 emissions has benefitted from strong scientific support. Contradictory results can mainly be explained by the geographic scale at which the impacts are observed, with studies focusing on inter neighborhood comparisons of built environment properties showing smaller effects on CO_2 emissions and travel behaviors.

6.2 *Objection 2: The costs of acting on urban forms are too high or unjustified*

Having established that urban forms entertain a strong relationship with travel behaviors, we can now turn to a more fruitful debate which is focused on whether acting on urban forms as a way of reducing travel demand and emissions is justified.

A central finding from urban economics is that cities expand spatially as i) their populations grow, ii) as household incomes increase, leading to more demand for housing and as iii) transport costs fall, allowing people to reach more distant locations for a given cost or within a given time-frame. Spatial expansion is indeed natural. The question is whether it is excessive, i.e. whether it is larger than is socially optimal (Brueckner, 2000, 2001). Spatial expansion can be deemed excessive if it is artificially encouraged by public policies which fail to price negative externalities associated with it correctly[9]. The failure can take several forms. The main one would be transport prices

[9] Controlling for population growth or movements between regions is not a desirable or realistic (within a country) option. Similarly, deliberately limiting income growth is unrealistic. This

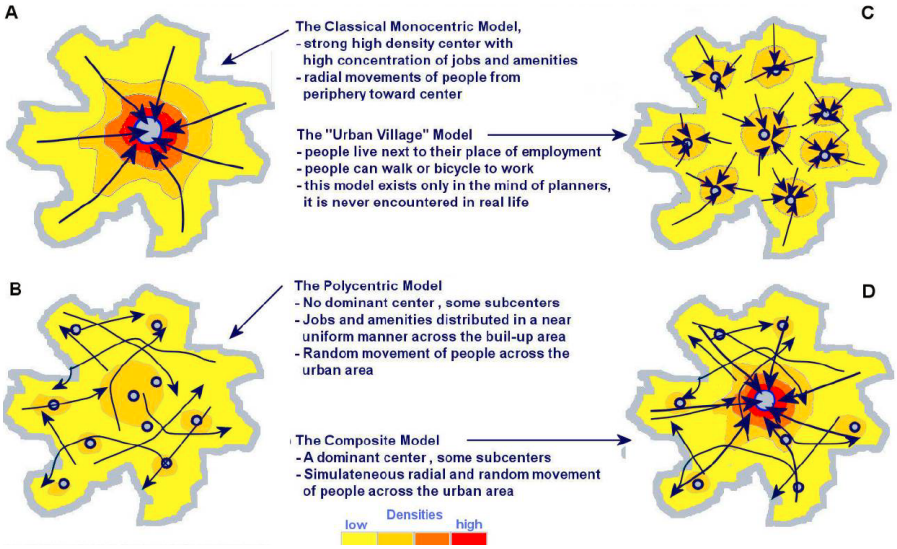

Figure 1.9: Internal urban structures and associated commuting flows. Source: Hoornweg et al. (2011), pp110 based on Bertaud (2002).

that do not cover the negative externalities of the transport demand they induce (congestion, pollution, road fatalities or CO_2 emissions). Parry and Small, show that the costs of congestion by far dominate other externalities from transport (Parry and Small, 2005).

Another key failure would be implicit land development subsidies that encourage land consumption in the outskirts of cities without factoring in the costs of servicing distant land plots with infrastructure (sewage, roads, electricity etc...) or the induced transport demand they will trigger. If these externalities were properly accounted for through public policies, spatial expansion should not be deemed excessive and in fact aiming to achieve more compact urban forms would lead to lower social welfare as it would increase land scarcity and thus land and indirectly housing prices. Mechanisms and policies to correctly price negative externalities generated by urban expansion theoretically exist as Brueckner describes (2000): congestion tolls, land development fees... However, the are some large difficulties in understanding the impacts of urban expansion on some behaviors such as travel (as the present introduction has discussed) and the links between these and climate change impacts are even less well understood as demonstrated by the large debates on the correct price of carbon, see for example the Report of the High Level Commission on Carbon Prices (Stiglitz et al., 2017) and its background papers. In total, it appears that while the economic forces of urban expansion are *natural* and strong, actions to curb urban growth are legitimate. The open debate is on what form they should take and how stringent they should be[10].

Another criticism of policies and discourses aiming to achieve or promote compact urban forms comes from scholars that point to the decentralization of jobs as allowing, potentially, for simultaneous urban sprawl and reduction in transport demand (while allowing for lower housing costs). The logic

leaves transport and land use policies and investment choices as the main levers to act on urban forms.

[10] It should be noted that if the focus is specifically on emissions from transport, rather than on the size of urban areas, the definition of optimal policies is further complicated because of mode choice between collective and less pollutant and private cars.

behind these claims is that the observed tendency of jobs to decentralize in parallel to population decentralization could allow at least partially for co-location of workers and homes (Gordon, Kumar, and Richardson, 1989; Gordon, Richardson, and Jun, 1991). This job decentralization follows the same principles as population decentralization: decreases in transport costs would allow firms to settle in more distant locations and to enjoy cheaper land[11]. Co-location of firms and workers would provide both with the benefits of being close to services they need to access on an irregular basis while significantly curbing the amount of commuting on a daily basis. Models of internal urban structures and possible commuting patterns have been illustrated by Alain Bertaud (see Figure 1.9) and these schematic drawings are useful to comprehend the possible transport outcomes associated. Recent research assesses that the monocentric model is no longer dominant in US metropolitan areas and that the best descriptions of urban areas would be closer to the composite model below. In fact Angel and Blei show that travel patterns to jobs are mainly chaotic between dispersed jobs and residences, despite evidence of some degree of colocation (Angel and Blei, 2015a,b)[12]. This conclusion points to limited scope for co-location of jobs and homes to reconcile urban sprawl and reduced commuting.

There are many possible reasons for this absence of perfect co-location between homes and jobs. First, multi-worker households would tend to prefer locations that provide all workers with a reasonable access level to their job location, making perfect co-location impossible. Second, many other factors enter the locational decisions that households take: the availability of good neighborhood schools for children, the availability of nearby leisure options (cinemas, restaurants, bookshops,...). Third, with high job turnovers, household are less likely to move each time they change jobs as this would lead to large transaction costs.

6.3 *Objection 3: The possibility of compensatory travel*

A last area of discussion of the link between urban forms and travel behaviors stems from the possibility that leisure travel would be higher for urban residents living in dense areas. The underlying rationale is that residents of dense urban areas crave the outdoors and to escape the densely built environment for green sceneries when they have a chance, implying longer (and more emitting) travels on the weekends or during the holidays. In parallel, residents of low density areas in the outskirts of cities, would not have such desires because they already reside in the vicinity of green sceneries. In France, such a behavior has been termed the "barbecue effect" (Orfeuil and Soleyret, 2002), where people living in central apartments would leave the core city on the weekend to enjoy some fresh air and a barbecue in the periphery of urban areas thereby travelling longer distances. Another explanation for compensatory travel is that central residents would reinvest the time and money saved on a daily basis with short commutes into ex-

[11] As described briefly at the beginning of this introduction, not all firms will choose to decentralize – those that face large land costs and that benefit less from agglomeration economies would be better candidates.

[12] The authors, Angel and Blei document the evolution of the spatial dimensions of labor markets in the US. They identify that this spatial pattern can be best described by a "Constrained Development model" which has some employment centralities but mostly dispersed residences and jobs, many chaotic commuting patterns, and where the residential moves to remain within reasonable times and distances of jobs play a role in maintaining an integrated labor market alongside densification and improvements in travel speeds.

tended leisure trips. This interpretation is consistent with time and monetary travel budgets. The barbecue effect or compensatory travel hypothesis can go beyond travel to the urban periphery and extend to airplane or car travel to more distant cities. In this case, the motivation for compensatory travel would not be access to nature but the desire to break a daily routine (Czepkiewicz, Heinonen, and Ottelin, 2018). The concern with such compensatory behavior is whether it could outweigh the benefits in terms of travel and emissions of a more carbon sober daily commute that dense urban areas provide (Holden and Norland, 2005). The concern finds some rationale in the fact that leisure mobility nowadays accounts for a very large share of total personal travel – between 27% and 57% in 2010 for "occasional mobility" (vs. daily mobility) in Geneva and Zurich depending on whether people reside in the city center, in the suburbs or in peri-urban areas (Munafò, 2017). The possibility for such behaviors has triggered a line of literature that, while employing different methods, seems to conclude that compensatory travel exists to a certain extent but that its magnitude would not be sufficient to offset the daily environmental benefits of living in denser areas (Næss, 2006, 2016). It could also be argued that, compensatory travel, especially when it manifests itself through air travel, could be tackled through different policy options such as fuel and airplane taxes rather than by seeking to alter urban forms which structure regular travel behaviors.

7 PATH DEPENDENCE IN URBAN FORMS REQUIRES EARLY ACTION

Built-up areas display strong inertia because of the very large sunk costs involved in building structures and infrastructure. Urban structures share a "putty-clay" quality (Lall, Henderson, and Venables, 2017): once built, they are difficult to modify and can stay in place for more than 150 years (Hallegatte, 2009). Because of these large sunk costs, long structure lifetimes and transaction costs, urban forms can only evolve slowly at the pace of new construction and gradual structure renewal. They cannot adapt fast to changing conditions (such as changes in oil prices or population influxes for example) even when large social gains would be possible. A fascinating illustration of this phenomenon is provided by the reconstruction in the aftermath of the Great Boston fire in 1872. The scale of the destruction was so large that entire neighborhoods were destroyed, but in the process the reconstruction efforts were able to reshape the city entirely and overcome some of the irreversibility associated with built structures. It was estimated that the increases in land values alone were comparable to the values of the buildings destroyed (Hornbeck and Keniston, 2017). A similar natural experiment in San Francisco after the 1906 fire shows that, in neighborhoods that were razed and rebuilt, population densities were 60% higher compared to unburned areas and that a large density differential remains today (Siodla, 2015). Both these examples illustrate the large redevelopment frictions that exist in cities and the persistence of development pattern. A last example of urban path dependence is the persistence of higher density in proximity to where street cars used to run in Los Angeles. While street cars operated mainly around the 1910s, had declining ridership after that and were totally off the road in 1963, structures to date in proximity to these routes are significantly denser, including newly built structures. This persistence cannot be explained by the preferential geographic location of old streetcars nor subsequent public investments and involves some path dependence

in zoning regulation together with agglomerative forces (Brooks and Lutz, 2014).

A corollary to the inertia of urban forms is that, in mature cities that experience slow demographic growth, reductions in urban transport emissions associated with increased compacity has limited potential (Gordon, 2008). A doubling of the average density discussed in the previous sections for example would be virtually unattainable. Reducing the urban footprint would be very difficult, so that increases in density would have to come from new population residing in denser neighborhoods. Just as an example for an urban area which is growing at rate of 1.5%/year, this would take 47 years and would imply that the construction industry is able to find available land or would be able to rebuild most buildings at higher densities in such a time-frame. Conversely, in fast growing cities of the developing world, where urban population is expected to double over the next 30 years or so, the potential to achieve dense cities and depart from highly energy and transport intensive pathways is unique and large. But the magnitude of this potential hinges crucially on making the appropriate policy choices now as these cities are currently growing. Whatever urban and transport policy and investment choices are made today (including planning and public transport investments) in fast growing cities of the developing world will shape their urban form for decades or centuries to come. This means that there is a slim window of opportunity to "get it right" and steer urban development on a pathway to sustainability in these settings.

In facing this window of opportunity decision makers in fast growing cities, when deciding how their cities should grow and how much to invest in collective transport, should recognize the asymmetric nature of the choice they have. While accelerated urban expansion is always possible if future information indicates that current urban growth is too stringent or if future technologies become available to reconcile urban sprawl and low transport emissions, the opposite is not true. The path dependence of urban forms creates an option value attached to density and collective transport infrastructure. So that the robust strategy in the context of uncertainty is the compact city (Crifo et al., 2012).

Vogt-Schilb, Meunier, and Hallegatte (2018), illustrate the robustness of compact cities and strong public transport networks by showing that it is less costly in the long-run to start with costly CO_2 emissions abatement options – such as public transport – than cheaper options. This runs counter-intuitive to common reading of Marginal Abatement Costs Curves (MACCs) which lead to prioritizing cheap abatement options and then gradually working toward more costly options. The difference can be explained by the fact that MACCs implicitly assume that abatement options are continuous, i.e. people can drive a few miles less each day or, natural gas power plants can run a few more hours a day compared to coal plants. However, many emission abatement options require one-time, indivisible investments such as public transport infrastructure. Because of the long-lived nature of these investments, early implementation will increase the abatement potential in the long run.

8 WHAT DOES THIS DISSERTATION LOOK AT?

While climate change is one of the most daunting challenges of this century, it is certainly not the only one. Eradicating extreme poverty, providing access to key public services such as water and sanitation and making

sure people have access to affordable housing for example are other key objectives. And decision makers throughout the World, recognize these as priorities. An urban emissions' mitigation strategy that would imperil reaching these other basic needs would carry no value. This is the reason why, when investigating urban and transport policy options that could curb GHG emissions in the future, it is important to understand the consequences on household's welfare, including through housing in urban areas.

This is precisely the objective of this dissertation: i) identify and evaluate policy options that have the technical potential to curb urban transport-related CO_2 emissions and ii) assess whether their implementation will come at the expense of households' welfare. The logic behind this two-pronged approach is that policies aiming to limit CO_2 emissions that dramatically deteriorate household welfare run the risk of being widely opposed and of being abandoned even before they are implemented. France is a case in point with two recent attempts at instituting or increasing carbon taxes in 2010 and 2018 having led to strong popular demonstrations and the subsequent policy implementation postponement or cancellation.

To be able to achieve such a comprehensive picture, one that encompasses both the effectiveness of policies or investments to curb urban-transport emissions and the impacts these can have on household welfare, there is a need for tools that can restitute the complexity of urban development. In particular, how transport and land uses interact to define welfare levels and what are the tradeoffs and synergies that policy makers face when devising strategies (Viguié and Hallegatte, 2012). In this dissertation we use a land use – transport model (LUTI) to investigate various urban and transport policies and investments. This model is simple enough that its results are understandable easily and its fundamental mechanisms likely to remain true over a long period of time[13] and yet detailed enough that it can shed light on the welfare of urban residents in particular through housing market mechanisms.

First, this dissertation investigates how a subset of urban and transport policies and investments can contribute to curb transport-related CO_2 emissions (or the impacts of climate change in a special spotlight to this dissertation) in urban settings through the lens of a micro-economically founded applied land use – transport model. The model used is developed for, calibrated on and applied to specific urban contexts (Paris, Buenos Aires, Toulouse) both to demonstrate its appropriateness in replicating major local urban trends, its usefulness to think through policy options in specific contexts and to provide realistic, albeit necessarily incomplete, assessments of the impacts of the tested policies. The framework retained for the choice of policies tested is illustrated by Figure I.10 below, where urban transport-related CO_2 emissions can be influenced through direct measures such as fuel taxation, public transport fare policies or through indirect measures such as land development/planning incentives or investments in infrastructure.

Secondly, this dissertation aims to document how, beyond CO_2 emissions outcomes, the tested policies are likely to affect household welfare, housing affordability, the internal structure of the urban area, urban sprawl and the political acceptability of mitigation strategies. These aspects are key, as discussed above, because CO_2 mitigation is but one of the objectives of decision makers at the national and local level. Moreover, if the objective is to reduce CO_2 emissions from urban transport, the effectiveness of a policy

[13] This is a key prerequisite for a prospective model that investigates the impact of policies on curbing GHG emissions, typically a long term issue.

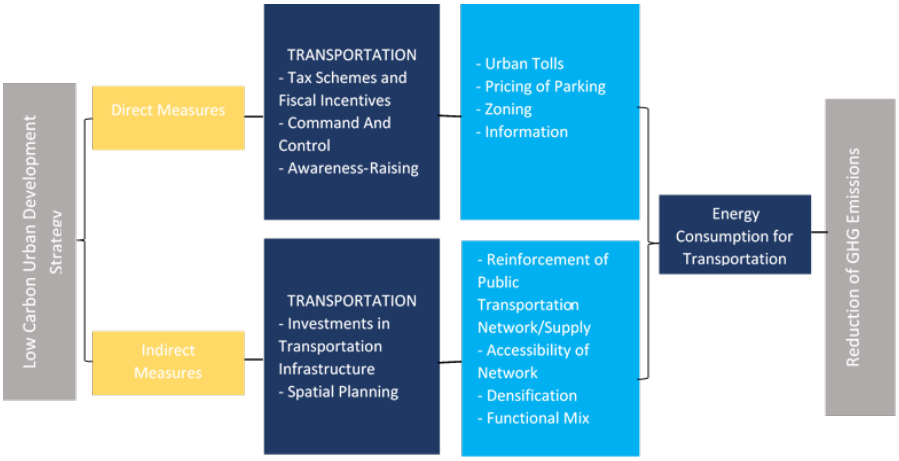

Figure 1.10: Channels for mitigating greenhouse gas emissions from urban transport. Figure adapted from Gracia et al. (2015).

will hinge on how politically acceptable it is. At the center of these potential tradeoffs stands the land use and transport couple. When reductions in CO_2 emissions are achieved through increased transport costs, they often entail significant increases in housing costs too, thereby reducing welfare. This dissertation looks into such tradeoffs but also investigates how to reconcile disincentives to private transport with more affordable housing.

The sub-questions/case studies that we look into in this dissertation are:

1. What are the consequences of investing in public transport on the effectiveness of carbon tax? Or framed differently, how much more acceptable are carbon taxes when public transport is available?

2. Can a land value tax whose rate is negatively linked to local built-up densities contribute to limiting urban sprawl? And if it can, will this come at the expense of housing affordability?

3. Are transit subsidies the best use of scarce public resources? Or can alternative uses deliver better results in terms of welfare, urban sprawl, commuting-related CO_2 mitigation? And what are the redistributive consequences of reforming transit subsidies?

To present our analyses and results regarding these questions, the dissertation is organized into four chapters (one modelling chapter and three analyses/results chapters) and one spotlight.

Chapter one presents in many details the applied urban economics model that is used throughout this dissertation. NEDUM-2D, originally developed in CIRED by Vincent Viguié and Stephane Hallegatte, was further adapted to be able simulate the alternative policy options investigated in this dissertation and enhanced where needed to capture key dynamics (addition of an endogenous transport technology module for example). For the purpose of this doctorate, NEDUM-2D was applied to three urban areas: Paris, France; Toulouse, France and Buenos Aires, Argentina. Each application required a full calibration exercise, in turn requiring the collection and processing of city-specific data on household incomes, population size and density distribution, transport infrastructure and costs for various modes, land use constraints and regulations, the land and housing markets as well as on construction technologies and costs. The philosophy of the model and its

main equations are described in this first chapter as a first step. Following this general presentation, a detailed calibration exercise for the urban area of Paris is presented in full with the description of the data used, the choices for key parameter values and the results of the validation. Subsequent chapters will only indicate where the modelling choices depart from this initial presentation (and in the case of Buenos Aires, the calibration and validation will be included as an annex). This technical chapter is the most arid of the dissertation and can be skipped by the reader that is not interested in model details. It is however indispensable for the reader that wants to understand the urban model's philosophy and choices given that NEDUM-2D is the main workhorse for the rest of the dissertation.

Chapter two is based on a paper titled "Carbon Price Efficiency: Lock-in and Path Dependence in Urban Forms and Transport Infrastructure" co-authored with Jun Rentschler and Stéphane Hallegatte and published as World Bank Policy Research Working Paper (Avner, Rentschler, and Hallegatte, 2014). This paper's main result is that a given level of carbon tax would be twice as effective to curb commuting-related CO_2 emissions in the short to medium term in an urban area where (decarbonized) public transport is available compared to an otherwise identical urban area but without public transport. This means that a given carbon tax level would achieve commuting-related CO_2 emission reductions that are twice as high with public transport. Alternatively, a given emission reduction objective could be achieved with carbon taxes that are 50% lower (and therefore more acceptable) with public transport than without in the short to medium term.

To assess the impact of public transport on the efficiency of the tax, the paper proceeds as follows. It investigates two exogenous scenarios using NEDUM-2D calibrated for the urban area of Paris: (i) a scenario with the current dense public transport infrastructure, and (ii) a scenario without. In the presence of public transport, households have three options to mitigate the adverse impacts of higher fuel costs: 1/ relocate closer to job opportunities, 2/ purchase more efficient vehicles and 3/ switch to public transport. Without public transport, households can only rely only on the first two options. It is shown that the price elasticity of CO_2 emissions is twice as high in the short run if public transport options exist. Reducing commuting-related emissions thus requires lower (and more acceptable) tax levels in the presence of dense public transportation. The emission elasticity also depends on the baseline scenario (especially population and income growth) and increases over time. In the longer run, elasticities are similar in the scenarios with and without public transport, due to larger urban reconfiguration in the latter scenario. The time profiles of the respective contribution of urban reconfiguration, fuel efficiency and modal switch (when available) towards CO_2 emissions mitigation are also documented. They capture the inertia and path dependencies that characterize the adaptation of urban forms to new economic conditions. This analysis may help calibrate general equilibrium models by providing price elasticities that depend on socio-economic and public transport infrastructure scenarios. If the goal of a carbon or gasoline tax is to change behaviors and reduce energy consumption and CO_2emissions (not to raise revenues), then there is an incentive to increase the price elasticity through complementary policies such as innovation support and infrastructure development. These results are not only of relevance in the context of emission reduction, but also for mitigating the effects of rising oil prices and the impacts of other externalities such as congestion, accident and air pollution. They suggest that where urban planning and

public transport are concerned, *"pollute now and clean up later"* can be a very inefficient strategy.

The spotlight departs from the rest of the dissertation as it is not focused on urban transport-related CO_2 emissions mitigation. Instead it looks at the mitigation of the impacts of the Urban Heat Island effect in urban areas. The spotlight is a reproduction of the main output of a cross-disciplinary project, of which I was part, aiming at integrating models at various scales to explore the magnitude of the Urban Heat Island effect in the long term in contrasting futures on the urban areas of Toulouse and Paris. In this case socio-economic, geographical, architectural, building energetics, urban climate and atmospheric models were combined in the ACCLIMAT project for the urban area of Toulouse. It equally investigates how urban planning strategies can affect energy demand for cooling. We include this article in this PhD dissertation as a spotlight and not as standalone chapter. The reasons are twofold. First, this journal article is the result of very large collaboration from many researchers and as a consequence, my contribution, although substantive, is only a fraction of the end result. Second, the topic of this article is mainly focused on adaptation, in this case on the mitigation of the impacts of the Urban Heat Island effect and therefore falls outside the main scope of this dissertation. For both these reasons, we chose not to include this article as a standalone chapter. Nevertheless, its inclusion as a spotlight seemed relevant because this article i) demonstrates that the NEDUM-2D model can be used convincingly to investigate adaptation strategies at the urban scale, ii) illustrates how NEDUM-2D can be coupled with another urban model, harnessing their respective strengths, and integrated into a stream of models investigating complex phenomena. This articles was published in the Urban Climate journal, volume 10 in 2014.

Chapter three is based on a paper titled "When taxation Construction leads to More Construction: Modelling the Impact of a Land Value Tax on Low Density" co-authored with Vincent Viguié, Stephane Hallegatte and Basile Pfeiffer. A French version of the paper was published and further improved (Avner, Viguié, and Hallegatte, 2013). This paper shows that a specific land value tax whose rate is lower when local built-up densities are higher can contribute to limiting urban sprawl if it is applied correctly. It is further shown that, again conditional on specific implementation, this urban sprawl mitigation does not come at the expense of higher housing costs and lower household welfare making it a-priori a useful tool.

The externalities caused by urban sprawl are the subject of intense research activities. The overwhelming conclusion is that this phenomenon has major environmental disadvantages including higher energy consumption and excessive usage of land at the detriment of agriculture and natural sceneries. The Payment for Insufficient Density is a measure that made its entry into French law in 2012. It enables mayors to tax real estate developers in the case where the floor-area ratio of a new building does not meet a defined Minimum Density Threshold. Such a policy aims to mitigate urban sprawl. However, its potential consequences on housing supply and the revenues it can generate are not easy to anticipate. In this study, we investigate the potential impacts of such a policy, and analyze how it can be best used to gain efficiency, while keeping social costs low. We carry out this study by using a simple dynamic Land-use transport integrated urban model (NEDUM-2D) applied to the urban area of Paris. It is found that, if appropriately implemented, the Payment for Insufficient Density can limit urban sprawl, and, at the same time increase overall housing supply.

Surprisingly, the Payment for Insufficient Density by taxing construction can thus lead to an increase in total floor space, and therefore to a decrease in average housing prices. However, implementing such a policy can be tricky. The choice of the Minimum Density Threshold conditions its efficiency in a non-trivial way. The choice of the optimal threshold will vary, depending on the prime objective of the policy. Limiting urban sprawl, maximizing access to public transport or decreasing commuting distances, for example, lead to different optimal threshold choices. This paper deepens our knowledge on the capacity of policy incentives targeting the use of land to limit urban sprawl and its associated transport-related energy consumption. It also investigates whether the mitigation of urban sprawl comes at the expense of affordable housing, another important political objective and concludes to the absence of a tradeoff in this specific case.

Chapter four is based on a paper titled "Buses, Houses or Cash? Socio-economic, Spatial and Environmental Consequences of Reforming Public Transport Subsidies in Buenos Aires" co-authored with Shomik R. Mehndiratta, Vincent Viguié and Stéphane Hallegatte and published as World Bank Policy Research Working Paper (Avner et al., 2017). This paper, set in the urban area of Buenos Aires, asks the question of whether transit subsidies are the best use of scarce public resources or whether alternatives could produce better outcomes in terms of household welfare, urban sprawl, and commuting-related CO_2 mitigation. And what would the redistributive consequences of reforming transit subsidies be? The paper shows that the ideal candidate to replace transit subsidies – a lump sum transfer – would indeed lead to higher household welfare but that this would come at the expense of higher commuting-related CO_2 emissions and short term harsh redistributive impacts for homeowners situated in the periphery. Other alternative uses of the subsidy fund would overall perform less well than transit subsidy scheme.

Transit subsidies in the urban area of Buenos Aires had sky-rocketed since the financial crisis in 2001 until 2018 when they were reformed. In 2012, these transit subsidies amounted to US$5 billion. They have been challenged on several counts: suspected of driving urban sprawl and associated infrastructure costs and failing to reach the poor among others. In this context, this paper examines the impacts of cost recovery fares under a range of different policy scenarios that could cushion the impact of fare increases. The alternative scenarios are the uncompensated removal of the transit subsidy, its replacement by a lump sum transfer, and its replacement by two different construction subsidy schemes. On one hand, the removal of a transit subsidy is likely to decrease public transport usage and would tend to increase transport-related CO_2 emissions. On the other hand, the increase in transportation costs would incentivize households to reduce their transport demand, which would tend to mitigate CO_2 emissions. Using a dynamic urban model calibrated for the urban area of Buenos Aires, all scenarios are assessed along four dimensions: (i) the efficiency/welfare impact on residents, (ii) the impacts on the internal structure of the urban area and sprawl, (iii) the impact on commuting-related CO_2 emissions, and (iv) the redistributive impacts, with a focus on the poorest households. A series of results emerge. First, there are consumption-related welfare gains for residents associated with replacing the transit subsidy by a lump sum transfer. Second, there are only moderate reductions in urbanization over time and thus infrastructure costs associated with the subsidy removal. Third, the replacement of the transit subsidy leads to only moderate increases in

CO_2 emissions despite lower public transport mode shares. Finally, the replacement of the transit subsidy by a lump sum transfer will lead to short-term harsh redistributive impacts for captive transit users in some areas of the urban area. Medium-term adjustments of land and housing prices will partially mitigate the negative impacts of higher transport costs for tenants, but will further hurt homeowners. This paper addresses the complex design of a transit pricing policy under multiple objectives and sheds light on the potential tradeoffs between mitigating emissions and welfare and equity objectives.

A final section concludes the dissertation. It summarizes the main findings of the doctorate, raises some questions worthy of further investigation and points to the path ahead.

REFERENCES

Ahlfeldt, Gabriel M. and Daniel P. McMillen (2015). "The vertical city: the price of land and the height of buildings in Chicago 1870-2010." In: *SERC Discussion Papers*, SERCDP0180.

Angel, Shlomo and Alejandro M. Blei (2015a). "Commuting and the productivity of American cities." In: *NYU Marron Institute of Urban Management* Working paper #19, pp. 1–44.

— (2015b). "Commuting and the spatial structure of American cities." In: *NYU Marron Institute of Urban Management* Working paper #20, pp. 1–55.

Audoly, Richard, Adrien Vogt-Schilb, and Celine Guivarch (2014). *Pathways toward zero-carbon electricity required for climate stabilization*. Tech. rep. WPS7075. The World Bank, pp. 1–20.

Avner, Paolo, Shomik Raj Mehndiratta, Vincent Viguie, and Stéphane Hallegatte (2017). "Buses, houses or cash ? socio-economic, spatial and environmental consequences of reforming public transport subsidies in Buenos Aires." In: *World Bank Policy Research Working Paper* 8166, pp. 1–54.

Avner, Paolo, Jun E. Rentschler, and Stéphane Hallegatte (2014). "Carbon Price Efficiency: Lock-In and Path Dependence in Urban Forms and Transport Infrastructure." In: *World Bank Policy Research Working Paper* 6941.

Avner, Paolo, Vincent Viguié, and Stéphane Hallegatte (2013). "Modélisation de l'effet d'une taxe sur la construction: le Versement pour Sous-Densité." In: *Ville et Logement*. Ed. by Sabine Le Bayon, Sandrine Levasseur, and Christine Rifflart. Revue de l'OFCE - Débats et Politiques 128. Puteaux: Editions du Net.

Baer, Paul, John Harte, Barbara Haya, Antonia V. Herzog, John Holdren, Nathan E. Hultman, Daniel M. Kammen, Richard B. Norgaard, and Leigh Raymond (2000). "Equity and Greenhouse Gas Responsibility." In: *Science* 289.5488, p. 2287. DOI: 10.1126/science.289.5488.2287.

Baum-Snow, Nathaniel (2007). "Suburbanization and transportation in the monocentric model." In: *Journal of Urban Economics* 62.3, pp. 405–423. ISSN: 00941190. DOI: 10.1016/j.jue.2006.11.006.

Bento, Antonio M., M. L. Cropper, A. M. Mobarak, and K. Vinha (2005). "The effects of urban spatial structure on travel demand in the United States." In: *Review of Economics and Statistics* 87.3, pp. 466–478. ISSN: 0034-6535, 1530-9142. DOI: 10.1162/0034653054638292.

Bertaud, Alain (2002). "The spatial organization of cities: Deliberate outcome or unforeseen consequence?" In: *World Development Report 2003, background paper*.

Brooks, Leah and Byron F. Lutz (2014). "Vestiges of Transit: Urban Persistence at a Micro Sale." In: *SSRN Electronic Journal*. ISSN: 1556-5068. DOI: 10.2139/ssrn.2752034.

Brownstone, David and Thomas F. Golob (2009). "The impact of residential density on vehicle usage and energy consumption." In: *Journal of Urban Economics* 65.1, pp. 91–98. ISSN: 0094-1190. DOI: 10.1016/j.jue.2008.09.002.

Brueckner, Jan K. (2000). "Urban sprawl: Diagnosis and remedies." In: *International regional science review* 23.2, pp. 160–171.

— (2001). "Urban Sprawl: Lessons from Urban Economics [with Comments]." In: *Brookings-Wharton Papers on Urban Affairs*, pp. 65–97. ISSN: 15287084.

Chateau, Bertrand, Domenico Rossetti, European Union, European Commission, and Directorate-General for Research and Innovation (2011). *World and European energy and environment transition outlook: WETO-T*. Luxembourg: Publications Office of the European Union. ISBN: 978-92-79-20044-1.

Crane, R. (2000). "The Influence of Urban Form on Travel: An Interpretive Review." In: *Journal of Planning Literature* 15.1, pp. 3–23. ISSN: 0885-4122. DOI: 10.1177/08854120022092890.

Creutzig, Felix, Peter Agoston, Jan C. Minx, Josep G. Canadell, Robbie M. Andrew, Corinne Le Quéré, Glen P. Peters, Ayyoob Sharifi, Yoshiki Yamagata, and Shobhakar Dhakal (2016). "Urban infrastructure choices structure climate solutions." In: *Nature Climate Change* 6.12, pp. 1054–1056. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate3169.

Creutzig, Felix, Rainer Mühlhoff, and Julia Römer (2012). "Decarbonizing urban transport in European cities: four cases show possibly high co-benefits." In: *Environmental Research Letters* 7.4, p. 044042. ISSN: 1748-9326. DOI: 10.1088/1748-9326/7/4/044042.

Crifo, Patricia, Matthieu Glachant, Stéphane Hallegatte, Eloi Laurent, and Raphaël Gibert (2012). *L'économie verte contre la crise*. Hors Collection. PUF. ISBN: 978-2-13-060798-4.

Czepkiewicz, Michał, Jukka Heinonen, and Juudit Ottelin (2018). "Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel." In: *Environmental Research Letters* 13.7, p. 073001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aac9d2.

Dargay, Joyce, Dermot Gately, and Martin Sommer (2007). "Vehicle Ownership and Income Growth, Worldwide: 1960-2030." In: *The Energy Journal* 28.4, pp. 143–170. ISSN: 01956574, 19449089.

Deloitte (2016). *Deloitte Africa Automotive Insights*. Tech. rep. Deloitte.

Dijkstra, Lewis and Hugo Poelman (2014). *A harmonised definition of cities and rural areas: the new degree of urbanisation*. Tech. rep. WP 01/2014. European Commission.

Ewing, Reid and Robert Cervero (2010). "Travel and the Built Environment: A Meta-Analysis." In: *Journal of the American Planning Association* 76.3, pp. 265–294. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944361003766766.

Fay, Marianne, Stéphane Hallegatte, Adrien Vogt-Schilb, Julie Rozenberg, Ulf Narloch, and Tom Kerr (2015). *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. The World Bank. ISBN: 978-1-4648-0479-3 978-1-4648-0606-3. DOI: 10.1596/978-1-4648-0479-3.

Fujii, Hidemichi, Kazuyuki Iwata, and Shunsuke Managi (2017). "How do urban characteristics affect climate change mitigation policies?" In: *Journal*

of Cleaner Production 168, pp. 271–278. ISSN: 09596526. DOI: 10.1016/j.jclepro.2017.08.221.

Fujita, Masahisa (1989). *Urban economic theory: land use and city size*. Cambridge, New York: Cambridge University Press. ISBN: 978-0-521-39645-5.

GEA (2012). *Global Energy Assessment - Toward A Sustainable Future*. Ed. by Thomas B. Johansson, Anand Patwardhan, Nebojša Nakićenović, Luis Gomez-Echeverri, and International Institute for Applied Systems Analysis. Cambridge : Laxenburg, Austria: Cambridge University Press ; International Institute for Applied Systems Analysis. ISBN: 978-1-107-00519-8 978-0-521-18293-5.

Gillingham, Kenneth, Alan Jenn, and Inês M.L. Azevedo (2015). "Heterogeneity in the response to gasoline prices: Evidence from Pennsylvania and implications for the rebound effect." In: *Energy Economics* 52, S41–S52. ISSN: 01409883. DOI: 10.1016/j.eneco.2015.08.011.

Glaeser, Edward L. and Matthew E. Kahn (2010). "The greenness of cities: Carbon dioxide emissions and urban development." In: *Journal of Urban Economics* 67.3, pp. 404–418. ISSN: 00941190. DOI: 10.1016/j.jue.2009.11.006.

Gordon, Ian (1997). "Densities, urban form and travel behaviour." In: *Town and Country Planning* 66.9, pp. 239–241.

— (2008). "Density and the built environment." In: *Energy Policy* 36.12, pp. 4652–4656. ISSN: 03014215. DOI: 10.1016/j.enpol.2008.09.002.

Gordon, Peter, Ajay Kumar, and Harry W. Richardson (1989). "The influence of metropolitan spatial structure on commuting time." In: *Journal of Urban Economics* 26.2, pp. 138–151. ISSN: 00941190. DOI: 10.1016/0094-1190(89)90013-2.

Gordon, Peter and Harry W. Richardson (1989). "Gasoline Consumption and Cities: A Reply." In: *Journal of the American Planning Association* 55.3, pp. 342–346. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944368908975421.

Gordon, Peter, Harry W. Richardson, and Myung-Jin Jun (1991). "The Commuting Paradox Evidence from the Top Twenty." In: *Journal of the American Planning Association* 57.4, pp. 416–420. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944369108975516.

Gracia, Clémence, Fabio Grazi, Nicole Madariaga, and Ophélie Risler (2015). *Cities in Climate Change Mitigation Policy*. A Question of Development 21. AFD.

Gudipudi, Ramana, Till Fluschnik, Anselmo García Cantú Ros, Carsten Walther, and Jürgen P. Kropp (2016). "City density and CO2 efficiency." In: *Energy Policy* 91, pp. 352–361. ISSN: 03014215. DOI: 10.1016/j.enpol.2016.01.015.

Hallegatte, Stéphane (2009). "Strategies to adapt to an uncertain climate change." In: *Global Environmental Change* 19.2, pp. 240–247. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2008.12.003.

Helsley, Robert W. and William C. Strange (2008). "A game-theoretic analysis of skyscrapers." In: *Journal of Urban Economics* 64.1, pp. 49–64. ISSN: 00941190. DOI: 10.1016/j.jue.2007.08.004.

Henderson, J. Vernon, A. J. Venables, T. Regan, and I. Samsonov (2016). "Building functional cities." In: *Science* 352.6288, pp. 946–947. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.aaf7150.

Holden, Erling and Ingrid Norland (2005). "Three challenges for the compact city as a sustainable urban form: Household consumption of energy and transport in eight residential areas in the greater Oslo Region."

In: *Urban Studies* 42.12, pp. 2145–2166. ISSN: 0042-0980, 1360-063X. DOI: 10.1080/00420980500332064.

Hoornweg, Daniel, Mila Freire, Marcus J. Lee, Perinaz Bhada-Tata, and Belinda Yuen (2011). *Cities and Climate Change: Responding to an Urgent Agenda*. The World Bank. ISBN: 978-0-8213-8493-0 978-0-8213-8667-5. DOI: 10.1596/978-0-8213-8493-0.

Hornbeck, Richard and Daniel Keniston (2017). "Creative Destruction: Barriers to Urban Growth and the Great Boston Fire of 1872." In: *American Economic Review* 107.6, pp. 1365–1398. ISSN: 0002-8282. DOI: 10.1257/aer.20141707.

Huriot, Jean-Marie and Lise Bourdeau-Lepage (2009). *Économie des villes contemporaines*. Paris: Économica. ISBN: 978-2-7178-5694-1.

IEA (2009). *Transport, energy and CO2: moving toward sustainability*. Paris: International Energy Agency. ISBN: 978-92-64-07316-6.

— (2011). *World Energy Outlook 2011*. Paris: International Energy Agency. ISBN: 978-92-64-12413-4.

— (2016a). *CO2 Emissions from Fuel Combustion - 2016 edition - Key CO2 Emissions Trends*. Tech. rep. Paris: International Energy Agency.

— (2016b). *Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems*. Paris: International Energy Agency.

IEA and WBCSD (2004). *Sustainable Mobility Project*.

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]* Geneva, Switzerland: IPCC.

Jacquet, Pierre, R. K. Pachauri, Laurence Tubiana, Tata Energy Research Institute, Institut du développement durable et des relations internationales, and Agence française de développement, eds. (2010). *Cities: steering towards sustainability*. New Delhi: Teri Press. ISBN: 978-81-7993-131-8.

Karathodorou, Niovi, Daniel J. Graham, and Robert B. Noland (2010). "Estimating the effect of urban density on fuel demand." In: *Energy Economics* 32.1, pp. 86–92. ISSN: 01409883. DOI: 10.1016/j.eneco.2009.05.005.

Lall, Somik V., ed. (2013). *Planning, connecting, and financing cities–now: priorities for city leaders*. Washington, DC: World Bank. ISBN: 978-0-8213-9839-5.

Lall, Somik V., J. Vernon Henderson, and Anthony J. Venables (2017). *Africa's Cities: Opening Doors to the World*. Washington D.C.: The World Bank. ISBN: 978-1-4648-1044-2. DOI: 10.1596/978-1-4648-1044-2.

Munafò, Sébastien (2017). "Forme urbaine et mobilités de loisirs : l'« effet barbecue » sur le grill." In: *Cybergeo*. ISSN: 1278-3366. DOI: 10.4000/cybergeo.28634.

Næss, Petter (2006). "Are short daily trips compensated by higher leisure mobility?" In: *Environment and Planning B: Planning and Design* 33.2, pp. 197–220. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b31151.

— (2012). "Urban form and travel behavior: experience from a Nordic context." In: *Journal of Transport and Land Use* 5.2. ISSN: 1938-7849. DOI: 10.5198/jtlu.v5i2.314.

— (2016). "Urban Planning: Residential Location and Compensatory Behaviour in Three Scandinavian Cities." In: *Rethinking Climate and Energy Policies*. Ed. by Tilman Santarius, Hans Jakob Walnum, and Carlo Aall. Cham: Springer International Publishing, pp. 181–207. ISBN: 978-3-319-38805-2 978-3-319-38807-6. DOI: 10.1007/978-3-319-38807-6_11.

Neuman, M. (2005). "The Compact City Fallacy." In: *Journal of Planning Education and Research* 25.1, pp. 11–26. ISSN: 0739-456X. DOI: 10.1177/0739456X04270466.

Newman, Peter W. G. and Jeffrey R. Kenworthy (1989a). *Cities and automobile dependence: a sourcebook*. Aldershot, Hants., England ; Brookfield, Vt., USA: Gower Technical. ISBN: 0-566-07040-5.

— (1989b). "Gasoline Consumption and Cities." In: *Journal of the American Planning Association* 55.1, pp. 24–37. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944368908975398.

Orfeuil, J and D Soleyret (2002). "Quelles interactions entre les marchés de la mobilité à courte et à longue distance ?What are the interactions between the short and long-distance travel markets?" In: *Recherche - Transports - Sécurité* 76, pp. 208–221. ISSN: 07618980. DOI: 10.1016/S0761-8980(02)00013-4.

Parry, Ian W. H. and Kenneth A. Small (2005). "Does Britain or the United States Have the Right Gasoline Tax?" In: *The American Economic Review* 95.4, pp. 1276–1289. ISSN: 00028282.

Roberts, Mark, Brian Blankespoor, Benjamin P. Stewart, and Chandan Deuskar (2017). *Urbanization and development : is Latin America and the Caribbean different from the rest of the world?* Tech. rep. WPS8019. The World Bank, pp. 1–37.

Schipper, Lee, Celine Marie-Lilliu, and Roger Gorham (2000). "Flexing the link between transport and greenhouse gas emissions." In: *IEA*.

Seto, Karen C. et al. (2014). "Human settlements, infrastructure and spatial planning." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Ottmar Edenhofer et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Sims, R. et al. (2014). "Transport." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Siodla, James (2015). "Razing San Francisco: The 1906 disaster as a natural experiment in urban redevelopment." In: *Journal of Urban Economics* 89, pp. 48–61. ISSN: 00941190. DOI: 10.1016/j.jue.2015.07.001.

Stiglitz, Joseph E. et al. (2017). "Report of the High-Level Commission on Carbon Prices." In:

UN DESA (2015a). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. Tech. rep. New York, NY: UN Department of Economic and Social Affairs.

— (2015b). *World Urbanization Prospects. The 2014 Revision*. Tech. rep. New York: UN Department of Economic and Social Affairs.

Viguié, Vincent (2012). "Urban Dynamics Modelling, application to economics assessment of climate change." PhD thesis. Université Paris-Est.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Vogt-Schilb, Adrien, Guy Meunier, and Stéphane Hallegatte (2018). "When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment." In: *Journal of Environmental Economics and Management* 88, pp. 210–233. ISSN: 00950696. DOI: 10.1016/j.jeem.2017.12.001.

Waisman, Henri-David, Celine Guivarch, and Franck Lecocq (2013). "The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility." In: *Climate Policy* 13.sup01, pp. 106–129. ISSN: 1469-3062, 1752-7457. DOI: 10.1080/14693062.2012.735916.

Wang, H., P. Zhou, and D.Q. Zhou (2012). "An empirical study of direct rebound effect for passenger transport in urban China." In: *Energy Economics* 34.2, pp. 452–460. ISSN: 01409883. DOI: 10.1016/j.eneco.2011.09.010.

Zahavi, Yacov and Antti Talvitie (1980). "Regularities in travel time and money expenditures." In: *Transport Research Record* 750, pp. 13–19.

1

THE FORCES OF LAND AND TRANSPORT – A SIMPLE AND ROBUST MODELLING FRAMEWORK

- À partir de maintenant ce sera moi qui décrirai les villes, avait dit le Khan. Et toi dans tes voyages, tu vérifieras si elles existent.

Mais les villes que Marco Polo visitait étaient toujours différentes de celles que l'empereur imaginait.

« Et pourtant, j'ai bien construit en esprit un modèle de ville à partir duquel déduire toutes les villes possibles. Il contient tout ce qui répond à la norme. Comme les villes qui existent s'éloignent à des degrés divers de la norme, il me suffit de prévoir les exceptions à la norme et d'en calculer les combinaisons les plus probables. »

- Moi aussi j'ai pensé à un modèle de ville duquel je déduis toutes les autres, répondit Marco. C'est une ville qui n'est faite que d'exceptions, d'impossibilités, de contradictions, d'incongruités, de contresens. Si une ville ainsi faite est tout ce qu'il y a de plus improbable, en abaissant le nombre des éléments anormaux la probabilité grandit que la ville existe véritablement. Par conséquent, il suffit que je soustraie de mon modèle des exceptions, et de quelque manière que je procède j'arriverai devant l'une des villes qui, quoique toujours par exception, existent. Mais je ne peux pas pousser mon opération plus loin qu'une certaine limite : j'obtiendrais des villes trop vraisemblables pour être vraies.

Calvino, Italo. 2013. *Les Villes Invisibles*. Gallimard.

1.1 MODELLING CITIES – A VAST CHOICE OF SIMULATION MODELS

Modelling cities, at the very core, is about understanding and representing how land uses and transport influence each other (Iacono, Levinson, and El-Geneidy, 2008). How does the distribution of accessibility, and the transport infrastructure that underpins these, shape urban forms, population densities and the location decisions of firms? Symmetrically, how do land uses (including geography), housing and land regulations, land and housing rents, determine transport demand and transportation behavior? These questions are at the heart of Land Use and Transport Integrated models (LUTI).

There exists a vast array of models that seek to represent the interrelatedness between land use and transport. These models come from various modelling traditions and philosophies and the research field has seen a rapid development over the last sixty years, in particular since the 1990s and the parallel processes of 1/ progress in computer technology and 2/ a renewed interest in cities especially linked to environmental concerns (Wegener, 2014). A number of scholars have produced reviews of these models including historical perspectives, technical descriptions and typologies for the various LUTI models (Acheampong and Silva, 2015; Haase and Schwarz, 2009; Hunt, Kriger, and Miller, 2005; Iacono, Levinson, and El-Geneidy, 2008; Lefevre,

2007; Wegener, 2004, 2014; Wegener and Fürst, 2004). We do not attempt such a review here and instead refer the reader to the works cited above[1].

Models are simplifications of reality – otherwise they would, by definition, be the reality. It follows that models are necessarily incomplete and that none is perfect. In his 2012 commentary, Klosterman (2012) reproduces Box and Draper's quote which reads "All models are wrong; some are useful" (Box and Draper, 1987). Choosing the LUTI model to employ is tantamount to choosing a "useful" model. But a useful model depends on the question that researchers and policy makers are seeking to answer. A "useful" model for a given question can be totally useless for another. At the heart of the election of a "useful" LUTI model, to answer a given question, lies the tradeoff between simplicity and complexity (Saujot, 2013).

In a nutshell, simple models have the advantage of, precisely, their simplicity, which encompasses the ability to understand the philosophy, architecture, inputs and outputs of the model and the ability to use and adapt the model with scarce resources (time, money and manpower). Importantly simple models allow users to trace and understand the causal chains that link model outcomes, mechanisms and changes in inputs. This is a central element, when trying to understand the impact of a given policy for example. The main drawback of these models is that their simplicity necessarily comes at the cost of realism. At one extreme a model can lack so many fundamental mechanisms that it is no longer simple but becomes simplistic.

Complex models, on the other hand, have the ability to represent numerous and subtle mechanisms and can come very close to replicating real world city situations. Models such as TRANUS (De La Barra, 2001) and UrbanSim (Waddell, 2002), among others, offer quite spectacular abilities to reproduce a large number of features of the cities they are calibrated on. But this realism comes at a cost.

First, these sophisticated LUTI models are greedy in data, time and manpower, often requiring a dedicated team and between several months up to multiple years to produce a satisfactory baseline calibration of an urban area (Iacono, Levinson, and El-Geneidy, 2008; Saujot et al., 2016). This is an important human, time and monetary cost.

Second, these complex models, to be able to fine-tune their findings, will bundle together mechanisms that have different validity time-frames. For example, the proximity to good quality schools can be a key driver of locational choices of households in the short to the medium term. But school programs evolve and so do school rankings. Unless, the LUTI model is equipped with the possibility of exploring how the location of good quality schools will evolve – which is highly unlikely – these subtle mechanisms will constrain the validity time-frame of the model and restrict its use to the short term. By comparison models that rely on coarser, but more permanent, mechanisms, e.g. distance to the city center as an extreme example, will miss many local phenomenon but will also likely remain more accurate over the longer term (Klosterman, 2012).

Third, complex models require additional data that may not be available or correctly measured. Complex models also multiply the coefficients and constants which they rely on, often assigning them values found through econometric studies in the literature, despite the necessarily different contexts

[1] Volume 40, Issue 6 of *Environment and Planning B* published in 2013 is entirely focused on applied urban models and provides a good overview of the State of the Art in the domain as well as an important discussion of the challenges and way forward for practitioners.

in which they were estimated, and assuming the values of these coefficients will remain constant over time and geographies (Klosterman, 2012).

Fourth and finally, complexity can also blur the causal chains between an outcome of the model and its causes. But to be useful a model must be understood in terms of its philosophy and architecture but also fundamentally in terms of its ability to explain a given simulation result (Saujot et al., 2016). If not the risk of the model being perceived as a "black box" is too great and it will be very difficult to trust its results, irrespective of their validity. Note the paradox that by becoming more complex in order to better reproduce real world features, models become less understandable and trustworthy.

In terms of validity, i.e. the ability to be used for prospective simulations and "what if?" types of counterfactuals both types of models carry risks. Simple models run the risks of not representing essential mechanisms of the evolution of key variables in urban areas, in other words simple models run the risk of specification errors. Complex models on the other hand, by requiring data that are either absent or imperfectly measured and, resorting to numerous coefficients and constants, which are, sometimes abusively, assumed to remain constant over time, are at a greater risk of compounding and propagating measurement errors (Klosterman, 2012).

It follows that simple and complex models, if they can pass some validity test, will both be useful in different situations. Following Lee's formulation (1994) and later Hardy's (2012) interpretation, simple models can be useful for "strategic" planning while detailed and complex LUTI models might be better suited for "tactical" planning. Tactical planning is concerned with precision and the design of a specific projects or policy implementation for which a fine grain analysis is required. The realm of tactical planning is mainly the short to medium term. And meaningful results can typically be extracted at the level of the neighborhood. Strategic planning consists in exploring the long term future of urban areas through counterfactuals, abandoning most details to focus on the main mechanisms driving the evolution of urban areas characteristics (if the model does not suffer from major specification errors). Strategic planning aims to reveal the orders of magnitude of the consequences of implementing major policy changes or performing major infrastructure investments in the long term. Strategic planning is concerned with the big picture, at the expense of other important considerations and can be used as a tool to discuss alternative policy plans and visions of the future.

The model, NEDUM-2D, we use in the rest of this dissertation clearly falls into the category of "strategic planning". It does not pretend to be well suited to inform fine grain decisions at the neighborhood level, nor does it claim that it accounts for all the numerous mechanisms at play in cities. But it is a micro-economically and empirically validated tool for exploring largely contrasting futures depending on policy and investment choices. As this dissertation focuses on the long run consequences of policies (urban and transport related) aiming to curb CO_2 emissions from urban-transport, the model's scope and the research question are in coherence. We conclude that the model we will use in the rest of the dissertation is "useful" for the problem at hand and the following sections will introduce it, show its details and demonstrate its validity against a set of criteria.

1.2 DESCRIPTION OF THE NEDUM-2D MODELLING FRAMEWORK

Each work presented in this dissertation uses slightly different versions of the same model, adapted to better respond to the question at hand and/or

because local conditions (Paris, Buenos Aires) imposed slightly different choices. We believe it is useful, at this stage and before delving into the individual chapters, to present the modeling framework, data requirements and processing as well as model validation in their entirety and not only as appendices. We therefore chose to focus on one specific version of the model used in the second chapter. The reader should however keep in mind that each paper makes slightly different choices without fundamentally changing the philosophy of the model.

1.2.1 *General principles, main features and assumptions of NEDUM-2D*

NEDUM-2D is an extension of the standard urban economic model such as defined by Fujita (1989) and Brueckner (1987) building on the pioneering works of first Von Thünen (1826) and then Alonso, Mills and Muth at the end of the 1960s (Alonso, 1964; Mills, 1967; Muth, 1969). It aims at explaining the variation in land costs in cities and thus the level of real estate prices together with the distribution of the households and buildings in an urban area. Classically, it is based on two very simplified, yet realistic, fundamental mechanisms, assuming that a city is defined by a number of jobs located in a single location:

- First, households, choose their housing location in the agglomeration by arbitrating between larger and cheaper apartments further from the city center, and increased commuting costs to the city center where all jobs are supposed to be located.
- Second, the project developers (or landowners[2]) maximize their profits and choose to build more or less housing surface (how much to invest) in a given place depending on the level of real estate prices. The higher the real estate prices, the denser the developers choose to build.

These two trades-offs characterize a static equilibrium in the urban system.

NEDUM-2D, developed in CIRED by Viguié and Hallegatte (Viguié and Hallegatte, 2012) building on works from Gusdorf and Hallegatte (2007a,b) and Gusdorf, Hallegatte, and Lahellec (2008), differs from the standard model developed in Fujita (1989) for three main reasons.

First, it can be used dynamically, which enables to take into account the effect of a global change in income or population. As explained in Gusdorf, Hallegatte, and Lahellec (2008), urban economics has mostly been used to explore the characteristics of long run equilibria. However, the existence of urban stationary equilibria is questionable: when population, transport prices, or income vary (sometimes in unpredictable ways), housing infrastructure cannot adapt instantaneously to changing conditions. NEDUM-2D explicitly takes these dynamics into account and describes cities as non-equilibrium systems. The model can also be run at the equilibrium for a specific year if data for a larger time period are not available.

Second, the theoretical model described by Fujita (1989) represents spatial differences solely as a function of the distance to the city center. As the name suggests NEDUM-2D is two dimensional meaning that it is an urban model that represents urbanization on a map rather than on a single axis.

[2] A standard calculation (Fujita, 1989) proves that this hypothesis does not change the results of the model : in the model, the reasoning and the calculations that are conducted are identical whether project developers have to rent or buy the land from landowners.

NEDUM-2D uses a grid with cells of variable size (classically 1km^2). It can therefore account for spatial differences in land use and accessibility at a much finer scale. The model can represent differences between two cells situated at the same distance from the city center such as the amount of land that can be built upon or the proximity to public transport.

Third, the classic urban economy model only represents one means of transport. In NEDUM-2D there are three main transport options: private cars, public transport and walking. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination of these as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged. In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse, 1987). We follow a common approach in transportation economics by using a multinomial logit model which assigns usage probabilities to each transport mode (see Salon, 2009; Washbrook, Haider, and Jaccard, 2006). This method ensures that even when one mode is much cheaper than the others, it will not be used by all residents in a location for all trips.

In the present dissertation, we use this model with a certain number of simplifying hypotheses. First, we assume that all households commute every day to the center of the urban area, where jobs are assumed to be located. This mono-centric hypothesis is a clear simplification but one that is widely used in the literature and that finds some support in the data for the specific cases of Paris and Buenos Aires. For instance, in 2012 more than 40% of all jobs in the Buenos Aires region are localized in Buenos Aires's city center, CABA, even though CABA only represents 5.3% of *Region Metropolitana*'s area.

Second, NEDUM-2D also relies on the hypothesis that all households within the urban area earn the same average income. It does not currently account for multiple household types and thus ignores income inequalities[3]. This simplification is acceptable for some indicators such as the extent of urbanization. However it can have some impacts for NEDUM-2D's ability to capture the dispersion in rents and real estate prices around an average. Indeed, real estate prices are strongly affected by neighborhood characteristics among which social segregation can play a role.

1.2.2 *Household behavior*

Each household is composed of one representative worker living at a distance r from the city business district (CBD) where all jobs are located. Each worker has to commute once a day to the CBD, and this commuting entails transportation costs $T(r)$. All households are supposed to earn the same income Y and – at the equilibrium – they have the same level of satisfaction described by a utility function U that depends on both the level of consumption of a composite good z and of the size of their dwelling q. The level of rents per square meter (or, equivalently, the annualized real estate price per

[3] A version of NEDUM-2D that is able to represent multiple household types differing by annual average income is currently being developed in CIRED.

Symbol	Signification
R	Housing rents (or, equivalently, annualized real estate price per square meter)
R_0	Metropolitan area border rent or transaction costs
L	Available land for construction
K	Invested capital
ρ	Depreciation rate of capital
i	Interest rate: cost of capital
p	Unitary transport cost/km
n	Household density
q	Flat size
N	Population in the agglomeration
r	Distance to the city center
r_f	Limit of the city, maximum radius to the center

Table 1.1: Nomenclature.

square meter) is $R(r)$, at each location in the city. Each household maximizes his utility function under a budget constraint.

$$\text{Max}_{r,z,q} U(z,q) \quad \text{s.t.} \quad z(r) + R(r)\, q(r) + T(r) \leq Y + \overline{L} \tag{1.1}$$

The term $\overline{L}$ found in (1.1) represents the annual amount accruing from land rents per household which is recycled in the urban economy in the form of increased incomes. It can schematically take on one of two values depending on the type of model used: Closed City model with Absentee landowners (CCA) or Closed City model with Public ownership of land (CCP). In the closed city model with absentee landowners (CCA), landowners are supposed to live outside the urban area which means that land rents are not recycled in the local economy in the form of increased incomes. In this case $\overline{L} = 0$. At the opposite end of the spectra, if all land plots are supposed to be owned by a local government (or by all households in equal shares) then $\overline{L} = \int_0^{r_f} \frac{\pi(r)}{N} dr$, where N is the number of households in the urban area, and land values $\pi(r)$ are described in the next paragraph.

1.2.3 *Landowners behavior*

Landowners choose what amount of capital $K(r)$ to invest at each distance, r, from the CBD to produce a housing surface $H(r) = F(L(r), K(r))$; in this framework, they are thus also the owners of the buildings. The construction function F is assumed to have constant returns to scale. The profit function of a landowner or equivalently the land value assuming $R(r)$ as exogenous and known is then given by:

$$\pi(r) = [(R(r) - R_0)\, F(K(r), L(r)) - (i + \rho) K(r)] \tag{1.2}$$

ρ represents the joined effect of real-estate depreciation and annual taxes payed by land owners on real-estate capital. i is the interest rate so that iK represents the annual cost of borrowing capital or its opportunity cost. Finally the border of the metropolitan area is defined by a rent R_0, below

which it is no longer profitable to build housing. This value corresponds to transaction costs in the building and renting process, such as the costs of finding tenants, ensuring that the communal areas of collective housing remain clean..., and can be considered to be proportional to the quantity of housing built. NEDUM-2D differs from traditional urban economics model in this respect, as they usually assume that the edge of the metropolitan area is given when land value for housing falls below the revenue that could be generated from using this land for agricultural purposes. Although this method is appealing, it is not supported by data which shows a clear disconnection between land values for agricultural and housing purposes even at the edge of urban areas. The much lower values for agricultural land are indicative that another mechanism is at play. We chose to capture this through transaction costs R_0.

Landowners maximize their profit function to determine how much housing to build and how much capital to invest:

$$K^*(r) = \text{Arg}\max[(R(r) - R_0) F(L(r), K(r)) - (\rho + i) K(r)] \tag{1.3}$$

The landowner in fact chooses the capital/land ratio $k = K/L$ that maximizes his land's value. If we assume that the housing production function has constant returns to scale[4], then this ratio does not change as a function of the amount of land that is used but varies only as a function of the distance to the CBD. We can then use $f(k) = \frac{F(K,L)}{L} = h$ as a proxy for housing density or building's height and define:

$$k^*(r) = \arg\max_k[(R(r) - R_0) f(k(r)) - (\rho + i) k(r)] \tag{1.4}$$

At the city limits we have:

$$R\left(r_f\right) = R_0$$

1.2.4 *Functional forms*

We use Cobb-Douglas functional forms with constant returns to define households' utility and the housing service construction function. This choice is widely shared in urban economics (Brueckner, 1980; Fujita, 1989; Mills, 1972). The popularity of Cobb-Douglas functions in urban economics can be explained by two elements. First, and importantly, these function are easy to manipulate and with simplifying hypotheses, the urban system resolution remains tractable and easily interpretable (see section 1.2.6 for a static resolution with simplifying hypotheses). Second, and probably more importantly, Cobb-Douglas functional forms have properties that match well with regularities observed in urban areas. For household utility, the implication of a Cobb-Douglas function is that the share of income (net of transport costs) devoted to housing expenditures is constant across the urban area. This is close to observations made by Davis and Ortalo-Magné (2011). Similarly for the housing production function, a Cobb-Douglas function implies that the elasticity of substitution between land and capital is constant and equal to one. This too has been supported by theoretical and empirical

[4] This is logical as a doubling of both capital and land factors should lead to two similar housing structures being built (Brueckner, 2011).

works (Ahlfeldt and McMillen, 2014; Epple, Gordon, and Sieg, 2010; Thorsnes, 1997).

$$U(z,q) = z^{\alpha}q^{\beta} \text{ where } \alpha,\beta > 0 \text{ and } \alpha+\beta = 1 \tag{1.5}$$

$$F(L,K) = AL^{a}K^{b} \text{ where } a,b > 0 \text{ and } a+b = 1 \tag{1.6}$$

1.2.5 *Dynamics of NEDUM-2D*

NEDUM-2D is a dynamic model which explicitly represents inertia and path dependence. This feature allows the model to account for the fact that housing infrastructure cannot adapt instantaneously to changing conditions (income, transport prices etc...). NEDUM-2D can therefore account for temporary imbalances between housing supply and demand.

There are two steps in defining the dynamic behavior of the NEDUM-2D model. First, developers' decisions on how much to build and where in the urban area are determined (or equivalently how much capital to invest for residential purposes in each location). This allows the model to determine the new housing stock which accounts for inertia in building decisions. Second rents, dwelling sizes and population densities (and all other model outputs) adjust in such a manner that an equilibrium utility can emerge consistently with the static version of the model. This two-tier approach to the dynamics of NEDUM-2D differs from the one used in Viguié, Hallegatte, and Rozenberg (2014), Viguié and Hallegatte (2012) and Avner, Viguié, and Hallegatte (2013). We will discuss these differences and their consequences a bit further in this section.

Step 1: In practice for each time step a "pseudo-equilibrium" value is computed for the housing stock. This "pseudo-equilibrium" value is the value toward which the housing stock state variable will evolve. It depends on the model input, but also on the value of the other state variables (rents, population densities, dwelling sizes...). Between this time-step and the following, the housing stock state variable will evolve towards its "pseudo-equilibrium" value with some inertia. At the following time step, a new "pseudo-equilibrium" value for the housing stock is computed. It can be identical to the last one, or can be different because the values of the other state variables have changed, or because model inputs are different (e.g. construction costs have changed). The housing stock state variable will now again evolve towards this new "pseudo-equilibrium" values etc. The pseudo-equilibrium value for the housing stock is computed in such a manner that, if exogenous model inputs (population, transport costs, construction costs, income...) do not evolve any more, the housing stock state variable converges towards the actual equilibrium value.

For each time step, developers when choosing whether or not and how much to build assess their expected profits using equation (1.2). In this version of the model the developers are considered to be myopic, meaning that they do not anticipate that housing rents from the previous time step will change as a function of different socio-economic conditions. They choose the new amount of capital that they would wish to instantaneously invest in each location ("pseudo-equilibrium"), or equivalently the capital to land ratio k' leading to the housing to land ratio h' through:

$$k'(r) = \underset{k(r)}{\arg\max}\left[\left(R(r) - R_0\right)h'(r) - (\rho+i)\,k'(r)\right] \tag{1.7}$$

Construction and building depreciation however, take time so that the capital invested does not translate immediately into new buildings or the destruction of old ones. We here follow Viguié, Hallegatte, and Rozenberg (2014) in supposing that financial investments are transformed into buildings with a time lag τ_H, which corresponds to the time required to achieve the construction. We also suppose that a decrease in current built floor space ratio to land ($h(r)$) can happen through depreciation only, with the timescale τ_{dH}. It follows that in a dynamic perspective housing evolution at each time step is given by:

$$\frac{dh(r)}{dt} = \begin{cases} \frac{h'(r)-h(r)}{\tau_H} \; if \; h'(r) \geq h(r) \\ -\frac{h(r)}{\tau_{dh}} \text{ if } h'(r) < h(r) \end{cases} \tag{1.8}$$

Step 2: At each time step the other model variables (rents, population densities, dwelling sizes...) adjust perfectly to the new socio-economic conditions and to the new housing stock. Indeed households adjust their locational and consumption choices in a way that ensures that utility levels are equal for all households throughout the urban area, consistently with the static version of the model. This second step of the dynamics of NEDUM-2D is equivalent to the maximization of households' utility in a static framework with an exogenous housing stock.

This two-tier approach of the dynamics of the model differs from the one chosen by Viguié in two ways. First the inertia only applies to the housing stock instead of all state variables. Second, the method followed in this dissertation leads to an equilibrium whereby all residents achieve an identical utility level throughout the urban area. In Viguié, Hallegatte, and Rozenberg (2014) different inertia parameters were applied to all state variables and, although they tended to converge toward their pseudo-equilibrium values, households within the urban area could reach different utility levels.

It can be argued that the method used in Viguié, Hallegatte, and Rozenberg (2014) had some advantages and some drawbacks. In terms of advantages it was one of the first models in an urban setting to consistently attribute specific inertia parameters to the evolution of their respective key variables. This is an important contribution as it enables the study of transitional periods in the evolution of urban systems (one could argue that urban system are always in transition) in a thorough and consistent manner. If one believes that moving from one location to another in the urban area as a result of changes in rents, transport costs and other factors takes time (probably years because of transaction costs) then arguing for inertia on all key variables makes a lot of sense. On the other hand, this modelling approach has certain drawbacks. First, it leads to some difficulties in the interpretation of results. Typically, this modelling approach leads to evolutions that display cycles. The inertia in dwelling size adjustments, in housing construction and households' moves can accumulate in such a manner that the model's representation of the situation is very far from the "pseudo-equilibrium" solution which can trigger a very strong subsequent response from the model in terms of building floor space for example. This spurt in housing building could be followed by a few time steps where not much more housing is built because the state of the urban system has gotten much closer to its natural equilibrium. These cycles are not problematic in themselves as they might actually prove to be reasonable representations of the real-world urban economy's dynamics. However, they can make the interpretations of results difficult: "can this result be attributed to the implementation of a new urban policy in the urban area or to the natural cycles of the model?" could then become

a difficult question to untangle. Second, because the inertia in the building process is much greater than in the decisions to move or in the decisions to adjust dwelling sizes for example, they actually hide the others and the inertia of the urban system ends up being determined to a large extent by the sole inertia on building decisions. Finally, the two-tiered approach adopted in this dissertation is less computationally heavy.

1.2.6 *The static equilibrium in the urban system with simplifying assumptions*

NEDUM-2D is a micro-economically founded applied land use – transport model which aims at representing in a realistic yet simple manner the main mechanisms at play in residents' locational decisions in specific urban areas (here the Paris metropolitan area). Therefore, it uses realistic data (in particular on land uses and transport costs and times) which makes analytic resolution impossible. However, it is useful to explicit the method for solving the urban system problem and display the main relationships between rents, housing consumption, capital invested for housing purposes and resident's utility in a simplified framework. We do so in the following paragraph, going back to a more classic urban economics model by adding some simplifying assumptions:

- Transport costs increase linearly with distance from the city center, $T(r) = pr$, where p is the generalized cost of transportation including the cost of time.
- The border rent R_0 is supposed to be null. This simplification is not necessary but it makes most of the calculations much easier.
- The agricultural rent R_a, which is traditionally used in most urban economics models as defining the urban border (where $\pi(r_f) = R_a$), is also set to zero.
- At each distance r from the city center, and assuming a perfectly circular city, we can define the available land as the following increasing function of r: $L(r) = lr$ where l=2π

1.2.6.1 *Households*

$$U(z,q) = z^{\alpha} q^{\beta} \quad \text{s.t.} \quad z(r) + R(r)\, q(r) + T(r) \leq Y + \overline{L} \tag{1.9}$$

Maximizing the utility function with respect to dwelling size, $\frac{\partial u}{\partial q} = 0$, yields the following results for households:

$$R(r,u)\, q(r,u) = \beta \left(\left(Y + \overline{L} \right) - pr \right) \tag{1.10}$$

$$z(r,u) = \alpha \left(\left(Y + \overline{L} \right) - pr \right) \tag{1.11}$$

For rents and housing consumption we find:

$$R(r,u) = \left(\alpha^{\alpha} \beta^{\beta} \frac{Y + \overline{L} - pr}{u} \right)^{\frac{1}{\beta}} \tag{1.12}$$

$$q(r,u) = \left(\frac{u}{\left(\alpha (Y + \overline{L} - pr) \right)^{\alpha}} \right)^{\frac{1}{\beta}} \tag{1.13}$$

1.2.6.2 *Landowners and developers*

At each location, landowners' combine land $L(r)$ and capital $K(r)$ to construct housing surfaces $H(r)$.

$$H = AK^b L^a \tag{1.14}$$

Landowners' profit, which is also the annual value of land, is the following:

$$\pi(r) = R(r) H(r) - (\rho + i) K(r) \tag{1.15}$$

Landowners choose the capital to invest for purposes in order to maximize their profits, $\frac{\partial \pi}{\partial K} = 0$, which yields:

$$k(r,u) = \left(\frac{Ab(R - R_0)}{\rho + i} \right)^{\frac{1}{a}} \tag{1.16}$$

$$h(r,u) = Ak^b = A^{\frac{1}{a}} \left(\frac{b(R - R_0)}{\rho + i} \right)^{\frac{b}{a}} \tag{1.17}$$

When the rent R is replaced by its expression in (1.12) and the transaction costs R_0 are assumed to be zero and disappear from (1.16) and (1.17) this yields:

$$k(r,u) = \left[\frac{Ab\alpha^{\frac{\alpha}{\beta}} \beta \left(Y + \overline{L} - pr \right)^{\frac{1}{\beta}}}{(\rho + i) u^{\frac{1}{\beta}}} \right]^{\frac{1}{a}}$$

$$h(r,u) = A^{\frac{1}{a}} \left[\frac{b\alpha^{\frac{\alpha}{\beta}} \beta (Y + \overline{L} - pr)^{1/\beta}}{(\rho + i) u^{1/\beta}} \right]^{\frac{b}{a}}$$

1.2.6.3 *Solving the urban system*

Households numbers/density at each distance, r, can be expressed as the housing surface at each point divided by the size of each dwelling. The available land at distance r is $L(r) = lr$, with $l = 2\pi$ in a perfectly circular city. We also assume linear transport costs which increase with the distance to the city center, $T(r) = pr$. Additionally setting $\gamma = \frac{1}{a\beta} > 0$, $B = \left(\frac{(b\beta)}{(\rho + i)} \right)^{\frac{b}{a}} A^{\frac{1}{a}} \alpha^{\frac{\alpha}{a\beta}}$, we get:

Households' density can be expressed as the housing surface at each point divided by the size of each apartment:

$$\begin{aligned} n(r,u) = \frac{H(r)}{q(r)} &= \left(\frac{(b\beta)}{(\rho + i)} \right)^{\frac{b}{a}} A^{\frac{1}{a}} \alpha^{\frac{\alpha}{a\beta}} \left[L(r) \frac{\left(Y + \overline{L} - T(r) \right)^{\gamma - 1}}{u^{\gamma}} \right] \\ \iff n(r,u) &= B \left[lr \frac{(Y + \overline{L} - T(r))^{\gamma - 1}}{u^{\gamma}} \right] \end{aligned} \tag{1.18}$$

When the border rent $R_0 = 0$ and the agricultural rent $R_a = 0$, then the distance from the center to the city border is given by:

$$R\left(r_f, u\right) = 0 \Leftrightarrow Y + \overline{L} - pr_f = 0$$

$$r_f(u) = \left(Y + \overline{L} \right) / p$$

We can now compute the utility of households by making sure that:

$$N = \int_0^{r_f} n\,(r, u)\,dr \tag{1.19}$$

which yields:

$$u = \left[lB \frac{\left(Y + \overline{L}\right)^{1+\gamma}}{\gamma\,(1+\gamma)\,Np^2} \right]^{\frac{1}{\gamma}} \tag{1.20}$$

The land rents recycled in the economy to households, $\overline{L}$, are given by solving equation (1.21). They will differ depending on the type of model used: 1/ cca – absentee landowners: in this case land rents are supposed to be consumed outside the urban area and not recycled into the local economy; 2/ ccp – public ownership of land: in this case land rents are entirely recycled in the urban economy and will accrue to households in equal proportion.

$$\begin{cases} \overline{L} = 0, & \text{in cca model} \\ \overline{L} = \frac{1}{N} \int_0^{r_f} \pi\,(r)\,dr, & \text{in ccp model} \end{cases} \tag{1.21}$$

Equation (1.21) yields:

$$\begin{cases} \overline{L} = 0, & \text{in cca model} \\ \overline{L} = \frac{1}{\gamma+1} Y, & \text{in ccp model} \end{cases} \tag{1.22}$$

Combining equations (1.20) and (1.22), we find the expressions of u and $\overline{L}$ which solve the closed city system with both absentee landowners and public ownership of land and endogenous housing structure.

Closed City with Absentee Landowners : CCA	**Closed city with Public Ownership of land: CCP**
$\begin{cases} u = \left[lB \frac{Y^{1+\gamma}}{\gamma(1+\gamma)Np^2} \right]^{\frac{1}{\gamma}} \\ \overline{L} = 0 \end{cases}$	$\begin{cases} u = \left[lB \frac{(Y(\gamma+2))^{1+\gamma}}{\gamma(1+\gamma)^{\gamma+2}Np^2} \right]^{\frac{1}{\gamma}} \\ \overline{L} = Y \frac{1}{\gamma+1} \end{cases}$

Table 1.2: The solutions to a stylized and simple urban system in two configurations: 1/ Closed City with Absentee landowners (cca) on the left and Closed City with Public ownership of land on the right (ccp).

1.3 DATA AND CHOICE OF PARAMETERS

We will detail in this section the data used and the choice of parameters for 1/ socio-economic and demographic inputs, 2/ household utility function 3/ developers' behavior, the housing production function and construction costs, 4/ transport data and modelling choices and 5/ land use and building regulation data.

1.3.1 *Socio-economic and demographic inputs*

- Population in the Paris urban area: The demographic scenario used in this exercise combines the projections of IAU and INSEE for the 2010 –

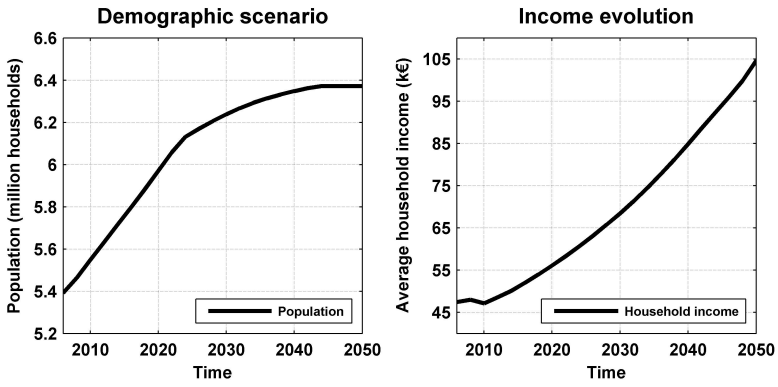

Figure 1.1: Evolution of the population (number of households) and the average household income over time in the baseline scenario.

2030 period for the urban area of Paris (Louchart, 2010) with INSEE's lowest demographic scenario for the whole of France for the 2030 – 2050 period relying on INSEE (Robert-Bobée 2006). Combining both these projections leads to a reasonably fast increase from 2010 to 2025 which slows down before stabilizing around 2040 and up to 2050. Household size decreases from 2.3 members per household in 2006 to 2.1 in 2030 and then remains constant through 2050. As a result population measured in number of households reaches a little under 6.4 million in 2050, i.e. 18% above its 2006 level (5.4 million).

- Income evolution of the median household: We only represent one household class in the model so we characterize the disposable income[5] of the average household in the urban area of Paris and its evolution over time. We selected it from one of the scenarios produced by the global energy modeling framework IMACLIM-R (Rozenberg et al., 2010; Waisman et al., 2012), which was used and detailed in a previous study (Viguié, Hallegatte, and Rozenberg, 2014). In this scenario, average incomes increase at an annual rate of 1.8% so that over the 2006 – 2050 period this income is multiplied by 2.2 starting from approximately 47,500 euros and nearly reaching 104,600 euros in 2050.

1.3.2 *Household utility*

The household utility function reads as follows:

$$U\left(z(r), q(r)\right) = z(r)^{\alpha} q(r)^{\beta} \text{ where } \alpha, \beta > 0 \text{ and } \alpha + \beta = 1 \tag{1.23}$$

Households spend a share β of their income net of transportation costs on housing. Indeed, maximizing (1.23) with respect to q and replacing z with the budget constraint by $Y - q(r)R(r) - T(r)$, we find: $q^*(r)R(r) = \beta(Y - T(r))$. For the purpose of the simulations in this study we must characterize β. We chose a value of 0.3 for β and thus 0.7 for α. This means that in the city center, where transportation costs are assumed to be zero in the monocentric theory, households will spend 30% of their income on housing expenditures. This corresponds to the maximum household housing effort rate which is allowed for nor-

[5] Meaning income after direct taxation.

mal renting or borrowing in French urban areas, according to prudential measures designed to ensure renter household solvency, and closely corresponds to actual share of expenditures in the urban area of Paris (Coulombel, 2017).

1.3.3 *Housing production function*

The housing production function is defined by:

$$F\left(L(r), K(r)\right) = H(r) = AL(r)^a K(r)^b \text{ where } a, b > 0 \text{ and } a + b = 1 \quad (1.24)$$

The housing production function can be rewritten as the landowner in fact chooses the capital/land ratio $k = K/L$ that maximizes his land's value. Since F has constant returns to scale equation (1.24) can be simplified as the ratio of capital to land will only change as a function of rents and not the amount of land each landowner possess.

$$f\left(k(r)\right) = \frac{F\left(K(r), L(r)\right)}{L(r)} = A\left(\frac{K(r)}{L(r)}\right)^b = Ak(r)^b \quad (1.25)$$

In the absence of detailed datasets about construction costs, we relied on partial data gathered from the Centre Scientifique et Technique du Bâtiment (CSTB) that provided some information about average construction costs for various building heights. We interpolated the various data points and achieved a curve which seems to increase quasi linearly with building height. Model parameters A and b were calibrated so as to minimize discrepancy between the CSTB interpolated data and the simulated construction costs in the model. The calibration procedure led to values of $A = 1.73$ and $b = 0.66$ (with $a = 1 - b = 0.34$). As a result the construction cost curve of NEDUM-2D seems in general agreement with the partial data we have although it presents a more convex shape leading to an underestimation of costs for low building heights and an overestimation for larger number of floors (Figure 1.2). Parameter A of the construction function evolves over

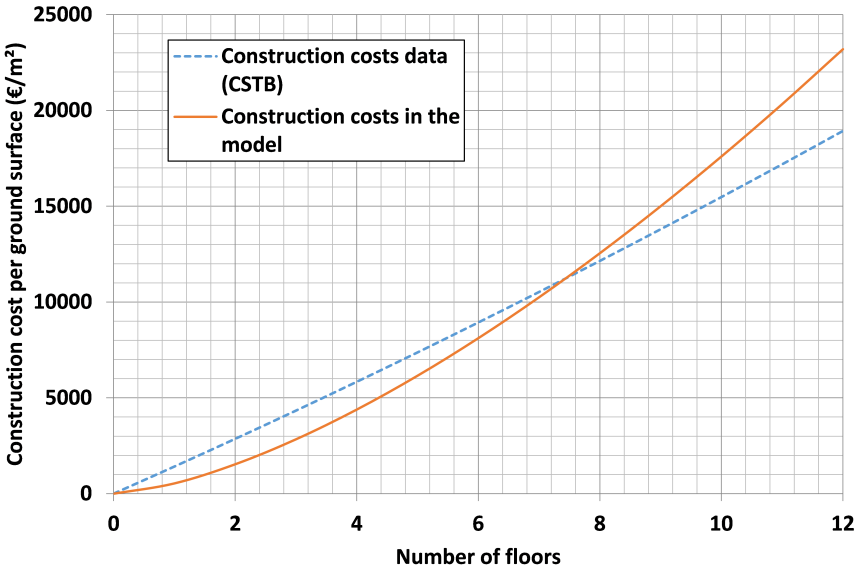

Figure 1.2: Comparison of data and simulated construction costs per square meter of ground floor as a function of number of floors of the building.

time with income as follows $A_t = A_0 \cdot (Y_t/Y_0)^{-b}$ to account for the upward trend observed in building construction costs over the 1998 – 2015 period (INSEE).

1.3.4 *Transport data and competition between modes*

Transport costs are essential to all land use – transport models. NEDUM-2D uses complete or generalized transport costs which encompass both the monetary and time components of travels.

- Walking times: they are calculated on the basis of the Euclidian distance to the CBD. We assign an average speed of 3km/hour to pedestrians, i.e. lower than the usually agreed upon 4km/hour to account for the fact that real world distances are longer than beelines.
- Public and private transport times: In terms of transportation trip duration, we relied on a study by Rouchaud and Sauvant (2004) as in several other studies using the NEDUM-2D model (Avner, Viguié, and Hallegatte, 2013; Viguié and Hallegatte, 2012; Viguié, Hallegatte, and Rozenberg, 2014). Rouchaud and Sauvant built a database of transport times to reach the center of Paris from different municipalities of Ile-de-France, by public and individual transport during morning and evening peak hours.
- Private car costs: For the purposes of our study, the model was enhanced by introducing a mechanism which links average fuel consumption of new cars (and therefore their CO_2 emissions) to the evolution of the price of fuel. The unitary cost of travelling one kilometer (€/km) using cars is thus determined by the price of fuel and the unitary consumption of cars (l/100km), itself dependent on the price of fuel. In the absence of policy interventions in the form of a carbon tax, it is assumed that the price of fuel increases by 55% over the whole period. In parallel, reacting to this increase in fuel prices, household will purchase lower consuming vehicles: in 2050 new vehicles consume close to 9% less fuel per kilometer and the average fleet vehicle will consume 6% less. In total, the baseline scenario will lead to unit cost of travelling by car (€/km) to increase by 45%. The introduction of carbon taxes in the alternative scenarios will bring the cost of fuel up but will also trigger more substantial technological changes leading to the production and adoption by households of less consuming cars.
- Public transport fares: In this study we make the assumption that public transport fares will evolve at a slightly lower pace than the cost of fuel reaching in 2050 142% of their 2006 level. And we assume that public transport users buy a monthly subscription at the beginning of each month as it constitutes the cheaper option. The cost of the subscription depends on the location of the household within the urban area as the larger Paris area is divided into five distinct fare zones. In 2011, the cost of the subscription for zone 6, the most distant from Paris center, is roughly 2.2 the cost of public transport in zone 1 and 2[6]. We assume that the costs of the public transport subscription will evolve

[6] A number of modifications have occurred since 2011 in the operation of the public transport network in the Paris urban area. Zone 6 no longer exists and has been integrated to zone 5; there are therefore only 4 distinct subscription zones today (with zones 1 and 2 sharing the same

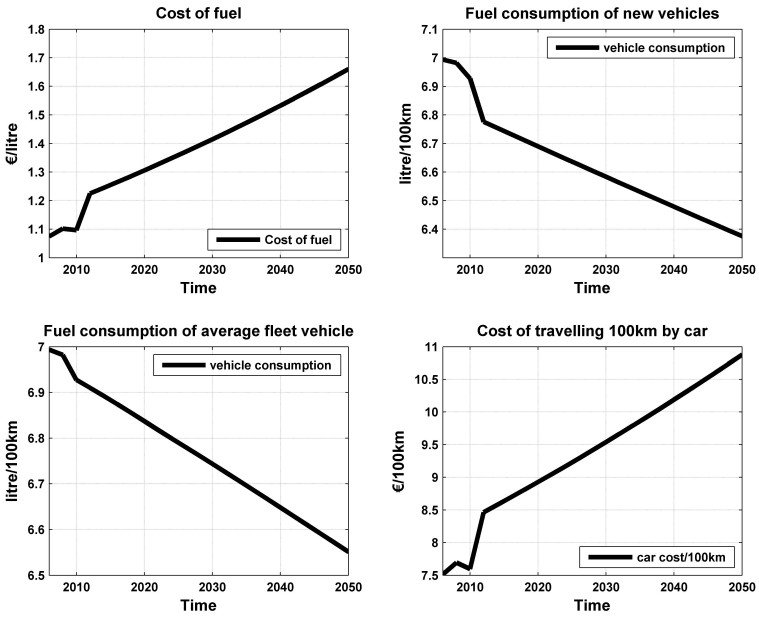

Figure 1.3: Evolution of the cost of fuel, the monetary cost of travelling 100km by car, the fuel consumption of new vehicles and the fuel consumption of the average fleet car in NEDUM-2D over time in the baseline scenario.

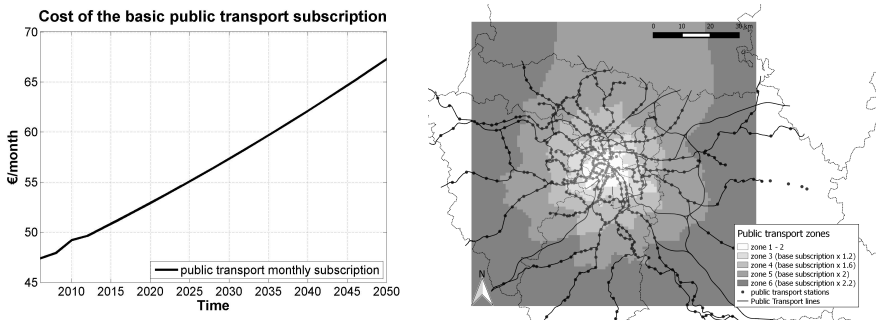

Figure 1.4: Evolution of the cost of the monthly basic public transport subscription for central zones 1- 2 on the left and spatial extent of the various public transport zones (1 – 2 to 6) on the right.

at the same pace irrespective of the zone – there are no relative price changes between zones.

- Cost of time: NEDUM-2D uses generalized transport costs which encompass both monetary and time costs. How to value transport times is however a difficult issue which has triggered a vast number of scientific papers and reports (Boiteux and Baumstarck, 2001; Mackie et al., 2003; Oort, 1969; Small, Winston, and Yan, 2005) without reaching a

fare structure). Furthermore, the fare structure is in the process of changing drastically, with the implementation of unique subscription cost throughout the urban area to reach downtown Paris. Because we calibrate our model on data from 2006, we chose to consider that the public transport fare structure will remain similar to what it was in 2006. Investigating the changes in zoning and public transport prices is a very interesting exercise, but it goes beyond the scope of this paper.

definite consensus. These papers focused mainly on the topic of how to quantify the benefits of transport investments which accrue in the form of travel time savings. As noted by Oort (Oort, 1969) "'reduction in travel time' does not carry a market price", yet it is critical because "the total social benefit of projects in the area of transport "infrastructure" will often consist to a large extent of time savings". In fact, if the cost of time is proportional to incomes with a non-negligible proportionality factor it becomes easy to understand that time costs will dominate generalized costs in high income countries (and increasingly so elsewhere). Especially as monetary transport costs per kilometer have fallen in proportion to incomes in many countries – in France for example since the oil crises – because of progress in transportation technologies and despite rises in the price of fuel. In particular, Small, Winston and Yan find that motorists exhibit high values for travel time but also large heterogeneities in these (Small, Winston, and Yan, 2005). Because of the importance of the cost of time and because of the absence of consensus in the scientific literature, Viguié, Hallegatte, and Rozenberg (2014) chose to define the cost of time through a calibration procedure rather than to resort to an a-priori fixed value. We follow their approach in this study. They computed this cost using data on the spatial distribution of housing rents (CLAMEUR, 2008). Assuming that the NEDUM-2D model is perfectly exact, it is indeed possible to estimate a theoretical generalized transportation cost that would lead to these rents and, deducting the monetary costs from these, to achieve time costs. Dividing these time costs by journey time the authors achieve a cost of time.

This marginal time cost seems to decrease with travel time, so they chose to model simply this decrease using a piecewise affine function. This representation leads the authors to use a cost time worth 105% of the net hourly wage when the travel time is less than 25 min (or, equivalently, when the distance to the center of Paris is less than 15 km), then a very low cost (6.6% of the net hourly wage) for portions of journey in excess of this limit. This observed decrease in marginal time cost can be attributed to the limits of the monocentric framework and the hypothesis that households make a round-trip per day towards the center of Paris. In the real world, in places where travel time exceeds 25 minutes, a large fraction of households do not commute to the center of Paris.

- Mode competition: The transportation module of the NEDUM-2D model represents modal choice. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination thereof as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged. In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse, 1987). We follow a common approach in transportation economics by using a multinomial logit model which assigns usage probabilities to each transport mode (see Salon, 2009; Washbrook, Haider, and Jaccard, 2006). This method

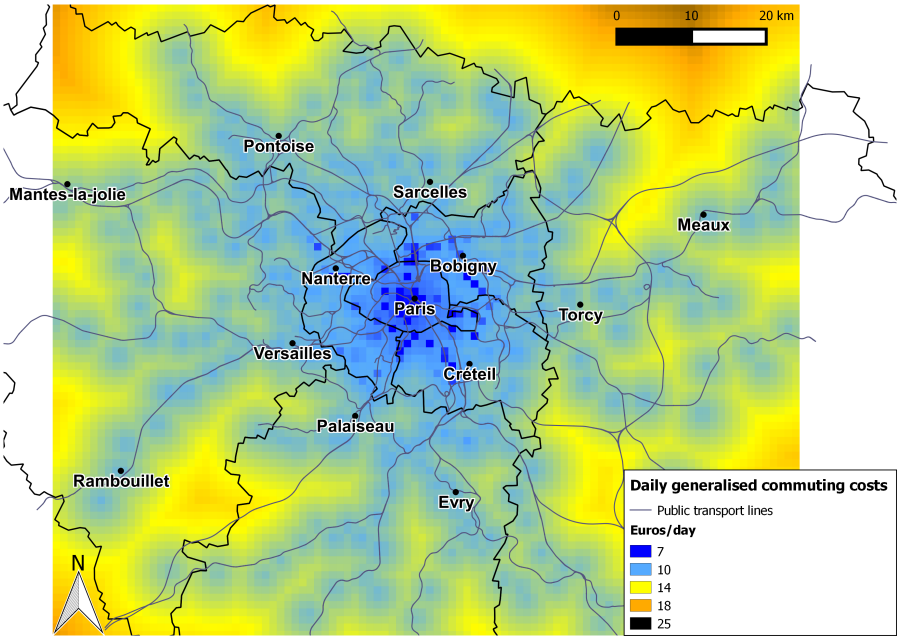

Figure 1.5: Daily generalized costs of commuting for the Paris urban area based on the simplifying hypothesis that all jobs are situated in the center of Paris. The transport costs thus tend to increase as we move away from downtown Paris. For a given distance to the center of Paris they are lower when one is close to a public transport line.

ensures that even when one mode is much cheaper than the others, it will not be used by all residents in a location for all trips.

$$P_{m_i} = \frac{e^{-\lambda \frac{p_i}{p_{\min}}}}{\sum_i e^{-\lambda \frac{p_i}{p_{\min}}}} \tag{1.26}$$

The probability of choosing mode i in a given location is given by a multinomial logit function and depends on the complete transport costs of travelling to the CBD with this mode. This cost is weighted by the inverse of the transport cost of the cheapest mode $\frac{1}{p_{\min}}$ and by a coefficient λ. The value of λ is calibrated so as to minimize average mode share discrepancies with the data and is estimated to be equal to 4 in this study. This means that in a city with two modes, if one of these modes is 50% more expensive than the other, then it will have a mode share of 15%, while the less expensive travel mode will have an 85% mode share. The mode share of public transport in the model in 2006 for the Paris urban area (measured as the share of people using public transport) is around 35.5%, so relatively close to the 40% observed in 2001 (DRIEA, 2005). Figure 1.5 shows the resulting map of daily generalized commuting costs used in this study.

1.3.5 *Land use and building restrictions*

Land uses incompatible with urbanization: In order to be able to reproduce the location and extent of urban areas in the Paris region correctly, NEDUM-2D accounts for regulations or land uses that are incompatible with the

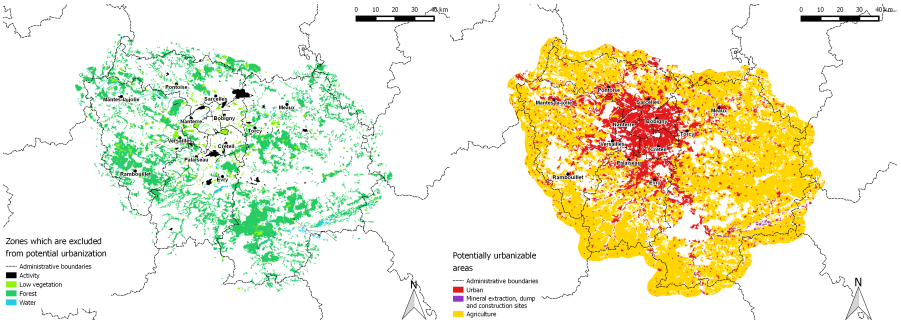

Figure 1.6: Left/ Land use exclusion map showing areas that are excluded from potential urbanization in the model; Right/ Zones which can be urbanized in NEDUM-2D.

development of residential areas. NEDUM-2D therefore requires a map of land use constraints which is used as a filter to exclude some zones from potential urbanization. For example, it excludes zones occupied by water or protected natural areas such as forests. These exclusion zones are defined by selecting a number of land use classes from the 2006 version of CORINE Land Cover (CLC), a land use map produced from satellite imagery for European countries. The exclusion map (left section of Figure 1.6) encompasses any area occupied by water bodies, forests, low vegetation such as parks and urban woods (in particular the Bois de Boulogne and Bois de Vincennes to the West and East respectively of central Paris), and rail networks, airports and ports (regrouped below under Activity). While the total area of exclusion is non-negligible, it remains, by far, lower than the area that could be potentially urbanized which goes far beyond the actual urbanized area of Paris (right section of Figure 1.6). This is indicative that although the exclusion map can avoid major discrepancies between the simulation and the data, it is not a main driver behind the overall accuracy of our results regarding the match between simulated and observed urbanized areas.

Land area available for buildings: We assume that in each pixel of our grid, after excluding for restricted land uses as shown in Figure 1.6, a maximum of 62% of the land area can be used for buildings. The remaining 38% is expected to be used for roads and infrastructure which are essential for any urban area to function correctly. This share of urbanisable land (excluding parks) that can be used for buildings is based on findings from APUR (Agence Parisienne de l'Ubanisme), that in the most densely populated part of the Paris urban area, Paris intra-muros, roofs account for 62% of land cover as measured through aerial photographs.

Building height regulations: An important clarification needs to be introduced. The model exclusively studies residential behaviour and as a consequence does not provide any information on buildings for other purposes such as leisure (museums, cinemas), shopping or working (offices). This simplification introduces a discrepancy between the Floor Area ratios (FAR) that are simulated by the model and the ones that are observed in practice. This discrepancy is reinforced because the FARs that are produced by NEDUM-2D do not account for residential building space used for corridors and lobbies or even courtyards. By way of comparison, in the centre of Paris, typical "Haussmanian" buildings usually have 6 floors which corresponds to a FAR of approximately 4 (because 75% of ground area is used[7]). How-

[7] http://www.iau-idf.fr/fileadmin/Etudes/etude_213/nr_384_Apprehender_la_densite_3.pdf.

ever, when we only account for living space, the maximum "living space FAR" measured as (maximum population density)x(dwelling sizes) is 1.5. NEDUM-2D typically produces what we called above "living space FAR". We therefore chose to set a maximum limit to building heights in the centre of Paris to 1.5 floors in the model which would correspond to approximately 6 stories in reality and adequately describe Haussmanian buildings.

1.3.6 *Other parameters*

A few other parameters are required by NEDUM-2D:

- Building's depreciation rate ρ: The depreciation rate of buildings ρ intervenes in landowner's profit function and plays a role in the determination of the amount of capital invested in structures throughout the urban area (equation (1.3)). It represents the natural depreciation of structures and is therefore used to express the average yearly annual costs of refurbishing them. Given that structures in urban areas tend to have widely varying lifetimes ranging from 30 to 150 years (Hallegatte, 2009) we chose a simple figure of 0.01 to express that on average annual maintenance costs are 1% of buildings' construction costs.
- Interest rate i: The interest rate also intervenes in the model by affecting construction costs as it represents the opportunity cost of capital or the financial cost of borrowing money to finance the construction of buildings. It is difficult to ascertain an interest rate that would adequately represent the annual financial burden of construction in an urban area like Paris which has developed over centuries. We therefore chose the value of 5% which appears to be reasonable.
- Border rent/transaction costs R_0: As discussed in section 1.2.3, NEDUM-2D differs from classic urban economic models because it chooses to model the edge of a city through a transaction cost below which it is no longer profitable to build structures instead of using an agricultural land value. The transaction cost that was retained in NEDUM-2D for the Paris urban area is 12€/m^2 in 2006. It was ascertained by visually capturing that housing rents tend to remain stable at around this value at the edge of the urban area of Paris. The border rent/transaction cost is assumed to evolve over time at the same rate as household income.
- Time lags for the dynamics of the housing stock: The inertia that characterizes investments in building structures, τ_H, is set to a value of 20 years. This time lag encompasses necessary time for the actual construction to take place and other transaction costs such as possibly negotiating a bank loan, finding the appropriate location and land plot, finding a suitable construction firm and negotiating building permits. This value of 20 years means that each year only a twentieth of the optimal construction can take place. In terms of the inertia that characterizes the destruction of buildings, τ_{dH}, it is set at the same value as the depreciation rate, ρ, meaning that without any investments, buildings would be destroyed over the course of a century.

1.4 VALIDATION OF NEDUM-2D

Figure 1.7 below provides an idea of the model's ability to reproduce Paris' urbanized area. It can be seen from Figure 1.7 that the simulated and the actual

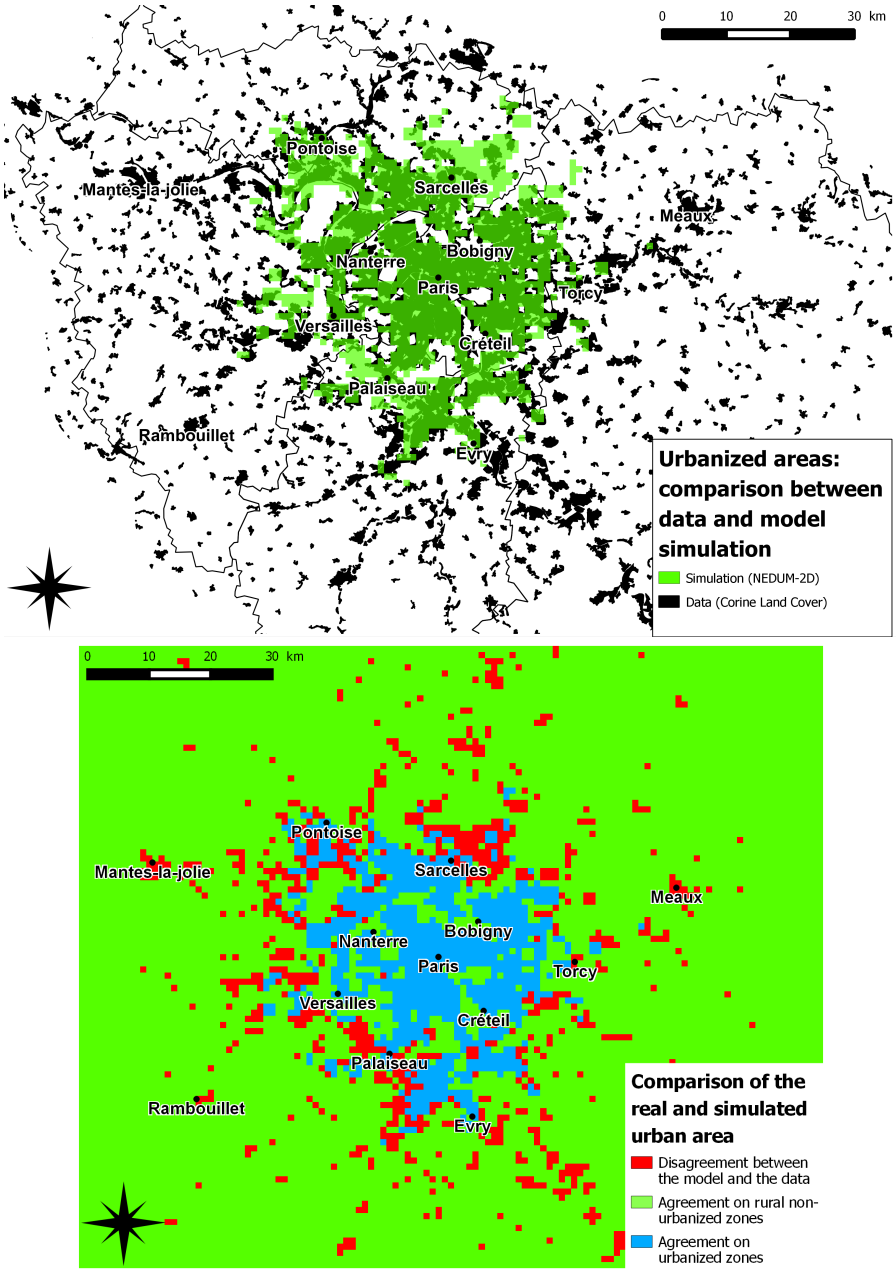

Figure 1.7: Top panel The simulated and real urban area of Paris in 2006. The green shade corresponds to the simulation whilst the black is geographic data (Source: Corine Land Cover (European Union and SOes, 2006)). The dark green shade shows areas where the model accurately predicts urbanization. Light green shows areas where the model inaccurately predicts urbanization. Black stands for areas where the model fails to reproduce urbanization. Finally where the map is white, there is no urbanization and the model agrees with the data. Bottom panel The agreement and disagreement between the data and the model on the urbanized and non-urbanized zones of the Paris urban area in 2006. The green and blue shades show agreement between the model and the data respectively for non-urbanized and urbanized zones. The red shade shows disagreement between the model and the data.

urban area in 2008 (date for which we have built-up footprint data) coincide quite well. The model captures the general size of urbanized area but also its shape and specific urbanization directions along the transportation network. There are however some discrepancies. In particular it can be seen that the map misses some areas towards the South-East in particular. This can mainly be explained either by the existence of local secondary employment centers that attract settlements or the presence of local amenities. It can also be seen that the simulations over-predict urbanization in the North close to Sarcelles.

Beyond the general agreement on the shape and size of the urbanized area between simulation and data (documented above), it is equally important to understand if and to what extent NEDUM-2D is able to reproduce the internal structure of the Paris urban area. The internal structure of an urban area can be understood as the spatial distribution of main variables such as population densities and rents. The following section documents how the simulations fit the data for the internal structure of the Paris urban area and validates the model further.

1.4.1 *Internal structure of the Paris urban area*

Figure 1.8 shows the classic result that population densities decline as the distance to the city center increases both in the data and the simulations. It shows the population density data at the communal level (Robert-Bobée, 2006) represented by grey circles whose size are proportional to the area (in km^2) of the commune as well as the average of the data (dashed blue line). The green area captures the spread of the 80% most central simulations for a given distance to the CBD, while the red plotted line represents the average of the simulation. There is a general agreement between the average of the data and the simulation and the way these decline with the distance to the CBD. There is however a discrepancy for the most central part of the city (within 5 km of the city center) where the simulations' average is somewhat higher than the data average. From km 7 onwards, the two lines are however virtually indistinguishable. It can also be seen that the simulation boundaries (for the 80% most central simulations) largely capture the actual population densities' spread as most grey circles lie within the green area. Finally the one dimensional R^2 coefficient – comparing the averages of the simulation and the data – is 90% meaning that the model can explain 90% of the one dimensional variance in the data. The two-dimensional R^2 coefficient – comparing the simulation and the data at each commune level both weighted by the area of the commune – is slightly lower yet remains high at 88% (plot not shown here).

Figure 1.9 has the same color codes and purpose as Figure 1.8 but looks into whether and to what extent the simulations and the data agree for housing unitary rents (€/m^2). A similar conclusion can be drawn from the figure, that there is a general agreement on the shape of the two curves representing the averages of the data and the simulations and that the model's spread captures a large share of the data points. The one-dimensional R^2 coefficient is high also at 0.94 meaning that the model can explain 94% of the variance between the simulation and data average. The two-dimensional R^2 coefficient comparing data and simulation at the communal level, and accounting for the population of each commune, is lower at 0.66.

Figure 1.10 compares simulation and data for average dwelling sizes and housing densities. There is a general agreement on the magnitude and slope of curves between data and simulation for these two variables although dwelling sizes appear to be lower by approximately 10 m^2 throughout the urban area.

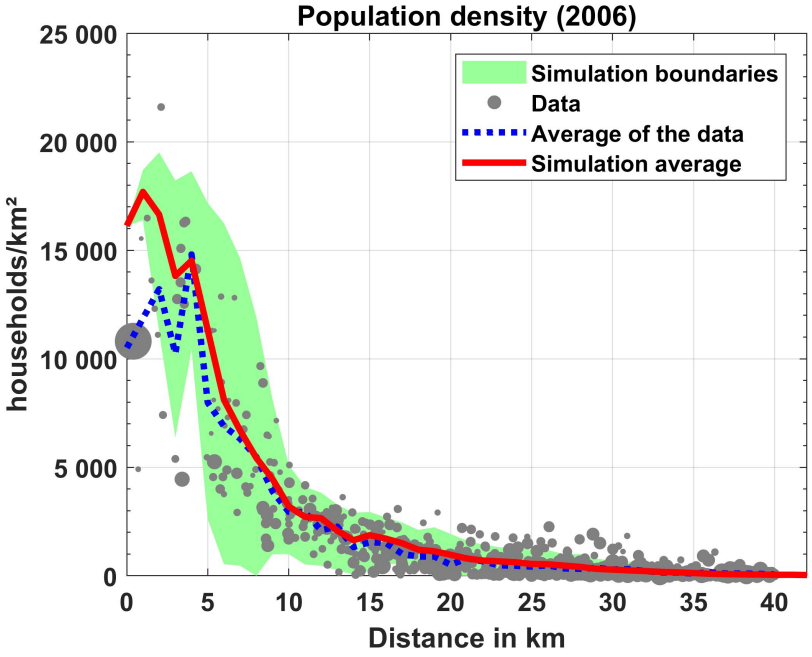

Figure 1.8: Household densities as a function of the distance to the city center. Comparison of model output with data (Robert-Bobée, 2006).

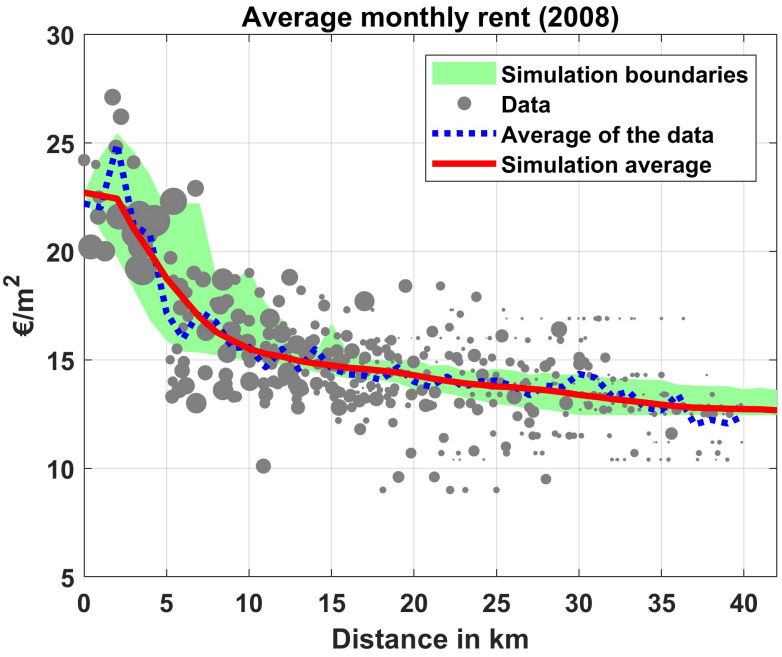

Figure 1.9: Rents per square meter as a function of the distance to the city center. Comparison of model output with data (CLAMEUR, 2008).

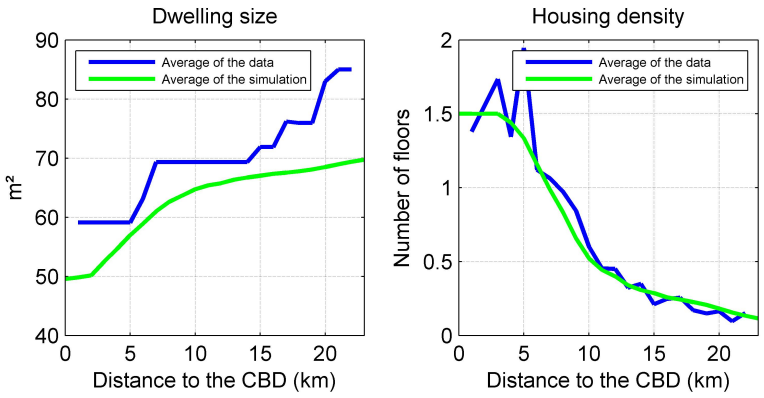

Figure 1.10: Comparison of average dwelling size (to the left) and average housing density (to the right) as a function of the distance to the city center.

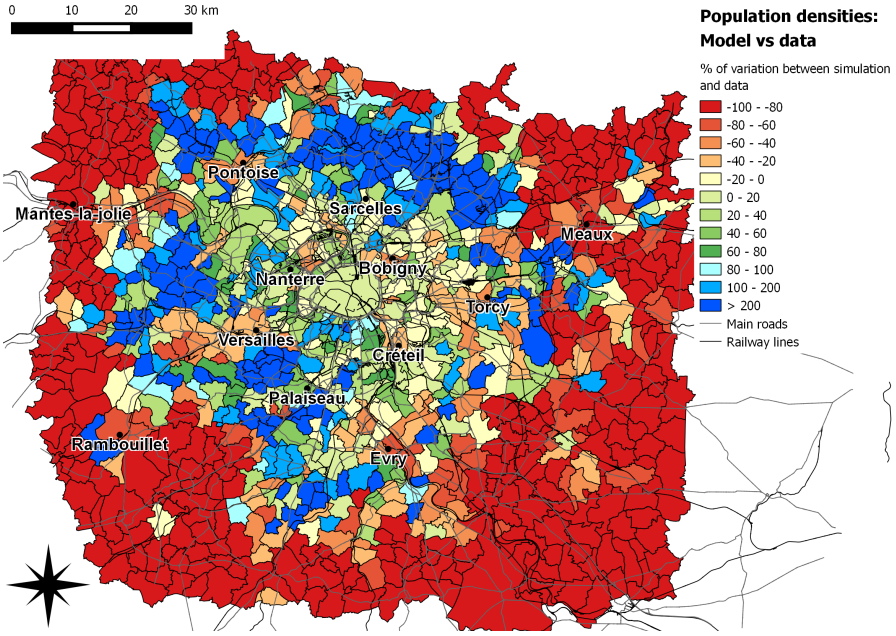

Figure 1.11: Household density variation between model simulations and data (Robert-Bobée, 2006) at the "commune" level for the Paris urban area.

Population density thresholds				
Error ranges	No threshold	1 household/ ha	5 household/ ha	10 household/ ha
< 20%	14.3%	25.0%	37.6%	40.5%
< 30%	19.8%	33.4%	49.3%	51.3%
< 40%	25.3%	43.4%	61.3%	64.6%
< 50%	30.9%	53.1%	72.6%	75.4%

Table 1.3: Share of communes which fall within a given error range for household density simulations depending on error ranges and population density thresholds used to exclude communes which have low populations and population densities.

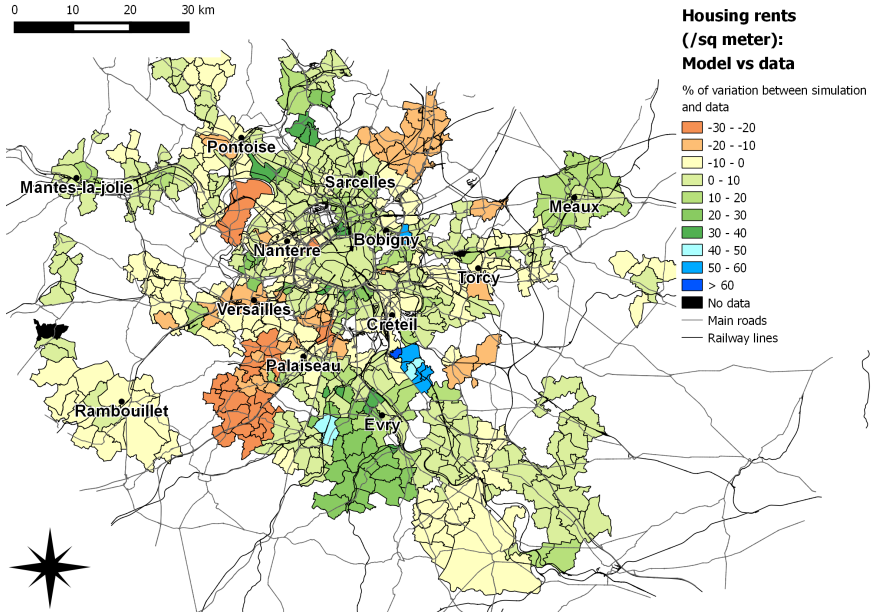

Figure 1.12: Housing rent variation between model simulations and data (CLAMEUR, 2008) at the "commune" level for the Paris urban area.

Figure 1.11 shows the variation between simulation and data for population densities at the communal level for the Paris urban area. It can be seen that when represented on a map, the discrepancy between data and simulation for household densities appears larger than when averaged over distance to the city center as in Figure 1.8. Indeed, whereas the variation between simulations and data is mostly comprised between -40% and $+40\%$ for Paris and the "Petite Couronne", beyond these and looking at the "Grande Couronne" the differences can be significant. In particular, the model over-estimates population densities toward the edge of the urbanized Paris urban area (represented in blue) quite significantly with variation rates reaching 100% and above in a number of locations. Beyond the urbanized area, the model always under-estimates population densities which is captured by the dark red shades on the border of the urbanized area.

However, the map representation grants the same weight to each commune even though some of them are very sparsely populated, mainly in the outskirts. This leads to a visual impression that simulations fail in reproducing data correctly for many communes (for example the red shades in the outskirts). While this may be true, the actual population which is misrepresented is in fact much lower. To try to account for this bias we can set a series of household density thresholds to observe how the share of communes which fall within a given error range changes when we exclude communes which have low household densities (Table 1.3).

Table 1.3 shows us that if we exclude "communes" which have a household density per hectare below one, the share of communes which fall within a 50% error range bounces from 31% to 53%. And if the threshold is increased to 5 or 10 household per hectare, the share of communes which fall within a 50% error range goes up further to 73% and 75%. For these three household density thresholds, the population that would be excluded amounts to 4%, 13% and 24% respectively of the urban area's total population.

Figure 1.12 shows the variation between simulation and data for unitary housing rents at the communal level for the Paris urban area. There are less

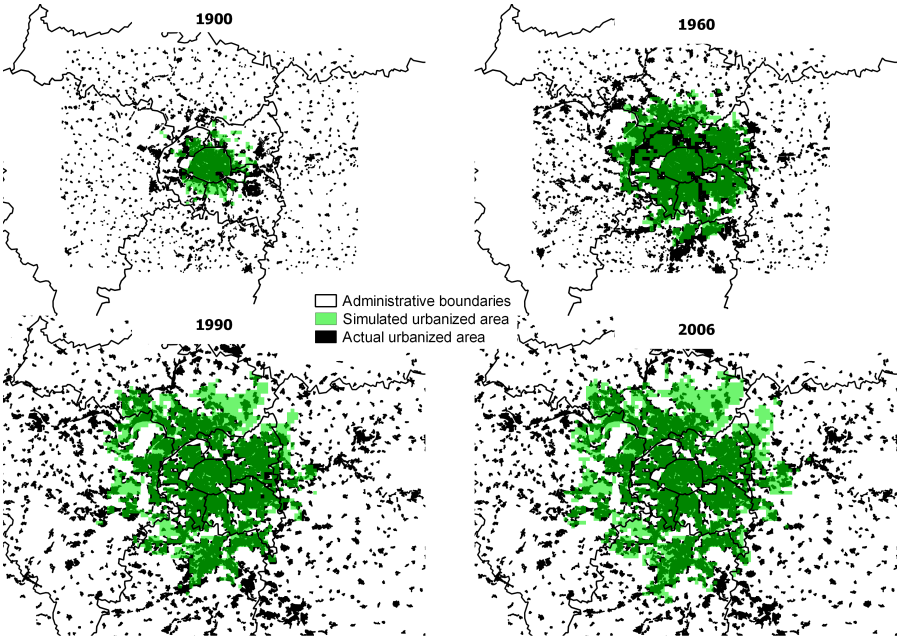

Figure 1.13: Comparison of the urban footprint of the urban are of Paris such as simulated by NEDUM-2D (transparent green) with actual data (in black, source: IAU, MOS database for 1900 and 1960 and EU and SOeS, Corine Land Cover for 1990 and 2006). The dark green shade shows areas where the model accurately predicts urbanization. Light green shows areas where the model inaccurately predicts urbanization. Black stands for areas where the model fails to reproduce urbanization. Finally where the map is white, there is no urbanization and the model agrees with the data. (Figure reproduced based on Viguié (2012)).

communes where the comparison was possible as data for rents were not collected everywhere. In the sample of 510 communes for which we have data in the Paris urban area, the map shows a good agreement between simulation and data. In fact, 66% of communes fall within a 10% error range. This figure goes up to 87%, 96% and 98% for 20%, 30% and 40% error ranges respectively.

1.4.2 *Validation over time*

The sections above aimed at providing some elements to validate NEDUM-2D as a simple, yet realistic land use – transport model in a static framework by comparing simulation output to data for various important variables. By doing so, we hoped to have convinced the reader that this model can be used to reproduce the internal structure of a city in terms of spatial distribution of rents, households, dwelling sizes and housing. We equally believe that this validation exercise has demonstrated that NEDUM-2D could be used to assess the impacts of shocks (related to transport or urban policies, socio-economic changes etc...) to the urban system[8] on these main variables. NEDUM-2D is however a dynamic model which aims at capturing the evolution of urban areas over the long term. It is therefore important to understand NEDUM-2D's ability to reproduce the evolution of city systems

[8] Providing that these shocks affect either the inputs to the model or the behavior of urban residents and landowners when choosing where to locate, how much land/housing to consume or where and how much residential floor space to build.

over time. Such an exercise was precisely conducted by Viguié (2012) for the urban area of Paris over the 1900 – 2008 period. We reproduce some of the main results of this exercise below in order to provide the reader with a complete description of NEDUM-2D and its thorough validation procedure.

To simulate the evolution of the Paris urban system over time, a more complex variation of the dynamic equations described in section 1.2.5 was used but the main principles and behaviors are the same (see Viguié, Hallegatte, and Rozenberg (2014) and its annex A for a full description of these equations). All relevant data were collected and parameters' value in the past were calculated based on the same evolution rules than for their future evolution.

Because of the lack of data, Viguié (2012) used the same transport network as in 2008 for the three simulations. As for 2008, there is a general agreement on the shape and size of the urbanized area of Paris for 1900 through to 2008. The description of the city in 1900 is not as good as for the following years[9] in part because the transport network at that time differs vastly from what it is today. However, large-scale trends between 1900 and 2008 are well described, suggesting that the model captures the main determinants of city shape evolution.

1.5 SENSITIVITY TO THE VALUE OF KEY PARAMETERS – VISUAL ILLUSTRATION

This section investigates graphically the sensitivity of the main model outputs – in a version of the model with linearly increasing transport costs with distance to the city center – to variations of the model's main parameters. In each of the below plots, the blue line corresponds to the evolution of a variable (population density, housing rents,...) as a function of the distance to the city center for the calibrated value of a given parameter and the red line is the corresponding plot of the variable if the value of the calibrated parameter was decreased by 10%. It is visually apparent, that whereas all parameters have significant and varying impacts (magnitude, direction, curve convexity/concavity...), the most important parameter is b, the parameter that intervenes in the construction function and that translates invested capital into built housing surfaces. This points to the central role of housing construction technologies in affecting urban forms as well as welfare outcomes.

[9] For instance, bus and tramway networks are not modeled, whereas they were of great importance at the beginning of the 20th century.

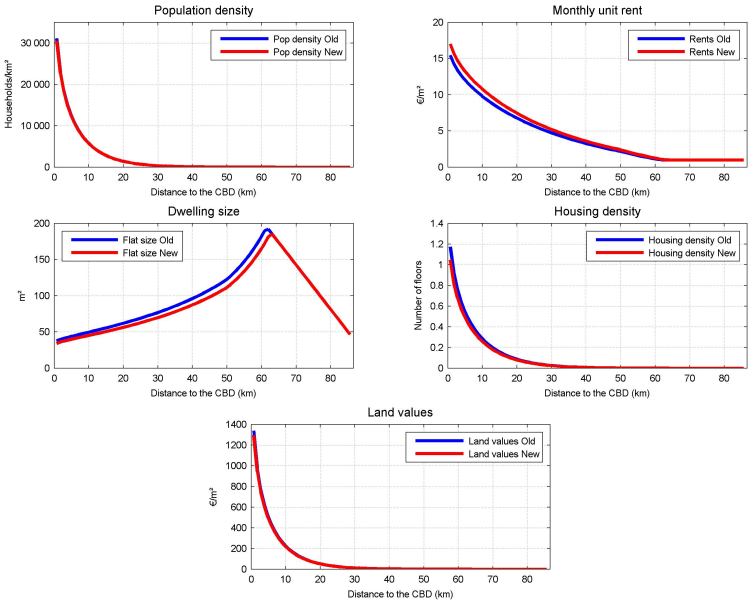

Figure 1.14: Sensitivity test performed by changing the value of the construction function parameter A. Visually a 10% decrease in its calibrated value leads from the blue to the red curve.

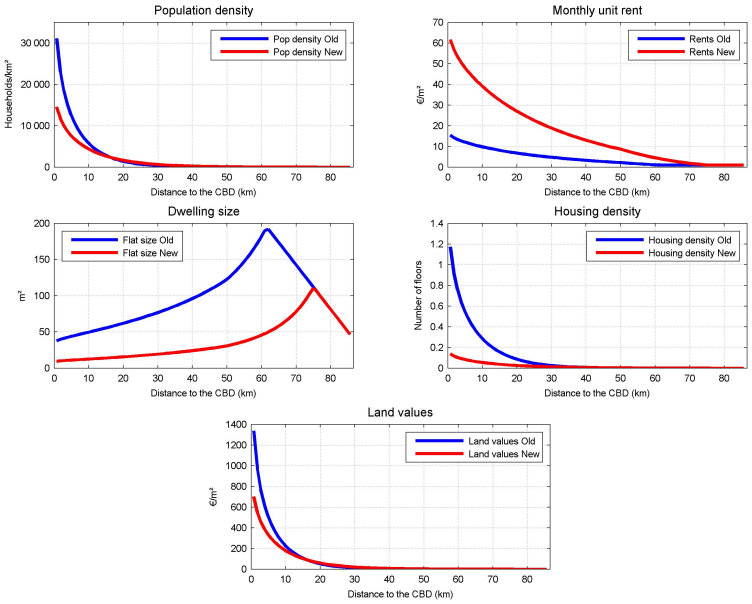

Figure 1.15: Sensitivity test performed by changing the value of the construction function parameter b. Visually a 10% decrease in its calibrated value leads from the blue to the red curve.

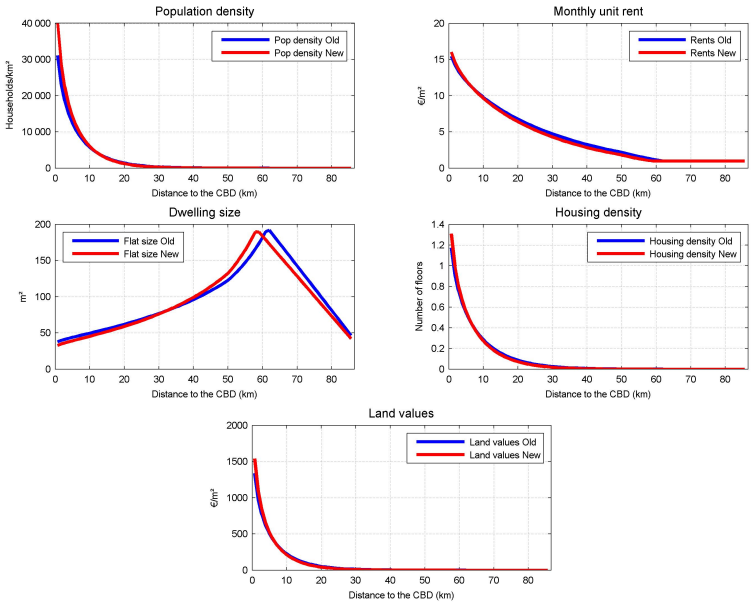

Figure 1.16: Sensitivity test performed by changing the value of the Household utility function parameter β. Visually a 10% decrease in its calibrated value leads from the blue to the red curve.

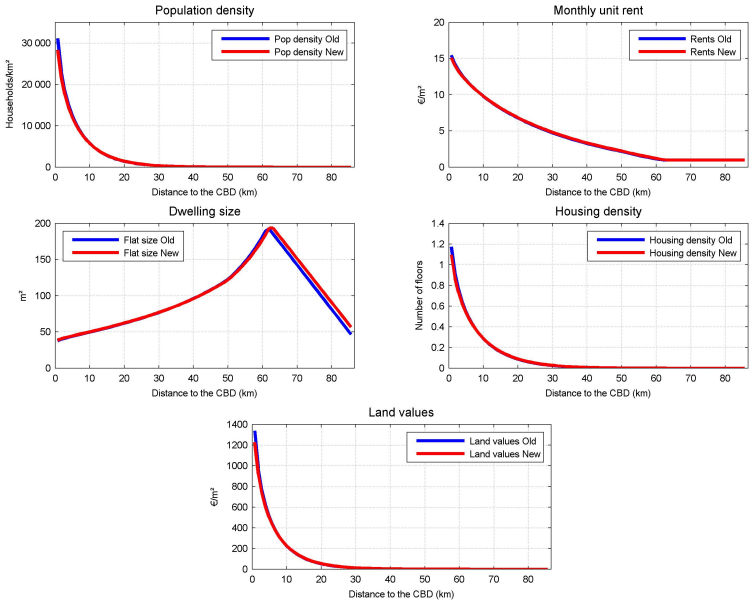

Figure 1.17: Sensitivity test performed by changing the value of the transport cost function parameter – change in the value of time as expressed as a function of household income. Visually a 10% decrease in its calibrated value leads from the blue to the red curve.

REFERENCES

Acheampong, Ransford Antwi and Elisabete Silva (2015). "Land use–transport interaction modeling: A review of the literature and future research directions." In: *Journal of Transport and Land Use*. ISSN: 1938-7849. DOI: 10.5198/jtlu.2015.806.

Ahlfeldt, Gabriel and Daniel P. McMillen (2014). "New Estimates of the Elasticity of Substitution of Land for Capital." In: *ERSA conference papers" European Regional Science Association*.

Alonso, W. (1964). *Location and land use: toward a general theory of land rent*. Harvard University Press.

Avner, Paolo, Vincent Viguié, and Stéphane Hallegatte (2013). "Modélisation de l'effet d'une taxe sur la construction: le Versement pour Sous-Densité." In: *Ville et Logement*. Ed. by Sabine Le Bayon, Sandrine Levasseur, and Christine Rifflart. Revue de l'OFCE - Débats et Politiques 128. Puteaux: Editions du Net.

Boiteux, Marcel and Luc Baumstarck (2001). *Transports: choix des investissements et coût des nuisances*. Tech. rep. Paris, La Documentation française: Commissariat général du plan.

Box, George EP and Norman R. Draper (1987). *Empirical model-building and response surfaces*. John Wiley & Sons. ISBN: 0-471-81033-9.

Brueckner, Jan K. (1980). "A vintage model of urban growth." In: *Journal of Urban Economics* 8.3, pp. 389–402. ISSN: 0094-1190. DOI: doi:DOI:10.1016/0094-1190(80)90039-X.

— (1987). "Chapter 20 The structure of urban equilibria: A unified treatment of the muth-mills model." In: *Handbook of Regional and Urban Economics*. Ed. by Edwin S. Mills. Vol. Volume 2. Urban Economics. Elsevier, pp. 821–845. ISBN: 1574-0080.

— (2011). *Lectures on urban economics*. Cambridge, Mass: MIT Press. ISBN: 978-0-262-01636-0.

Coulombel, Nicolas (2017). "Prudential measures in housing access: Should one include transport costs in the front-end ratio?" In: *Journal of Transport and Land Use* 10.1, pp. 627–654. ISSN: 19387849.

Davis, Morris A. and François Ortalo-Magné (2011). "Household expenditures, wages, rents." In: *Review of Economic Dynamics* 14.2, pp. 248–261. ISSN: 10942025. DOI: 10.1016/j.red.2009.12.003.

De La Barra, Tomas (2001). "Integrated land use and transport modeling: the TRANUS experience." In: *Planning Support Systems: Integrating Geographic Information Systems, Models and Visualization Tools*. Ed. by RK Brail and RE Klosterman. Redlands, CA: ESRI Press, pp. 129–156.

De Palma, André and Jacques-François Thisse (1987). "Les modèles de choix discrets." In: *Annales d'économie et de statistique* n°9.

DRIEA (2005). *Les déplacements des Franciliens en 2001 - 2002. Enquête Globale de Transports*. Tech. rep. Direction Régionale de l'Equipement Ile-de-France.

Epple, Dennis, Brett Gordon, and Holger Sieg (2010). "A New Approach to Estimating the Production Function for Housing." In: *The American Economic Review* 100.3, pp. 905–924. ISSN: 0002-8282.

European Union and SOes (2006). *Corine Land Cover, 2006*.

Fujita, Masahisa (1989). *Urban economic theory: land use and city size*. Cambridge, New York: Cambridge University Press. ISBN: 978-0-521-39645-5.

Gusdorf, François and Stéphane Hallegatte (2007a). "Behaviors and housing inertia are key factors in determining the consequences of a shock in

transportation costs." In: *Energy Policy* 35.6, pp. 3483–3495. ISSN: 03014215. DOI: 10.1016/j.enpol.2006.12.022.

— (2007b). "Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks." In: *Energy Policy* 35.10, pp. 4826–4838. ISSN: 03014215. DOI: 10.1016/j.enpol.2007.04.017.

Gusdorf, François, Stéphane Hallegatte, and Alain Lahellec (2008). "Time and space matter: How urban transitions create inequality." In: *Global Environmental Change* 18.4, pp. 708–719. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2008.06.005.

Haase, Dagmar and Nina Schwarz (2009). "Simulation Models on Human-Nature Interactions in Urban Landscapes: A review including spatial economics, system dynamics, cellular automata and agent-based approaches." In: *Living Reviews in Landscape Research* 3.2.

Hallegatte, Stéphane (2009). "Strategies to adapt to an uncertain climate change." In: *Global Environmental Change* 19.2, pp. 240–247. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2008.12.003.

Hardy, M. H. (2012). "Simplified Integrated Transportation and Land Use Modeling to Support Metropolitan Planning Decisions: An Application and Assessment." PhD thesis. George Mason University.

Hunt, J. D., D. S. Kriger, and E. J. Miller (2005). "Current operational urban land-use–transport modelling frameworks: A review." In: *Transport Reviews* 25.3, pp. 329–376. ISSN: 0144-1647, 1464-5327. DOI: 10.1080/0144164052000336470.

Iacono, M., D. Levinson, and A. El-Geneidy (2008). "Models of Transportation and Land Use Change: A Guide to the Territory." In: *Journal of Planning Literature* 22.4, pp. 323–340. ISSN: 0885-4122. DOI: 10.1177/0885412207314010.

Klosterman, Richard E (2012). "Simple and complex models." In: *Environment and Planning B: Planning and Design* 39.1, pp. 1–6. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b38155.

Lee, Douglass B. (1994). "Retrospective on Large-Scale Urban Models." In: *Journal of the American Planning Association* 60.1, pp. 35–40. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944369408975549.

Lefevre, Benoît (2007). "La soutenabilité environnementale des transports urbains dans les villes du sud. Le couple "transport - usages des sols" au coeur des dynamiques urbaines." PhD thesis. Ecole des Mines de Paris - ENSMP.

Louchart, Philippe (2010). *Près d'un million de ménages Franciliens en plus à l'horizon 2030*. Tech. rep. 495. IAU.

Mackie, P. J., M. Wardman, A. S. Fowkes, G. Whelan, J. Nellthorp, and J. Bates (2003). *Values of travel time savings UK*. Tech. rep. University of Leeds, Leeds, UK: Institute of Transport Studies.

Mills, Edwin S. (1967). "An Aggregative Model of Resource Allocation in a Metropolitan Area." In: *The American Economic Review* 57.2, pp. 197–210. ISSN: 00028282.

— (1972). *Studies in the structure of the urban economy*. Baltimore: Published for Resources for the Future by Johns Hopkins Press. ISBN: 0-8018-1367-0 978-0-8018-1367-2.

Muth, Richard F. (1969). *Cities and housing; the spatial pattern of urban residential land use*. Chicago: University of Chicago Press.

Oort, C. J. (1969). "The Evaluation of Travelling Time." In: *Journal of Transport Economics and Policy* 3.3, pp. 279–286. ISSN: 00225258. DOI: 10.2307/20052155.

Robert-Bobée, Isabelle (2006). *Projections de Population pour la France Métropolitaine a l'horizon 2050*. Tech. rep. 1089. INSEE.

Rouchaud, D. and A. Sauvant (2004). "Prix des logements et coûts de transports: un modèle global d'équilibre en Ile-de-France." In: *Notes de synthèses du SES, DAEI, Ministère de l'équipement*.

Rozenberg, Julie, Stéphane Hallegatte, Adrien Vogt-Schilb, Olivier Sassi, Céline Guivarch, Henri Waisman, and Jean-Charles Hourcade (2010). "Climate policies as a hedge against the uncertainty on future oil supply." In: *Climatic Change* 101.3, pp. 663–668. ISSN: 0165-0009. DOI: 10.1007/s10584-010-9868-8.

Salon, Deborah (2009). "Neighborhoods, cars, and commuting in New York City: A discrete choice approach." In: *Transportation Research Part A: Policy and Practice* 43.2, pp. 180–196.

Saujot, Mathieu (2013). "Analyse économique et simulation prospective dans la planification de la ville sobre en carbone. Application à Grenoble du modèle TRANUS+." PhD thesis. École Nationale Supérieure des Mines de Paris.

Saujot, Mathieu, Matthieu de Lapparent, Elise Arnaud, and Emmanuel Prados (2016). "Making land use – Transport models operational tools for planning: From a top-down to an end-user approach." In: *Transport Policy* 49, pp. 20–29. ISSN: 0967070X. DOI: 10.1016/j.tranpol.2016.03.005.

Small, Kenneth A., Clifford Winston, and Jia Yan (2005). "Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability." In: *Econometrica* 73.4, pp. 1367–1382. ISSN: 0012-9682, 1468-0262. DOI: 10.1111/j.1468-0262.2005.00619.x.

Thorsnes, Paul (1997). "Consistent Estimates of the Elasticity of Substitution between Land and Non-Land Inputs in the Production of Housing." In: *Journal of Urban Economics* 42.1, pp. 98–108. ISSN: 0094-1190. DOI: 10.1006/juec.1996.2015.

Viguié, Vincent (2012). "Urban Dynamics Modelling, application to economics assessment of climate change." PhD thesis. Université Paris-Est.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

Von Thünen, J. H. (1826). *Isolated State*. Pergamon, Oxford.

Waddell, P. (2002). "UrbanSim: Modeling urban development for land use, transportation, and environmental planning." In: *Journal of the American Planning Association* 68.3, pp. 297–314.

Waisman, Henri, Céline Guivarch, Fabio Grazi, and Jean-Charles Hourcade (2012). "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." In: *Climatic Change* 114.1, pp. 101–120. ISSN: 0165-0009. DOI: 10.1007/s10584-011-0387-z.

Washbrook, Kevin, Wolfgang Haider, and Mark Jaccard (2006). "Estimating commuter mode choice: A discrete choice analysis of the impact of road pricing and parking charges." In: *Transportation* 33.6, pp. 621–639.

Wegener, Michael (2004). "Overview of land-use transport models." In: *Handbook of transport geography and spatial systems* 5, pp. 127–146.

— (2014). "Land-Use Transport Interaction Models." In: *Handbook of Regional Science*. Ed. by Manfred M. Fischer and Peter Nijkamp. Springer Berlin Heidelberg, pp. 741–758. ISBN: 978-3-642-23429-3 978-3-642-23430-9.

Wegener, Michael and Franz Fürst (2004). *Land-use transport interaction: state of the art*.

2

CARBON PRICE EFFICIENCY: LOCK-IN AND PATH DEPENDENCE IN URBAN FORMS AND TRANSPORT INFRASTRUCTURE[1]

"All of the blood that was shed for these cities to grow,
all of the bodies that fell
The roots that were dug from the earth
so these games could be played –
I see it tonight
in the stains on my hands."

Tempest, Kate. 2017. *Let Them Eat Chaos*. First U.S. edition. New York: Bloomsbury.

2.1 INTRODUCTION

Urban car transport is a significant source of carbon dioxide (CO_2) emissions and contributes to climate change, with global impacts on social welfare over centuries. In theory, it would be possible to use Pigouvian taxation (Pigou, 1920) to internalize this negative externality. In this case, a tax is introduced on energy consumption or carbon emissions at a level that corresponds to their social cost.[2] The implementation of such a unique price of carbon equal to the social cost of carbon would change behaviors in a way that maximizes social welfare. There is a vast literature investigating optimal taxation (Cremer, Gahvari, and Ladoux, 1998; Sandmo, 1975) and the social cost of carbon (Interagency Working Group on Social Cost of Carbon, 2010; Nordhaus, 2008; Perrissin Fabert, Dumas, and Hourcade, 2012; Tol, 2005).

However, Pigouvian taxation is difficult to implement in practice, and is unlikely to be optimal on its own (Hallegatte, Fay, and Vogt-Schilb, 2013). The reasons for this include knowledge spill-overs (Acemoglu et al., 2012), imperfect foresight and the lack of credibility of a long-term carbon price (especially for long-lasting infrastructure, see Vogt-Schilb and Hallegatte (2014)), the political obstacle due to the policy impact on existing polluting capital and stranded assets (Rozenberg, Vogt-Schilb, and Hallegatte, 2014), and the difficulty in estimating the right level of a Pigouvian tax (e.g., the debate of the social cost of carbon, see Pindyck (2013)).

For these reasons, the debate on climate change policies has been mostly framed in a cost-effectiveness approach, in which a target is set in terms of carbon budget or emissions at one point in time (e.g., the -20% in emissions

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[2] Carbon emission is hardly the only externality generated by car transport. While road congestion can be experienced closely in many urban regions on a daily basis, other externalities from road transport are as important: local air pollution, noise and accidents have significant economic and social costs, and calls have been made for policy intervention (Bento et al., 2014; IMF, 2013). These other externalities should also be taken into account when designing urban and transport policies.

by 2020 compared to 1990 levels in the EU climate policy), with policies then designed to reach the target at the lowest possible cost. In this paper, we start from a similar cost-effectiveness approach in which an emission reduction target is introduced with a time horizon that lies between 2020 and 2050.

We investigate the *effectiveness* of a higher gasoline tax or a carbon price, i.e. their ability to reduce emissions and meet the pre-determined emission-reduction target, and its *efficiency*, i.e. the cost of reaching the target, in contexts that differ in terms of public transport availability and land-use patterns. We focus on the elasticity of urban transportation emissions with respect to the carbon price, which can vary widely depending on availability of public transport infrastructure. Public transport offers a substitution option away from individual car and is therefore a major determinant of emission elasticity and carbon-pricing effectiveness. Higher elasticity reduces the negative impact of the tax and increases the acceptability of the carbon or gasoline tax, an important consideration in view of the opposition met in recent attempts to introduce such fiscal instruments (Jenkins, 2014; Rozenberg, Vogt-Schilb, and Hallegatte, 2014).

This analysis is highly policy-relevant, as many cities in developing countries are in the process of designing and building their infrastructure network – thus shaping their urban form for the next century and beyond (Lecocq and Shalizi, 2014). It is therefore critical to understand how these short-term decisions will affect how these cities could implement a carbon price in the future and how effective this price would be in cutting emissions. To investigate this issue, we compare two cities: Paris as it exists in 2010, and a counterfactual Paris in which no public transport infrastructure would have been built. We use a transport – land use model (NEDUM-2D) calibrated for these two scenarios to compare the resulting CO_2 emissions and their response to carbon pricing or other gasoline taxes.

While looking at the complete absence of public transport might seem extreme, it reflects infrastructure investment decisions currently at play in developing country cities. In Manila, for example, an urban area of 12 million inhabitants, there is virtually no public transport – only one rail line, no real bus system and an overwhelming share of investments directed toward roads instead of public transport. So, the choice decision makers in developing country cities have to make today is between auto-dependence and transit oriented development or, in provocative terms, in resembling either Atlanta or Singapore. A more subtle analysis looking at the benefits and costs of incremental public transport investments is interesting and an avenue for future research but is not the question we are trying to address in this paper.

We find that both the effectiveness and efficiency of carbon or gasoline taxes are much higher when a dense public transport network is available. In the short to medium term the price elasticity of commuting-related CO_2 emissions is about twice as high when public transport exists. In the longer term however, price elasticities tend to converge although they remain higher by about 20% on average when public transport is available. These results provide a quantified estimate of how much more effective price signals are in changing behaviors when complemented by other instruments such as public transport investments.[3] This exercise provides estimates of the extent to which fast growing cities in the developing world will be able to curb

[3] However, optimal taxation is decreasing with the price elasticity of demand (Ramsey, 1927). If a carbon tax is implemented to raise government revenue, not to change behaviors, there is no incentive to implement complementary policies that increase price elasticity.

their future transport emissions, depending on their near-term infrastructure investment decisions.

The remainder of this paper is structured as follows: In Section 2.2 we decompose commuting related CO_2 emissions and express the elasticity of emissions to fuel prices consequentially. In Section 2.3 we present the main features of the urban model NEDUM-2D that is used to assess emissions on the Paris urban area. Then we outline the method for building the two scenarios: one with public transport as it currently exists, and the other without. Section 2.4 presents the estimated effects of introducing various carbon or gasoline taxes in the two scenarios. Section 2.5 compares our results with econometric estimates of car travel or fuel consumption price elasticity, and explores whether our model results can help to explain these results. Section 2.6 summarizes the findings and concludes.

2.2 FUEL PRICE ELASTICITY OF CO_2 EMISSIONS FROM COMMUTING – THE ANALYTICAL BASIS

A useful way of understanding and representing CO_2 emissions is to resort to a Kaya type equation (Kaya and Yokobori, 1997; Schipper, Marie-Lilliu, and Gorham, 2000), which identifies the key drivers of emission dynamics.

Assuming that public transportation is carbon-free[4], we decompose the aggregate emissions from commuting in Paris in a given year E_c, as:

$$E_c(p) = Pop \cdot \left(\frac{KM(p)}{Pop} \right) \cdot CAR(p) \cdot E_{CAR}(p) \tag{2.1}$$

where Pop denotes the population size, KM is the distance between people's residential and work places, CAR is the fraction of commuting that is done with individual vehicles, and E_{CAR} is the average emissions per kilometer of private vehicles. With the exception of Pop[5], all variables depend on the on the price of gasoline p.

The fact that CAR depends on p reflects the possibility of modal shift, i.e. people shifting from individual vehicles to public transportation (or walking or cycling) and vice versa as the relative prices of each transport mode evolve. The fact that KM depends on fuel prices reflects the possibility that people may decide to live closer to their workplace, and that urban forms change with the price of energy (Gusdorf and Hallegatte, 2007). For instance, urban density can increase to allow more people to live close to their jobs, resulting in higher buildings, smaller dwellings, and higher land fraction used for buildings (e.g. instead of parks). The fact that E_{CAR} depends on the price of fuel reflects the changes in technologies and cars, from the purchase of smaller, more efficient cars (or even two-wheelers) to more radical changes in car technologies (hybrid cars, electric vehicles).[6] In line with above, the fuel price elasticity ξ can be written as:

$$\xi = \frac{\Delta E_c}{\Delta p} \cdot \frac{p}{E_C} = \frac{\Delta CAR}{\Delta p} \cdot \frac{p}{CAR} + \frac{\Delta KM}{\Delta p} \cdot \frac{p}{KM} + \frac{\Delta E_{CAR}}{\Delta p} \cdot \frac{p}{E_{CAR}} \tag{2.2}$$

[4] This assumption is reasonable for metro and trams in Paris, which use low-carbon electricity due to the high ratio of nuclear energy in the French electricity mix. In other countries and when considering buses or electricity produced with fossil fuels, public transport can be a large emitter, especially where they are inefficient and transport few passengers (Kopp, Block, and Iimi, 2013). This simplification does not affect the main qualitative conclusions of the paper, however.

[5] We assume that p, the price of gasoline does not affect migration between cities and rural-urban localization choices in a significant way.

[6] In this analysis, we treat income levels as exogenous.

In practice this price elasticity can be influenced through a number of channels, affecting various elements of the above expression:

- *Investments* (both public and private) can affect CAR, i.e. the share of people using private cars for commuting. As public transport infrastructure gets denser, its convenience for users and its efficiency (in terms of decreased transport times) increases (Bertaud, 2002). Investments in public transport infrastructure therefore allow commuters to shift to public transport modes when confronted with a fuel price increase triggered by a carbon or gasoline tax. On the other hand, if the public transport system is inefficient or inexistent, the modal shift will inherently be limited.

- *Public policies and regulation* can improve cars' fuel (or carbon) efficiency, i.e. the term E_{CAR}. This can be affected through the provision of public incentives to purchase lower emitting cars (e.g. the feebate program introduced in France to tax energy-consuming cars and subsidize efficient ones). Stronger regulatory tools such as standards on the fuel efficiency of cars or on the CO_2 emissions/km can also have significant impacts on the fuel consumption of the fleet of automobiles as has been noted both in the US and in Europe (Anderson et al., 2011). Fuel efficiency can also increase as a result of R&D investments in the car industry. Some of these investments will be directly triggered by the increase in fuel prices as the automobile industry seeks to maximize profits and thus adapts to new conditions. Other investments will only be initiated if the state provides a certain amount of subsidies. These subsidies can materialize in the form of R&D subsidies, rebates on corporate taxes, or even as public-private partnerships to promote the use of low-carbon vehicles. Regardless of their form, as subsidy levels vary, the technological progress towards fuel efficient vehicles is also likely to vary, and thus to directly impact on the elasticity of emissions to fuel price variations.

- *Behaviors and cultural norms* can also influence the ability to lower emissions from commuting. The choice of commuting by car rather than by bus is not only a rational decision based on relative costs, but can also be strongly influenced by deeply embedded beliefs. In a large survey in Scotland, Ellaway et al. (2003) for instance find that car transport provides individuals (in particular males) with psychological benefits such as self-esteem, and feelings of autonomy and prestige, which could not be derived from public transport. Even though such beliefs vary strongly across place and time, their prevalence is likely to hinder modal shift and thus the ability to decrease emissions from transport. The average emissions per kilometer of private vehicles can equally depend on behaviors such as driving style: reduced speed decreases fuel consumption.

In addition to these factors, it is also necessary to distinguish between long and short term elasticities, as impacts manifest themselves at different timescales (Vogt-Schilb, Meunier, and Hallegatte, 2012, 2013):

- *The emissions per kilometer traveled in an individual vehicle* can change over relatively short timescales, when individuals replace their old car with smaller or more fuel efficient vehicles. This timescale depends on the replacement pace of vehicles – we assume this to be ten years as

in Turton and Moura (2008). Over a longer timescale, and assuming that the price of gasoline changes in regions or countries that are large enough to influence marketing choices and R&D policies of automakers, then the supply of vehicles will also change, allowing for a more radical reduction in E_{CAR} by supplying technologically more advanced vehicles.

- *The change in kilometers traveled* to commute also involves several timescales. Over short timescales, a small share of individuals will move closer to their workplace, leading to an increase in rents around business districts, and thus a reduction in average dwelling size. This can occur reasonably quickly as apartments can be split without extensive structural work on buildings, and as housing practices can evolve: students may stay with their parents, or apartments may be shared by several individuals. Significant changes in density, however, can only be achieved over the long term, when buildings are extended or replaced. In historical neighborhoods, it may take centuries; in locations with more recent building stock, it may take a few years or decades.[7]

- *Modal shift* can be instantaneous, as people can decide overnight to take public transportation. However, as explained above, the ability to shift depends on the availability of suitable public transport alternatives, for which public investment plays a critical role in the long term. In this study we do not account for potential congestion effects in public transit that this modal shift could trigger. It is assumed that small investments can be made in order to increase carrying capacities of the existing infrastructure or that service regularity can be increased over a short period of time.

Particularly over long timescales these different mechanisms can take effect, resulting in a larger price elasticity of emissions from commuting. In this paper, we propose to illustrate and quantify this effect for the specific case of Paris, distinguishing between the short and the longer term.

2.3 METHODOLOGY

NEDUM-2D, comprehensively described in Chapter 1 is used for this study. It is equally shown in Chapter 1 that NEDUM-2D is able to convincingly reproduce the main features of the urban area of Paris. To avoid burdening the reader, the full description of NEDUM-2D and the presentation of its validation have been removed from this section. The next sections will simply document the modelling additions made for this study and how NEDUM-2D was used in practice.

2.3.1 *Description of the transport module*

The transportation module of the NEDUM-2D model represents modal choice. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination thereof as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is

[7] See for instance how single-family houses are rapidly replaced by multi-story multi-family buildings in downtown Lima, Peru.

assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged. In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse, 1987). We follow a common approach in transportation economics by using a multinomial logit model which assigns usage probabilities to each transport mode (see Salon, 2009; Washbrook, Haider, and Jaccard, 2006). This method ensures that even when one mode is much cheaper than the others, it will not be used by all residents in a location for all trips. The mode share of public transport in the model in 2006 for the Paris urban area (measured as the share of people using public transport) is around 35.5%, so relatively close to the 40% observed in 2001 (DRIEA, 2005).

For the purposes of our study, the model was enhanced by introducing a mechanism which links average emissions of new cars to the evolution of the price of fuel. The fuel consumption[8] of new internal combustion engine vehicles decreases with the price of fuel as follows:

$$\log(E_{CAR_t}) = \log(E_{CAR_{t-1}}) + \gamma \log\left(\frac{P_t}{P_{t-1}}\right) \tag{2.3}$$

where γ represents the fuel price elasticity of consumption of new vehicles. Building on work conducted by Li, Timmins, and Haefen (2009) which examines the effects of gasoline prices on vehicle fleet composition in 20 US cities, we have selected a value of -0.2 for this elasticity. New vehicles are only acquired gradually, depending on both renewal of the existing fleet and new demand. Vehicles are assumed to have a ten year life cycle (Turton and Moura, 2008), such that only a tenth of the fleet is renewed each year. New demand is created due to demographic dynamics, as newcomers may choose to commute by car. Overall, the average fuel consumption of vehicles will decrease as fuel prices increase, but with a certain degree of inertia. This way of representing evolution of fuel efficiency allows capturing rebound effects as commuting decisions are ultimately based on travel prices per km and not on the price of gasoline. An increase in the fuel efficiency of cars has two opposite effects on CO_2 emissions: First it lowers the emissions per km whilst at the same time, by reducing the cost of traveling by car, it tends to increase the amount of traveling leading to an increase in CO_2 emissions. The net impact is a decrease in carbon dioxide emissions that is lower than could be expected from fuel efficiency with unchanged behaviors.

2.3.2 *Application to commuting in the Paris metropolitan region*

In order to investigate the impact of carbon or gasoline taxes on CO_2 emissions and mobility, our study relies on projections of the various inputs to the NEDUM-2D model until 2050; in particular the future evolution of transport prices, income, and population. We selected these from one of the scenarios produced by the global energy modeling framework IMACLIM-R (Rozenberg et al., 2010; Waisman et al., 2012), which was used and detailed in a previous study (Viguié, Hallegatte, and Rozenberg, 2014). In this scenario, the prices of fuel and public transport increase at similar paces reaching respectively 155% and 142% of their 2006 levels in 2050. Average incomes

[8] As we only consider Internal Combustion Engines (ICE) and not alternative propulsion systems in this paper, we assume that CO_2 emissions per kilometer are proportional to the fuel consumption per kilometer.

increase at an annual rate of 1.8%, while population in the urban area in 2050 is 18% larger than in 2006.

The primary aim of this paper is to compare an unconstrained baseline to projections that involve a carbon or gasoline tax, keeping all other inputs unchanged. As a first step, the scenario we chose will enable us to do so for a given evolution pattern of main urban and transport determinants. In a second step, we will investigate the importance of the choice of the baseline scenario by exploring a trajectory in which all inputs (income and population) remain constant up to 2050. This extreme case will enable us to discuss how the fuel price elasticities of CO_2 emissions are affected when a city is not growing and the inertia is stronger (see section 2.4.5).

The exercise presented here consists of simulations of the urban expansion of the Paris agglomeration using NEDUM-2D from 2006 to 2050. A carbon or gasoline tax is then introduced in 2012, and it is assumed that its value increases over time at the same rate as households' mean income.[9] Various starting values (in 2012) of the carbon or gasoline tax are tested, ranging from 50 to 1000€/tCO_2. For simplicity the carbon tax values that are mentioned in the rest of this paper are the starting values in 2012, not the actual values at different points in time. Two series of simulations are conducted: the first considers private vehicles as the only means of transport whilst the second includes the currently existing public transport infrastructure.

The aim of this paper is then to compare the results achieved in terms of CO_2 emissions with or without the city's public transport infrastructure. The counterfactual scenario where public transport does not exist is achieved by limiting the choice of commuters in the transport module to only two modes: cars and walking instead of three possible when the public transport network is available.

Ideally, in an economy managed by a social planner that seeks to maximize social well-being with perfect foresight, the existence of a carbon constraint (or a carbon price) would trigger appropriate regulatory reforms and investments to adapt infrastructure. However, decision-makers can fail to anticipate evolutions of socio-economic conditions such as the future prices of energy carriers, and infrastructure decisions are usually driven by many non-economic constraints. Market and government failures such as the lack of access to credit to finance infrastructure development can impair the development of infrastructure (World Bank, 2012). Moreover, infrastructure is characterized by significant path dependencies, which implies that it cannot adapt rapidly to new constraints and new policies, including climate policies (Guivarch and Hallegatte, 2011; Vogt-Schilb, Meunier, and Hallegatte, 2012). This in turn provides a rationale for studying the long lasting impacts of infrastructure provision through the use of scenarios in which infrastructure provision is exogenous.

2.3.3 *Urban forms in the two scenarios*

The two cities that are simulated by NEDUM-2D have different urban forms depending on whether public transport is available (Figure 2.1). Without public transport, the agglomeration is more disk-shaped. Conversely, public transport introduction results in slightly more sprawl[10] as additional urban-

[9] The question of recycling carbon revenues, for example by re-investing them in low-carbon forms of transport, although interesting, is beyond the scope of this paper.

[10] This is because the addition of a transport mode in the model provides an interesting alternative to cars and walking in some locations, and therefore lowers the overall cost of transport. This

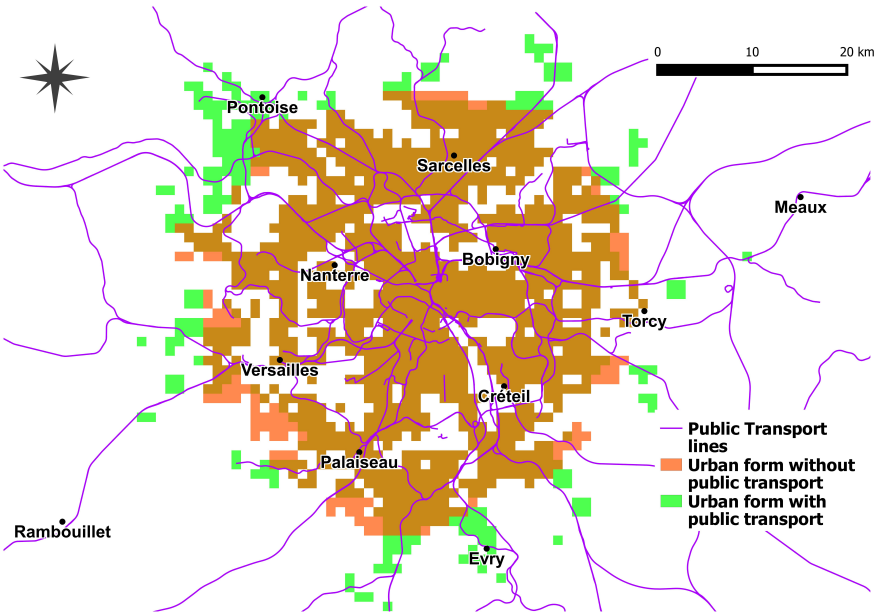

Figure 2.1: The simulated spatial extension of Paris with public transport (green) and without (orange). Where the figure is brown the two maps overlap.

ization takes place along the public transport lines. Without public transport, average population density is higher by around 7%, but also spatially more evenly distributed.

It is important to recognize that while the road network is identical in both scenarios, its capacity is higher in the scenario without public transport as travel times, and therefore congestion levels, remain identical despite higher road frequentation. There is a public investment substitution occurring between both scenarios: directed toward public transport lines in the transit scenario or toward roads in the alternative.

The cities that emerge from our modeling exercise present different spatial patterns from the start. As a consequence of the inertia that characterizes the evolution of urban systems, the late introduction of a public transport network in the counterfactual scenario would not enable a fast convergence towards the urban form that would emerge if a public transit network existed from the beginning. Not only would it be very costly since roads, buildings and infrastructure would have to be destroyed, but it would also take decades to build, with results materializing at a very slow pace. Indeed, the urban form can only change very slowly, at the rate of infrastructure renewal.

Figure 2.2 shows the spatial differences in population densities in the two scenarios, with and without public transport infrastructure. Without public transport, households have an incentive to locate closer to the city center in order to shorten their commutes. This can be seen from the red and orange shades that appear within the first 15km of the city center. Conversely when public transport exists, households tend to locate less homogenously and to settle along the public transport lines to benefit from quick and cheap access to central Paris. As seen in Figure 2.2, public transport loosens the

finding is consistent with related results in the literature (Baum-Snow, 2007; Brueckner, 2005; Viguié and Hallegatte, 2012). Although none of these papers have specifically studied the introduction of public transport they all indicate that lower transport costs will lead to urban spatial expansion.

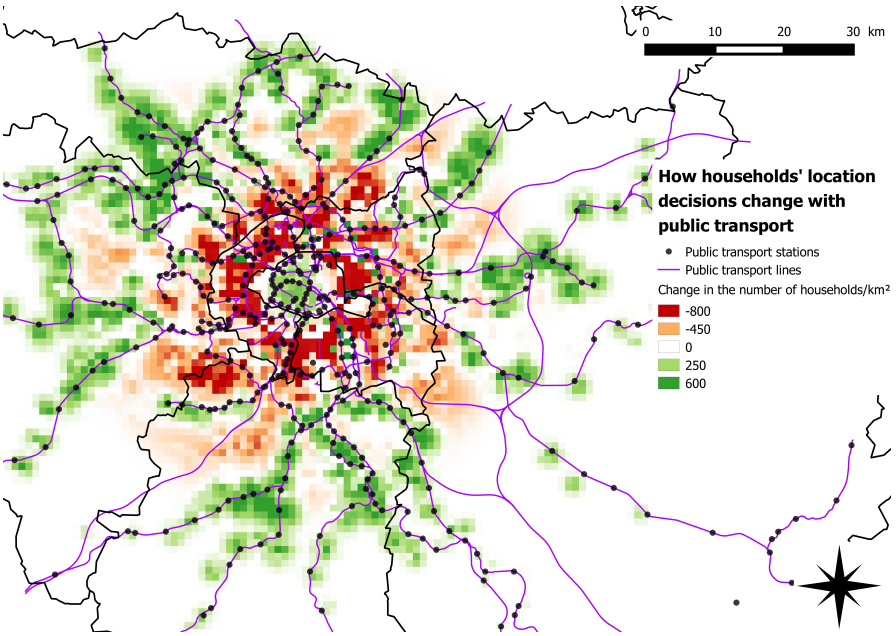

Figure 2.2: Comparison of households' location decisions when public transport exists relative to a counterfactual scenario without public transport

commuting constraint and enables households to move further away from the city center, but only along the public transport lines. The green shade shows that when public transport exists, there is population redeployment towards the outskirts of the urban area, which closely follows the public transport infrastructure.

In the absence of public transport, CO_2 emissions in Paris are much higher than in the presence of public transport infrastructure. In fact, they are up to 78% higher in the absence of a carbon tax. This large difference is also based on the assumption that public transport infrastructure is powered by low-carbon electricity, i.e. mainly nuclear power generation[11]. Considering figures for the year 2006 it appears that the model underestimates CO_2 emissions from transport. Actual emissions reached 7.8MtCO_2 (IAU îdF and Région Île de France, 2011) in 2005, whilst NEDUM-2D estimates them to be around 5.6MtCO_2. However, it is difficult to compare these figures as the model does not capture transport related emissions for other purposes than commuting. Nevertheless, the overall order of magnitude appears correct. We equally do not capture emissions from the residential sector and the fact that in a more sprawled out urban area with average larger dwellings emissions from heating and AC could potentially be higher. The underlying assumption is that residential emissions could be tackled with different instruments, such as technological improvements for better isolation, but that urban forms are key for urban transport demand management. This view is consistent with the latest IPCC Assessment report (Edenhofer et al., 2015).

[11] In 2012, 75.6% of French electricity was produced through nuclear power (IEA, Energy Statistics Database).

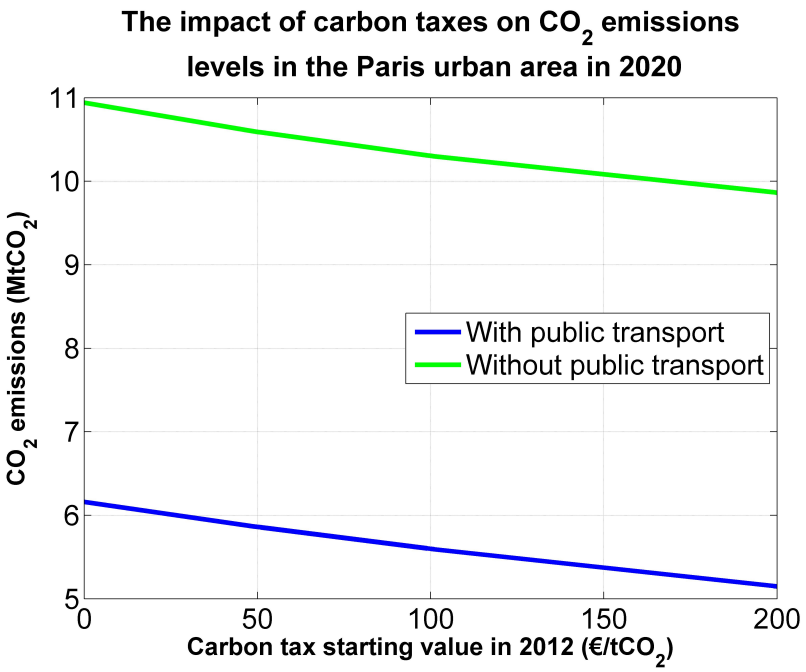

Figure 2.3: Commuting-related emission levels for an increasing carbon tax, with and without public transport in 2020

2.4 INTRODUCING A CARBON TAX

2.4.1 *The short and medium term impact of a carbon tax*

We examine the impacts in both scenarios over time based on the hypothetical introduction of carbon or gasoline taxes in 2012. Figure 2.3 provides a graphic illustration of simulated commuting-related CO_2 emissions for carbon or gasoline tax values ranging from 0 (i.e. no tax) to 200€/tCO_2 in 2020. These results confirm that increasing carbon or gasoline taxes are indeed able to reduce CO_2 emissions, which is consistent with other theoretical and empirical results (see for example Sterner (2007)).

Figure 2.4 presents the evolution of emissions in relative terms, as a function of tax values in 2020 (emission levels for each tax value divided by the emission level without tax), to demonstrate the effectiveness of CO_2 taxes in delivering emission reductions (with and without public transport in place).

It appears that carbon or gasoline taxes are more effective in curbing emissions that stem from transport when an alternative to fossil fuel intensive cars (such as public transport) exists: a 200€/tCO_2carbon tax results in 16% lower emissions (relative to a situation with no tax) with public transport, compared to a little less than 10% without (Figure 2.4). The ratio between the two is 1.6, i.e a 200€/tCO_2 carbon tax is greater than 60% more effective in the medium run when modal shift is possible. In the short run (i.e. until 2014), a 200€/tCO_2 carbon tax is 2.3 times more efficient in the presence of public transport than without (14% CO_2 emissions reduction with public transport compared to 6% without).

Another way of looking at Figure 2.4 is to consider the carbon or gasoline taxes required to achieve a given abatement objective. In the absence of public transportation, achieving a 6% decrease in CO_2 emissions would

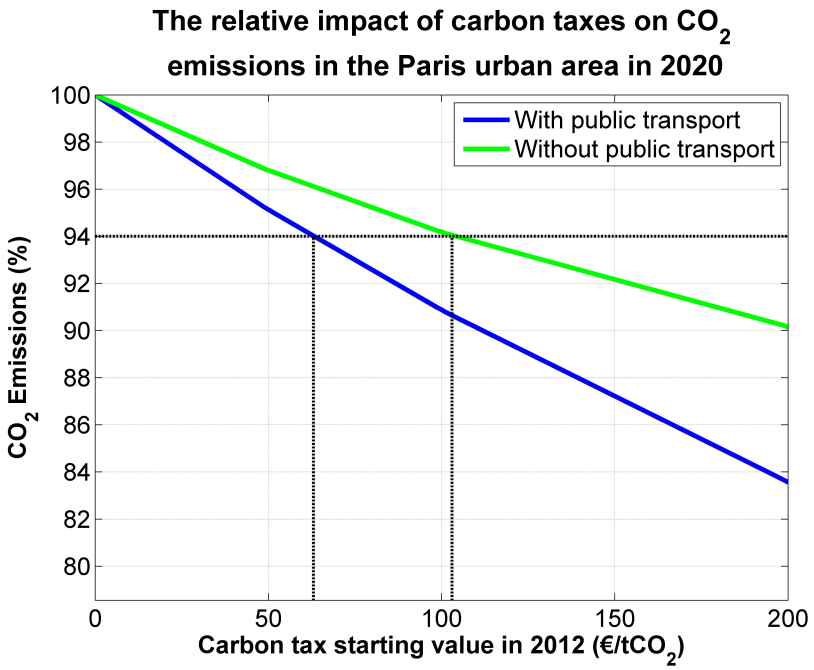

Figure 2.4: The relative impact of carbon taxes on commuting-related emission levels in 2020 for scenarios with and without public transport. When the horizontal dashed line crosses the blue and green curves we can read on the x-axis the carbon tax starting values that must be implemented in 2012 to achieve a 6% reduction in CO_2 emissions (63€/tCO_2 and 103 €/tCO_2 respectively with and without public transport).

require almost double the carbon tax compared to the scenario in which public transport exists (103 €/tCO_2 instead of 63€/tCO_2). Thus, a carbon or gasoline tax is more efficient in the presence of public transport.

Overall, it must be noted that even with public transport, carbon taxes need to be high in order to achieve a relatively small abatement target. For instance, in the scenario with public transport, achieving a 6% reduction in CO2 emissions requires a carbon tax of 63€/tCO_2 over eight years. By comparison, the carbon tax which was debated in France in 2008 was only 17€/tCO_2. Yet this bill failed in part because the financial burden on commuters living far from public transport was considered to be too high.

Part of this inefficiency of the carbon tax in reorienting behaviors towards more sustainable location and commuting decisions can be explained by the importance of the time cost component compared to the monetary component of commuting costs. Indeed Viguié, Hallegatte, and Rozenberg (2014) show that the cost of time in 2010 represents up to 90% of the generalized costs of transport in the Paris urban area (and 95% in 2050). Therefore even a strong increase in fuel prices will only marginally affect generalized costs and travel behavior.[12]

[12] In the presence of Pigouvian taxation, in which a carbon tax is introduced at a level equal to the "social cost of carbon", this low elasticity would translate into small emission reductions in the individual transport sector. In a cost-effectiveness framework, in which we start from a target in terms of emission reduction, the required emission reductions depend on how ambitious the target is. Importantly, considering the timescale of emission reduction in this sector, the need to reduce emissions in the transport sector will be affected by the long-term targets (2050 and below), not only short-term objectives. See an illustration for Brazil in (Vogt-Schilb, Hallegatte, and De Gouvello, 2014).

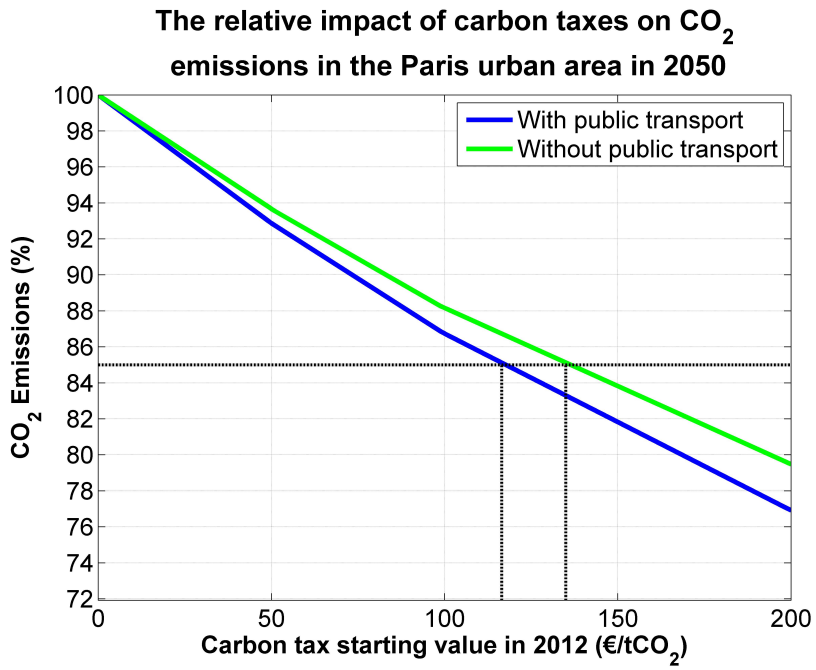

Figure 2.5: The impact of carbon taxes on commuting-related emission levels in 2050 for scenarios with and without public transport. When the horizontal dashed line crosses the blue and green curves we can read on the x-axis the carbon tax starting values that must be implemented in 2012 to achieve a 15% reduction in CO_2 emissions (116€/tCO_2 and 135 €/tCO_2 respectively with and without public transport.

2.4.2 *The long-run impact of carbon or gasoline taxes*

Figure 2.5 compares emission reductions in 2050 with and without public transport for various carbon tax values. The black dashed lines show that to achieve a 15% reduction in CO_2 emissions, the tax should be approximately 116€/tCO_2 with public transport, and 135€/tCO_2 without. The efficiency of carbon taxes remains higher for all tax levels if public transport exists[13]. However, in the long run (2050), the impacts of carbon or gasoline taxes on CO_2 emissions are much closer between a situation with and without public transport than in the short and medium run.

There is a straightforward explanation: without public transport, households can only mitigate the adverse effects of a carbon or gasoline tax by moving. Due to the inertia that characterizes construction and relocation decisions, such a strategy cannot have large impacts in the short term. Indeed, with fixed housing supply, the carbon price incentives to live close to employment centers mostly translate into higher rents that will cancel most of the incentives. Only when these higher rents translate into higher-density construction and larger housing supply near to employment centers can population relocation play a significant role in emission reduction.

2.4.3 *The roles of modal split, fuel efficiency and urban reconfiguration*

This section presents evidence for the different channels through which CO_2 emissions are reduced by carbon pricing. We find that in the presence of

[13] It should equally be noted that the absolute level of emissions remains much higher in a situation without public transport.

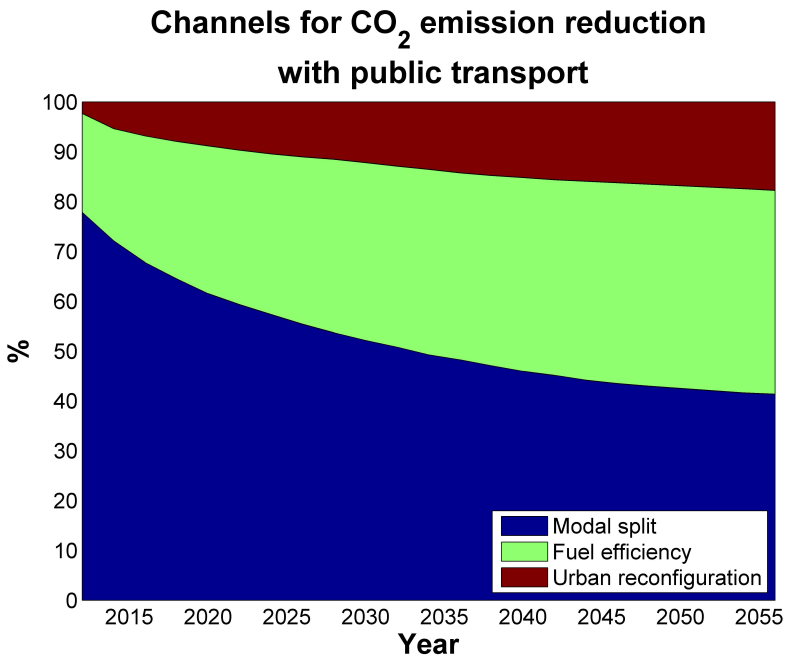

Figure 2.6: Contributions of different channels towards a CO_2 emission decrease with a 200€/tCO_2 tax with public transport.

a public transport system, the share of public transport usage is increasing over time. When no carbon or gasoline tax is introduced the share of public transport is estimated to increase from 36% (2014) to 38% (2050) due to a moderate relative decrease in transit prices. When a relatively high carbon or gasoline tax is introduced (equivalent to 200€/tCO2 in 2012), the modal share of public transport increases to 40% in 2014, and up to 41% in 2050. The rapid increase in transit usage reflects the fact that mode choice can evolve virtually overnight.[14] However, once the mode switch potential is exploited, the share of public transport is virtually constant throughout the whole simulation period. Generally, the share of public transport increases over time and this behavior is stronger for higher levels of the carbon or gasoline tax. However, while the overall modal transfer towards public transport is found to be significant, it is still relatively moderate in size.

Figure 2.6 indicates, for a 200€/tCO_2 tax, to what extent modal split and other channels contribute to the decrease in emissions.

Figure 2.6 suggests that, when public transport is available, modal split explains the largest share of emission reductions in the short term. Over a longer time span, the importance of urban reconfiguration and fuel efficiency grows, constituting together around 60% of the overall effect in 2055. Households will gradually relocate inside the urban area towards zones that allow shorter commuting distances. This inertia also characterizes the rate at which the vehicle fleet can be renewed. Therefore, switching to public transit is the most viable option in the short run if fuel prices increase.

In the scenario without public transport, both the progress in the development of fuel efficient vehicles and in urban reconfiguration are characterized

[14] The reader should be reminded that in this study we do not account for potential congestion effects in public transit. It is assumed that small investments can be made in order to increase carrying capacities of the existing infrastructure or that service regularity can be increased over a short period of time.

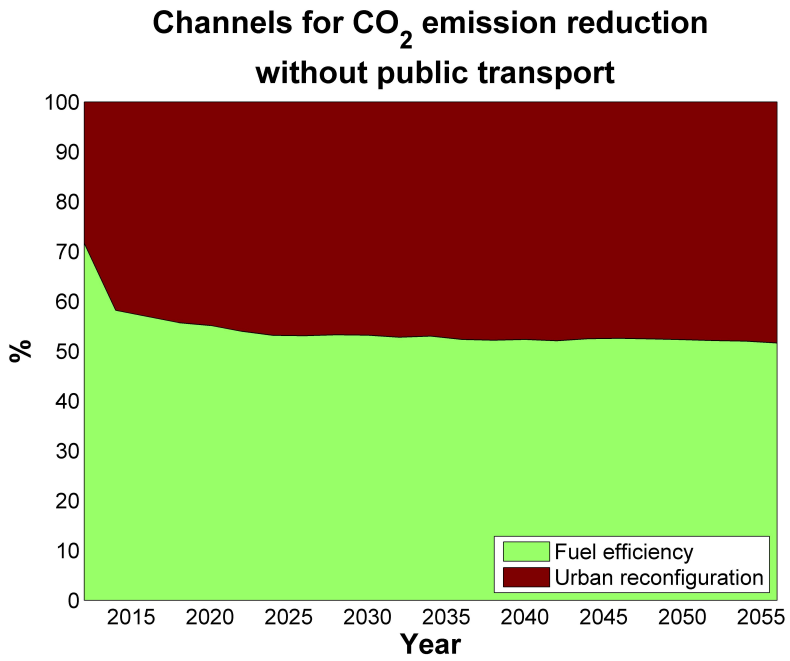

Figure 2.7: Contributions of different channels towards a CO_2 emission decrease with a 200€/tCO_2 tax without public transport.

by high inertia (Figure 2.7). They nearly evolve in parallel throughout the entire time frame, although in the very short term fuel efficiency prevails. Taken together, these figures show that when no immediate alternatives exist (e.g. switching to public transport), a very costly abatement option such as relocation is resorted to. These illustrations thus also highlight the high cost of reducing CO_2 emissions from commuting when no public transport exists.

2.4.4 *Price elasticities*

We find that decarbonizing commuting (in relative terms) is more efficient (i.e. cheaper) when public transport systems are available. The estimated fuel price elasticities of CO_2 emissions are presented in Table 2.1 for five different levels of carbon or gasoline taxes, both in the presence and absence of a public transit system. For each respective level of carbon or gasoline tax, the elasticities expressed in absolute terms are higher with public transport than without. This observation holds for any chosen level of carbon or gasoline tax, and for any considered time horizon. The elasticities with public transport are roughly twice as high as those without public transport in the short to medium term.

Furthermore, these elasticities also increase from the short to the long term (in absolute terms) from $[-0.44 - -0.60]$ to $[-0.52 - -0.62]$ with public transport and from -0.2 to $[-0.42 - -0.48]$ without. In the short run individual responses to fuel price increases are mainly limited to shifting to different means of transport (e.g. cycling, or public transport, if available) and putting more emphasis on fuel efficient driving. However, in the long run people have further options, e.g. by relocating closer to the workplace, or by adjusting the fleet of vehicles to the new price conditions. Since such long run options depend less on public transport, elasticities tend to not only increase, but also converge over time in both scenarios and for all considered

		50€/tCO_2		100€/tCO_2		200€/tCO_2		500€/tCO_2		1000€/tCO_2	
		With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport
Emissions' fuel price elasticity	Short term (2014)	−0.44	−0.20	−0.45	−0.20	−0.47	−0.20	−0.52	−0.20	−0.60	−0.21
	Medium term (2020)	−0.50	−0.32	−0.50	−0.31	−0.51	−0.30	−0.55	−0.27	−0.62	−0.27
	Long term (2050)	−0.52	−0.46	−0.53	−0.47	−0.55	−0.48	−0.57	−0.45	−0.62	−0.42

Table 2.1: Fuel price elasticities of emissions depending on the level of carbon tax and the presence or absence of a public transit system.

levels of carbon tax. Elasticities in the long run are in the $[-0.52 - -0.62]$ range with public transport and $[-0.42 - -0.48]$ without. On average over the five levels of carbon taxes, long run elasticities are higher (in absolute terms) by 20% with public transport.

We also find that the elasticities evolve with the level of tax: In the scenario with public transport, the elasticities strictly increase with every rise in the carbon tax across all three time horizons. However, in the scenario without public transport, short term elasticities are found to remain virtually constant for all considered carbon tax levels, as people have limited options to switch to alternative forms of transport. In the long term, the elasticity increases up to a certain level of carbon tax (200€/tCO_2) and then decreases.

One reason is the presence of non-linear construction costs. Indeed, the lack of public transportation leaves people with relocation as one of the main response options. However, moving closer to jobs will be increasingly costly, as high population density entails high construction costs. Real estate developers optimize building types and heights as a function of the expected revenues and costs. Higher rents justify higher buildings, but the non-linearity in construction costs means that the gain in density is lower when density is already high. These "decreasing returns from density" mean that, above a certain level, increasing density becomes a very expensive way of reducing transportation costs.

2.4.5 *Role of the baseline scenario*

In order to control for the role of population and income growth, we also conducted a set of simulations based on the hypothesis that income and population remain constant between 2006 and 2050. This scenario yields less favorable results in terms of the capacity to abate emissions.

Indeed, a growing city has many new buildings constructed every year. These new buildings can be designed to take into account the incentives created by the carbon price, i.e. at higher density close to employment centers and lower density at the outskirts. A city that is growing over time can therefore accommodate changes in relative prices through new construction, while a stagnating city needs to destroy and rebuild, a process that is slower and much more expensive.

It can be seen from Table 2.2 that the long term elasticities with public transport remain close to those presented before. Without public transport however, the no-growth assumption very much affects the capacity to

Long term elasticities (2050)	50€/tCO$_2$		100€/tCO$_2$		200€/tCO$_2$		500€/tCO$_2$		1000€/tCO$_2$	
	With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport	With Public transport	Without Public Transport
Initial baseline scenario	−0.52	−0.46	−0.53	−0.47	−0.55	−0.48	−0.57	−0.45	−0.62	−0.42
Baseline with constant population and income	−0.55	−0.37	−0.55	−0.37	−0.55	−0.36	−0.57	−0.36	−0.60	−0.36

Table 2.2: Comparison of long term emissions' fuel price elasticities depending on the chosen baseline.

decrease emissions. This should not come as a surprise, as the ability to reduce CO_2 emissions depends heavily on the capacity to relocate within the urban area. As relocation is more difficult when an urban area is not growing and building, the elasticities are much lower. In the short-run (not shown here), the elasticities are similar in the two scenarios whether public transport infrastructure is available or not. The changes in population and income relative to the initial baseline scenario are very marginal by 2014. This explains why, unlike for the long-run, there is little difference in the elasticities in the absence of public transport in the short-run between the two socio-economic scenarios.

Table 2.2 demonstrates the importance of the choice of the baseline. The capacity to mitigate GHG emissions depends on the reference socio-economic scenarios, including demographic, technological, and economic changes.

2.5 COMPARING RESULTS FROM THE MODEL VS. ECONOMETRIC ANALYSIS

To the best of our knowledge the only other modeling exercise aimed at exploring the price elasticity of fuel consumption from urban traveling is a study by Anas and Hiramatsu (2012) for the city of Chicago, which uses the RELU-TRAN2 model (an extension of the RELU-TRAN model described in (Anas and Liu, 2007)). They find a much lower elasticity of −0.081. While the reason for this difference is not obvious, the share of this elasticity which can be attributed to modal shift in the long run is 43%; i.e. quite similar to our own estimates (see Figure 2.6).

To see our results in context, it is useful to consider the substantial body of literature analyzing the price elasticity of fuel consumption and road transport based on econometric techniques. Graham and Glaister (2002) offer a comprehensive survey of this literature, based on hundreds of studies on income and price elasticities of fuel consumption. Their survey indicates that throughout the literature price elasticity estimates are surprisingly consistent, with short-term elasticities (up to one year in their definition) mostly falling within a −0.2 to −0.3 range and long-term elasticities falling between −0.6 and −0.8. These results are in line with other surveys by Goodwin (1992), Dahl (1995), Goodwin, Dargay, and Hanly (2004), and Kopp, Block, and Iimi (2013).

In a later meta-analysis, Graham and Glaister (2004) conclude that the price elasticity for car travel demand is −0.16 in the short-run and -0.26

	Fuel consumption		**Car travel**	
	Goodwin, Dargay, and Hanly (2004)	Graham and Glaister (2004)	Goodwin, Dargay, and Hanly (2004)	Graham and Glaister (2004)
Short term	−0.25	−0.2 to −0.3	−0.10	−0.16
Long term	−0.64	−0.6 to −0.8	−0.29	−0.26

Table 2.3: Short- and long-term elasticity estimates for fuel and car travel demand, based on literature surveys by Graham and Glaister (2004) and Goodwin, Dargay, and Hanly (2004).

in the long-run – i.e. significantly lower than their elasticity estimates for the demand for fuel. In the same order of magnitude, Goodwin, Dargay, and Hanly (2004) find corresponding elasticities of −0.10 in the short-run and −0.29 in the long-run. In this context, Goodwin, Dargay, and Hanly (2004) note that consistently throughout the literature price elasticities for fuel consumption are found to be larger than road traffic elasticities by a factor 1.5 to 2. They suggest that this is due to a more efficient use of fuel in response to a fuel price increase, i.e. individuals would still embark on the same journey by car as before the price increase, but commit to more fuel-conserving driving, and switch to more fuel-efficient vehicles. These results are fully consistent with Figure 2.7, which indicates that, in the absence of modal shift, around 50% of emission reductions can be expected from urban reconfiguration (and modal shift when available) and 50% from more efficient vehicles.

Regarding the difference between short and long-term effects, De Jong and Gunn's (2001) results for Europe are also consistent with our findings, as they find that short-term effects were mainly limited to shifts in the mode of transport, while long-term effects also included shifts in the choice of destination and travel frequency, as well as relocation of population and economic activities.

Overall the qualitative nature of our results and their relationship and proportions across different timescales are consistent with the evidence from the literature. In terms of the numerical magnitude of elasticities in the literature, we note that our results in the presence of public transport suggest higher elasticities than presented in Table 2.3. However, it is important to note that these results cannot be compared directly for various reasons: Considering commuting rather than general transport, implies that 'not traveling' is not an option as people still need to access their workplaces in order to earn their income. In the face of a fuel price increase one would expect that leisure trips, which are not indispensable, would be less frequent. If this were the case we would expect the price elasticities of fuel consumption for all travel purposes obtained through econometric methods to be higher in absolute value than our results. On the other hand, leisure trips tend to rely more on private vehicles or even air travel, because low emitting public transportation is a very imperfect substitute outside dense areas and for distant destinations. The city-based approach of our study means that average travel distances are shorter than in country based studies, thus possibly opening travel options such walking, cycling or public transit. This second effect would tend to make fuel price elasticities for commuting trips higher than for all trips.

Moreover, differences in the income level of countries or cities may complicate the comparison of transport elasticities. It has been found that historical price and income elasticities for both the demand for transport fuels and the demand for road transport have been decreasing (see Graham and Glaister (2004), for a comprehensive literature survey). Fouquet (2012) analyses income and price elasticities for transport demand in the UK, and shows that the price elasticity for transport demand has decreased from -1.5 in 1850 to -0.6 in 2010. He suggests that the reason for this decrease is due to both technological progress and associated reductions in transportation costs, as well as rising income. This observation is confirmed by Graham and Glaister (2004), who also note declining price elasticities throughout the past decades and suggest a negative relationship between price elasticities and real income. This implies that the standard of living can play a role in determining the demand for road transport, and provides a rationale for high price elasticities in developing countries. Hughes, Knittel, and Sperling (2008) focusing on the US also study whether the short-run price elasticities of fuel consumption for automobiles have changed since the 1990 as a result of increasing incomes, introduction of fuel consumption standards, and changing land-use patterns. They provide evidence of decreasing price elasticities of gasoline demand. However, they show that the decreasing responsiveness of consumers to gasoline prices cannot be attributed to income growth. They argue that the shift in price elasticities is likely to reflect changes in land-use such as high suburban development and lower accessibility to transit infrastructure. Our results tend to support their analysis.

In this context, a relatively small body of literature looks at city-level elasticities, and illustrates just how much elasticities can differ across cities, emphasizing that city-specific characteristics (such as the availability and efficiency of a public transportation system) play a significant role. Nowak and Savage (2013) for instance estimate cross-elasticities for fuel prices and public transport use for the city of Chicago. They find that for gasoline prices above US$3 per gallon, the elasticity for rail transport increases to 0.12–0.14 (from 0.05 for prices below US$3). For gasoline prices above US$4, elasticities increase further to 0.28–0.38. Zhang (2004) estimates the travel cost elasticity for car travel to be -0.14 in Boston, but -0.24 in Hong Kong SAR, China. For New York City, Salon (2009) focuses on commuting in particular and analyzes determinants for commute mode using a discrete choice model. She finds a price elasticity for car commute of -0.33 for the whole of New York City, while estimates vary across different locations within New York: the elasticity is -0.23 for Staten Island and -0.79 for Manhattan which has the highest access to public transport in the urban area. In comparison, the two scenarios in our study can be interpreted to represent two different cities – one with a public transportation system and one without. The significant difference between our results for the two scenarios underscores, in line with the literature, that city-specific characteristics play a critical role in determining the elasticity.

Finally, recent work that investigates how joint changes in gasoline prices and accessibility to transit affects vehicle miles travelled using cars in USA urban settings supports our findings (Spiller et al., 2014). The authors find that increases in gasoline prices are a large factor in limiting driving and that these impacts are highest when public transport is an adequate substitute to driving. In fact the authors find even larger elasticities (-0.74) of travelled miles by car, a proxy for gasoline consumption and CO_2 emissions, to gasoline prices when transit substitutability is considered than we report in this paper.

2.6 CONCLUDING REMARKS

This paper investigates the impact of path dependencies on the ability to reduce urban commuting CO_2 emissions with a carbon or gasoline tax. Due to imperfect decision-making and long planning and construction timescales of new infrastructure, investments in public transport are not always optimal, especially after changes in relative prices (e.g., due to carbon pricing). As a consequence, the provision of public transport does not adapt automatically and instantly to new socio-economic conditions. Exogenous scenarios that describe different patterns of public transport provision are therefore important for assessing the effectiveness and efficiency of price instruments.

We use two simplified and highly contrasted urban scenarios using the NEDUM-2D model. The first scenario looks at the Paris urban agglomeration, assuming that public transport service will remain equal to its 2012 level up until 2050. The second scenario investigates a counterfactual situation in which Paris would have developed without public transport infrastructure. These two scenarios are useful benchmarks to inform decision-makers in fast-growing cities, where decisions regarding public transport infrastructure are currently being made and will affect urban forms for decades and beyond. While the complete absence of public transport constitutes an extreme and hypothetical case, it is useful nevertheless for assessing the extent to which public transport impacts on the efficiency of price instruments to curb gasoline consumption and GHG emissions. Investing in roads or public transport is indeed a real question that many decision makers in developing country cities are facing today.

Our results show that public transport choices have a strong influence on the price elasticity of energy consumption and carbon emissions from urban individual transport. They provide an explanation for the varying responsiveness to price signals of different transport modes across time and space, as flagged in Kopp, Block, and Iimi (2013). For instance, the model supports and could help quantify one of the hypotheses made in Hughes, Knittel, and Sperling (2008): They note a decrease in transport price responsiveness in the US between the 1970s and the 2000s, and suspect that the increase in suburban development has made households more dependent on private vehicles and less able to respond to gasoline price changes.

The analysis can also provide scenario-based (e.g., with or without public investment in public transport) elasticity values that can be employed in CGE models, which are used to assess the cost of climate policies. Indeed CGE models usually rely on fixed price elasticities, which are independent of the stock of infrastructure. Our analysis shows that when public transport networks are insufficient or missing, these average elasticities can lead to an overestimation of the capacity to mitigate CO_2 emissions or decrease fuel usage from transport. This paper also demonstrates the importance of the choice of the baseline. The capacity to mitigate GHG emissions will depend on baseline socio-economic scenarios, including demographic, technological, and economic changes. This finding is consistent with the conceptual basis of the Shared Socio-economic Pathways (SSP). These scenarios which are currently developed to analyze climate policies are supposed to be contrasted in terms of capacity to mitigate GHG emissions (Ebi et al., 2013; O'Neill et al., 2013). This suggests that elasticities in energy-economy models are not set in stone: they will vary from one location to another depending on socio-economic evolutions and pre-existing conditions, and they can be affected by policies (especially infrastructure policies). Thus, this analysis

can provide useful inputs to calibrate CGE models more precisely and as a function of the chosen scenario.

A key result of this paper is that without complementary policies a carbon or gasoline tax would need to be considerably higher to achieve a given objective of (relative) emissions reduction. Our results not only suggest that emissions are higher without a public transport system in place, but also that the ability to mitigate them is lower. These results confirm and expand findings from Gusdorf and Hallegatte (2007), who showed that compact cities are less vulnerable to shocks in transport prices. They emphasize that synergies exist between transport and climate policies (Hallegatte et al., 2012): if we aim to increase gasoline prices in the future (e.g. through gasoline or carbon taxes) then the existence of a public transport network can significantly lower the costs. Considering recent failures to introduce carbon taxes (for example in France), it can even be argued that the absence of these complementary policies could prevent the implementation of environmental taxes entirely (Hammar, Löfgren, and Sterner, 2004).

Recent papers have suggested using a carbon tax (or revenues from cap-and-trade permit auctions) to raise government revenues to reduce debt and deficit or reduce other taxes (Carbone, Morgenstern, and Williams III, 2012; Goulder, 1995; Rausch and Reilly, 2012). While revenue raising can be an additional motive for implementing carbon pricing and – under some conditions – generate a double dividend, it is important to note that different rationales for implementing a carbon tax lead to different incentives regarding complementary policies. If the carbon tax is implemented to change behaviors and reduce GHG emissions, it makes economic sense to complement it with policies that increase the price elasticity of carbon emissions, such as technology and innovation support or the type of infrastructure investments discussed in this paper. If the carbon tax is implemented to raise revenues (and to increase taxation of under-taxed rents and reduce taxation of overtaxed factors of production Edenhofer, Mattauch, and Siegmeier (2013)), then there is a disincentive to increase elasticity through such measures.

These results provide interesting input for policy makers in fast-growing cities in developing countries. Even if emission reductions are not a priority for them today, they need to take into account that their capacity to abate emissions in the future critically depends on the decisions they make today: in the absence of public transport investments and/or urbanization regulations, our results suggest they will face a low price elasticity of fuel consumption and GHG emissions. In other words, there exists an option value attached to a dense public transport network. This option value consists of the possibility of reducing emissions at a lower cost in the future.

These results are not only of relevance in the context of emission reduction, but also for mitigating the effects of rising oil prices and the impacts of other externalities such as congestion, accidents and air pollution. They suggest that where urban planning and public transport are concerned, *"pollute now and clean up later"* can be a very inefficient strategy (World Bank, 2012).

REFERENCES

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012). "The Environment and Directed Technical Change." In: *American Economic Review* 102.1, pp. 131–166. ISSN: 0002-8282. DOI: 10.1257/aer.102.1.131.

Anas, Alex and Tomoru Hiramatsu (2012). "The effect of the price of gasoline on the urban economy: From route choice to general equilibrium." In: *Transportation Research Part A: Policy and Practice* 46.6, pp. 855–873. ISSN: 09658564. DOI: 10.1016/j.tra.2012.02.010.

Anas, Alex and Yu Liu (2007). "A Regional Economy, Land Use, and Transportation Model (RELU-TRAN©): Formulation, Algorithm Design, and Testing." In: *Journal of Regional Science* 47.3, pp. 415–455.

Anderson, Soren T., Ian W. H. Parry, James M. Sallee, and Carolyn Fischer (2011). "Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives." In: *Review of Environmental Economics and Policy* 5.1, pp. 89–108. ISSN: 1750-6816, 1750-6824. DOI: 10.1093/reep/req021.

Baum-Snow, Nathaniel (2007). "Suburbanization and transportation in the monocentric model." In: *Journal of Urban Economics* 62.3, pp. 405–423. ISSN: 00941190. DOI: 10.1016/j.jue.2006.11.006.

Bento, Antonio M., Daniel Kaffine, Kevin Roth, and M. Zaragoza (2014). "The Effects of Regulation in the Presence of Multiple Unpriced Externalities: Evidence from the Transportation Sector." In: *American Economic Journal: Economic Policy* 6.3, pp. 1–29. DOI: 10.1257/pol.6.3.1.

Bertaud, Alain (2002). "The spatial organization of cities: Deliberate outcome or unforeseen consequence?" In: *World Development Report 2003, background paper*.

Brueckner, Jan K. (2005). "Transport subsidies, system choice, and urban sprawl." In: *Regional Science and Urban Economics* 35.6, pp. 715–733. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2005.01.001.

Carbone, Jared C., Richard D. Morgenstern, and Roberton C. Williams III (2012). "Carbon taxes and deficit reduction." In: *unpublished paper*.

Cremer, Helmuth, Firouz Gahvari, and Norbert Ladoux (1998). "Externalities and optimal taxation." In: *Journal of Public Economics* 70.3, pp. 343–364.

Dahl, Carol (1995). "Demand for transportation fuels: a survey of demand elasticities and their components." In: *Journal of Energy Literature* 1.2, pp. 3–27.

De Jong, Gerard and Hugh Gunn (2001). "Recent evidence on car cost and time elasticities of travel demand in Europe." In: *Journal of Transport Economics and Policy*, pp. 137–160.

De Palma, André and Jacques-François Thisse (1987). "Les modèles de choix discrets." In: *Annales d'économie et de statistique* n°9.

DRIEA (2005). *Les déplacements des Franciliens en 2001 - 2002. Enquête Globale de Transports*. Tech. rep. Direction Régionale de l'Equipement Ile-de-France.

Ebi, Kristie L. et al. (2013). "A new scenario framework for climate change research: background, process, and future directions." In: *Climatic Change*, pp. 1–10. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0912-3.

Edenhofer, Ottmar, Linus Mattauch, and Jan Siegmeier (2013). "Hypergeorgism: when is rent taxation as a remedy for insufficient capital accumulation socially optimal?" In: *CESifo Working Papers Series* 4144.

Edenhofer, Ottmar et al., eds. (2015). *Climate Change 2014: Mitigation of Climate Change ; Summary for Policymakers Technical Summary ; Part of the Working Group III Contribution to the Fifth Asessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel on Climate Change. ISBN: 978-92-9169-142-5.

Ellaway, Anne, Sally Macintyre, Rosemary Hiscock, and Ade Kearns (2003). "In the driving seat: psychosocial benefits from private motor vehicle transport compared to public transport." In: *Transportation Research Part F: Traffic Psychology and Behaviour* 6.3, pp. 217–231.

Fouquet, Roger (2012). "Trends in income and price elasticities of transport demand (1850–2010)." In: *Special Section: Past and Prospective Energy Transitions - Insights from History* 50.0, pp. 62–71. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2012.03.001.

Goodwin, Phil B. (1992). "A review of new demand elasticities with special reference to short and long run effects of price changes." In: *Journal of transport economics and policy*, pp. 155–169.

Goodwin, Phil B., Joyce Dargay, and Mark Hanly (2004). "Elasticities of road traffic and fuel consumption with respect to price and income: a review." In: *Transport Reviews* 24.3, pp. 275–292.

Goulder, Lawrence H. (1995). "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis." In: *Journal of Environmental Economics and Management* 29.3, pp. 271–297. ISSN: 00950696. DOI: 10.1006/jeem.1995.1047.

Graham, Daniel J. and Stephen Glaister (2002). "The demand for automobile fuel: a survey of elasticities." In: *Journal of Transport Economics and policy*, pp. 1–25.

— (2004). "Road traffic demand elasticity estimates: a review." In: *Transport reviews* 24.3, pp. 261–274.

Guivarch, Céline and Stéphane Hallegatte (2011). "Existing infrastructure and the 2°C target." In: *Climatic Change* 109.3-4, pp. 801–805. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-011-0268-5.

Gusdorf, François and Stéphane Hallegatte (2007). "Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks." In: *Energy Policy* 35.10, pp. 4826–4838. ISSN: 03014215. DOI: 10.1016/j.enpol.2007.04.017.

Hallegatte, Stéphane, Marianne Fay, and Adrien Vogt-Schilb (2013). *Green Industrial Policies*. Tech. rep. The World Bank.

Hallegatte, Stéphane, G. Heal, M. Fay, and D. Treguer (2012). *From Growth to Green Growth-a Framework*. Policy Research Working Paper 5872. Washington DC.: World Bank.

Hammar, Henrik, Åsa Löfgren, and Thomas Sterner (2004). "Political Economy Obstacles to Fuel Taxation." In: *Energy Journal* 25.3, pp. 1–17. ISSN: 01956574.

Hughes, J. E., C. R. Knittel, and D. Sperling (2008). "Evidence of a shift in the short-run price elasticity of gasoline demand." In: *Energy Journal* 29.1, pp. 113–134.

IAU îdF and Région Île de France (2011). *L'environnement en Île de France - Mémento 2011*. Tech. rep. Institut d'Aménagement Urbain de la Région Ile de France.

IMF (2013). *Energy Subsidy Reform: Lessons and Implications*. Tech. rep. Washington, D.C.: International Monetary Fund.

Interagency Working Group on Social Cost of Carbon, US Government (2010). *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, 2*. Tech. rep.

Jenkins, Jesse D. (2014). "Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?" In: *Energy Policy* 69, pp. 467–477. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2014.02.003.

Kaya, Yoichi and Keiichi Yokobori (1997). *Environment, Energy and Economy; Strategies for Sustainability*. United Nations University Press. ISBN: 92-808-0911-3.

Kopp, Andreas, Rachel I. Block, and Atsushi Iimi (2013). *Turning the right corner: ensuring development through a low-carbon transport sector*. Directions in development, environment and sustainable development. Washington, D.C: World Bank. ISBN: 978-0-8213-9835-7.

Lecocq, Franck and Zmarak Shalizi (2014). "The economics of targeted mitigation in infrastructure." In: *Climate Policy* 14.2, pp. 187–208. ISSN: 1469-3062. DOI: 10.1080/14693062.2014.861657.

Li, Shanjun, Christopher Timmins, and Roger H. von Haefen (2009). "How Do Gasoline Prices Affect Fleet Fuel Economy?" In: *American Economic Journal: Economic Policy* 1.2, pp. 113–137. ISSN: 19457731. DOI: 10.2307/25760042.

Nordhaus, William D. (2008). *A question of balance: Weighing the options on global warming policies*. Yale University Press. ISBN: 0-300-16598-6.

Nowak, William P. and Ian Savage (2013). "The cross elasticity between gasoline prices and transit use: Evidence from Chicago." In: *Transport Policy* 29, pp. 38–45.

O'Neill, Brian C., Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stéphane Hallegatte, Timothy R. Carter, Ritu Mathur, and Detlef P. Vuuren (2013). "A new scenario framework for climate change research: the concept of shared socioeconomic pathways." In: *Climatic Change*, pp. 1–14. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0905-2.

Perrissin Fabert, Baptiste, Patrice Dumas, and Jean-Charles Hourcade (2012). *What social cost of carbon? a mapping of the climate debate*. Tech. rep. Nota di lavoro, Fondazione Eni Enrico Mattei: Climate Change and Sustainable Development.

Pigou, A. C. (1920). *The economics of welfare*. London: Macmillan and Co.

Pindyck, Robert S. (2013). "Climate Change Policy: What Do the Models Tell Us?" In: *Journal of Economic Literature* 51.3, pp. 860–872. DOI: 10.1257/jel.51.3.860.

Ramsey, F. P. (1927). "A Contribution to the Theory of Taxation." In: *The Economic Journal* 37.145, p. 47. ISSN: 00130133. DOI: 10.2307/2222721.

Rausch, Sebastian and John Reilly (2012). *Carbon tax revenue and the budget deficit: A win-win-win solution?* Tech. rep. MIT Joint Program on the Science and Policy of Global Change.

Rozenberg, Julie, Stéphane Hallegatte, Adrien Vogt-Schilb, Olivier Sassi, Céline Guivarch, Henri Waisman, and Jean-Charles Hourcade (2010). "Climate policies as a hedge against the uncertainty on future oil supply." In: *Climatic Change* 101.3, pp. 663–668. ISSN: 0165-0009. DOI: 10.1007/s10584-010-9868-8.

Rozenberg, Julie, Adrien Vogt-Schilb, and Stéphane Hallegatte (2014). *Transition to Clean Capital, Irreversible Investment and Stranded Assets*. Policy Research Working Papers. The World Bank. DOI: 10.1596/1813-9450-6859.

Salon, Deborah (2009). "Neighborhoods, cars, and commuting in New York City: A discrete choice approach." In: *Transportation Research Part A: Policy and Practice* 43.2, pp. 180–196.

Sandmo, Agnar (1975). "Optimal taxation in the presence of externalities." In: *The Swedish Journal of Economics*, pp. 86–98.

Schipper, Lee, Celine Marie-Lilliu, and Roger Gorham (2000). "Flexing the link between transport and greenhouse gas emissions." In: *IEA*.

Spiller, Elisheba, Heather Stephens, Christopher Timmins, and Allison Smith (2014). "The Effect of Gasoline Taxes and Public Transit Investments on Driving Patterns." In: *Environmental and Resource Economics* 59.4, pp. 633–657. ISSN: 0924-6460, 1573-1502. DOI: 10.1007/s10640-013-9753-9.

Sterner, Thomas (2007). "Fuel taxes: An important instrument for climate policy." In: *Energy Policy* 35.6, pp. 3194–3202. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2006.10.025.

Tol, Richard SJ (2005). "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." In: *Energy policy* 33.16, pp. 2064–2074.

Turton, Hal and Filipe Moura (2008). "Vehicle-to-grid systems for sustainable development: An integrated energy analysis." In: *Technological Forecasting and Social Change* 75.8, pp. 1091–1108.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

Vogt-Schilb, Adrien and Stéphane Hallegatte (2014). "Marginal abatement cost curves and the optimal timing of mitigation measures." In: *Energy Policy* 66, pp. 645–653. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2013.11.045.

Vogt-Schilb, Adrien, Stéphane Hallegatte, and Christophe De Gouvello (2014). "Long-term mitigation strategies and marginal abatement cost curves: a case study on Brazil." In: *World Bank Policy Research Working Papers* 6808.

Vogt-Schilb, Adrien, Guy Meunier, and Stéphane Hallegatte (2012). "How inertia and limited potentials affect the timing of sectoral abatements in optimal climate policy." In: *World Bank Policy Research Working Paper* 6154.

— (2013). "Optimal timing, cost and sectoral distribution of emission reductions: abatement cost curves vs. abatement investment." In: ASSA.

Waisman, Henri, Céline Guivarch, Fabio Grazi, and Jean-Charles Hourcade (2012). "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." In: *Climatic Change* 114.1, pp. 101–120. ISSN: 0165-0009. DOI: 10.1007/s10584-011-0387-z.

Washbrook, Kevin, Wolfgang Haider, and Mark Jaccard (2006). "Estimating commuter mode choice: A discrete choice analysis of the impact of road pricing and parking charges." In: *Transportation* 33.6, pp. 621–639.

World Bank (2012). *Inclusive Green Growth: The Pathway to Sustainable Development*. The World Bank. ISBN: 978-0-8213-9551-6 978-0-8213-9552-3. DOI: 10.1596/978-0-8213-9551-6.

Zhang, Ming (2004). "The role of land use in travel mode choice: evidence from Boston and Hong Kong." In: *Journal of the American Planning Association* 70.3, pp. 344–360.

SPOTLIGHT. ADAPTING CITIES TO CLIMATE CHANGE: A SYSTEMIC MODELLING APPROACH[1]

We include this article in this PhD dissertation as a spotlight and not as standalone chapter. The reasons are twofold. First, this journal article is the result of very large collaboration from many researchers and as a consequence, my contribution, although substantive, is only a fraction of the end result. Second, the topic of this article is mainly focused on adaptation, in this case on the mitigation of the impacts of the Urban Heat Island effect and therefore falls outside the main scope of this dissertation, focusing on urban transport related CO_2 emissions mitigation. For both these reasons, we chose not to include this article as a standalone chapter. Nevertheless, its inclusion as a spotlight seemed relevant because this article i) demonstrates that the NEDUM-2D model can be used convincingly to investigate adaptation strategies at the urban scale, ii) illustrates how NEDUM-2D can be coupled with another urban model, harnessing their respective strengths, and integrated into a stream of models investigating complex phenomena. This article was published in the Urban Climate journal, volume 10 in 2014. This article is Open access under CC BY-NC-ND license: https://creativecommons.org/licenses/by-nc-nd/4.0/

1 INTRODUCTION

Climate projections have foreseen both global warming, sea level rise and an increase in the frequency and intensity of extreme events (IPCC, 2013; Solomon, 2007), such as heavy rain and storm events (hurricanes, monsoons,

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and floods), heat waves, desertification, and giant forest fires. The IPCC assessment reports (IPCC, 2007, 2013) confirm that greenhouse gas emissions have to be drastically reduced to limit on-going global warming and the pace of the resulting climate change. These reports also acknowledge that adaptation of societies to a new climate context is of prime importance.

These issues have particular relevance to urban areas where valuable assets are concentrated and more than half the world's population resides. Moreover, in some instances the projected global-scale changes can be exacerbated by city-scale phenomena, such as the formation of heat islands (UHI), which during heat wave events, may result in many deaths (Gabriel and Endlicher, 2011; Johnson and Wilson, 2009).

Each of these project climate changes will have an impact on cities that will probably necessitate different adaptation strategies, depending on their specific features (and the interactions between them), the city characteristics and location, the local governance and the level of social and economic development.

At the international scale, the assessment of urban vulnerability to an altered climate is an emerging research topic as shown by projects such as Engineering Cities: how can cities grow while reducing vulnerability and emissions?[2] (Tyndal Centre, UK), "Urban lifestyles, sustainability and integrated environmental assessment" (Postdam Institute for Climate, Germany) and the New-York Climate and Health Project.

These works tackle different aspects of environmental risk in cities: flood risks (De Roo et al., 2007) and water system management (Rosenzweig et al., 2007); epidemiological impact of ozone and fine particle pollution (Bell et al., 2007); and heat-related mortality (Dessai, 2003; Knowlton et al., 2007) or discomfort (Kusaka, Hara, and Takane, 2012). Environmental risks and vulnerability are often quantified using empirical and statistical approaches (Bell et al., 2007; Dessai, 2003; Knowlton et al., 2007) instead of physically-based models (Kusaka, Hara, and Takane, 2012; Masson et al., 2013). Most of them, however, are not based on a interdisciplinary (systemic) approach that accounts for the social, economic and physical processes that interact together at the city-scale; instead they are often limited to one or a few closely related scientific fields.

In the field of atmospheric sciences, the BRIDGE project (Chrysoulakis et al., 2013) proposes a multi-model approach to simulate the impact of (specified) urban scenarios on the local atmosphere in terms of air pollution, CO_2 emission and the UHI. However, the city itself is not modelled either in terms of its metabolism or evolution over time. Kusaka, Hara, and Takane (2012) have studied the interaction between climate change scenarios and the UHI for three cities in Japan. They show that the main increase in temperature is governed by the global climate change signal and that the UHI does not change based on scenarios that do not permit the cities under study to evolve over the time span of the study. However Aguejdad et al. (2012) show that changes of urban patterns under the assumption of an unchanged climate influences the extent and magnitude of the UHI. Moreover, using a high-resolution atmospheric model, both De Munck et al. (2013) and Tremeac et al. (2012) show that, even if the structure of a city does not change, an increase in air conditioning use can lead to an increase in the UHI by 2°C in the centre of Paris. Masson et al. (2013) show that such an increase of the UHI can be reduced by changes in the strategy for suburban and rural

[2] See: http://www.tyndall.ac.uk/publications/other-tyndall-publications/engineering-cities.

crops and increases in the forested areas in the region of Paris. These few examples already show the variety of processes that can interact within the frame of urban meteorology alone when we consider the adaptation of cities to climate change. The results of the EPICEA project[3] highlight the potential effect of adaptation measures aiming to limit the intensity of the UHI over a big city (Lemonsu et al., 2013) by modifying the surface energy balance. These techniques are widely known (e.g. surfaces that reflect high proportions of solar radiation, high infrared albedo of roofs and wall surfaces, greening and watering of urban surfaces) but a detailed simulation of heat and mass transfers between the built area and the atmosphere is needed to assess their effect. An average reduction of 1 K over space and time may appear to be a modest result but such an effect could greatly influence the recorded mortality. The temperature decrease may be locally and temporarily higher depending on the many factors that drive the energy balance. This project also addresses some side effects of implementing adaptation measures (feasibility, cost, maintenance, and acceptability).

However, the main point is that none of these studies who have considered climate change and cities have allowed the city to change (either in form or function). Furthermore, the adaptation strategies that are proposed are mainly based on environmental benefits (Rosenzweig et al., 2007) but hardly investigate their cost and socio-economic consequences, which can sometimes be negative (Rosenzweig et al., 2011).

This paper presents a systemic (or interdisciplinary) modelling methodology to provide some initial insight into the interactions between climate change, city structures and urban economies. This work was carried out within the framework of three coordinated projects[4] (VURCA, MUSCADE and ACCLIMAT), each of which use this systemic methodology to examine cities can adapt and mitigate to aspects of climate change. These aspects include

- Adaptation to one type of extreme event, that of heat wave intensification;
- Mitigation of climate change by reducing energy consumption and;
- The impact adaptation scenarios on several human comfort and climatic indicators for urban areas.

The scientific challenges to developing a systemic modelling approach are discussed in Section 2. This approach requires that models designed for different purposes are coupled; the coupling strategy is presented in Section 3 and the main characteristics of the individual models are presented in Section 4. A validation on the cities of Paris and Toulouse follows in Section 5. The interdisciplinary indicators that result from this approach are shown in Section 6 and illustrative results on projections for the future of Toulouse in 2100 are given in Section 7.

[3] See: http://www.cnrm-game.fr/projet/epicea.

[4] See: http://www.cnrm.meteo.fr/ville.climat. The VURCA and MUSCADE projects focused on the Paris urban area, while the ACCLIMAT project studied Toulouse city area (in south-west France).

2 SCIENTIFIC CHALLENGES

2.1 *The city: a complex system*

Each city is concentration of population and capital stocks (housing, production, water delivery, transportation and infrastructures) that comprises a complex system with social, economic and environmental aspects. Each of these aspects has its own rules of behaviour and evolution but each is closely linked with the others. For example, people will choose their housing according their preferences, the local amenities, distance to their workplace, and their budget (Bjerke et al., 2006; Brasington and Hite, 2005; Hamilton and Morgan, 2010). The need to feed the population shapes the agricultural land around the city and beyond (even on other continents) and impacts the city environment, while interacting with the evolution of people's eating habits and transportation networks in the long run (Billen et al., 2012).

Such complex interactions lead to several scientific challenges:

1. First, studying even a part of these interacting processes requires a strong interdisciplinary approach. In this work, studying urban climate evolution and building adaptation strategies of cities involved urban planners, architects, meteorologists, building engineers, social scientists, geographers and economists.

2. Second, numerical modelling is an essential tool for the global comprehension of the city system and the underlying processes, which operate at different spatial and temporal scales. The interactions among the system components cannot be apprehended by human expertise only.

3. The systemic modelling approach, which is interdisciplinary by nature, must link models designed for different purposes (e.g. planning and urban climate models). This requires a broad comprehension of the information exchanged between the models themselves and of the links between scenarios and models (each scenario driving all models in a coherent manner).

The problem of the adaptation of cities to climate change induces an additional scientific challenge, that of the time horizon.

2.2 *A 2100 time horizon*

Addressing climate change and cities entails the examination of both the changing climate and city system. Resolving this problem means that several processes need to be considered, each of which has a typical duration:

1. Projections of climate change have a horizon of a century; for example, depending on the GES emission scenario, global warming will cause a temperature rise of several °C by in 2100 and more beyond (IPCC, 2013).

2. Structural modifications in cities occur slowly (Grazi, Bergh, and Ommeren, 2008). For example, in most parts of Europe, city structures have grown up over centuries (Grazi and Bergh, 2008) and an urban building has a lifetime of 50 to more than 100 years (Balaras et al., 2007; Gusdorf, Hallegatte, and Lahellec, 2008).

3. Lifestyles also evolve over lengthy timescales depending on the influence of available technologies, social history, etc. Education plays a relatively strong role in such evolution, meaning that the time-scale can extend over one or two generations.

In other words, if cities are to be adapted to the projected future climate, it is necessary to start adaptation now by modifying city structure, building design, urban planning habits, etc. Dealing with this timescale raises some scientific challenges for the systemic approach: the scenarios employed to the year 2100 must be constructed coherently for the different disciplines (climate, economy, technology, urban planning, etc.) included and the models adopted must be pertinent for such a time-scale (and validated on a similar period of the past). Moreover, the uncertainties associated with the results must be quantified (as has already been done for climate projections in IPCC reports).

3 THE SYSTEMIC MODELLING APPROACH

3.1 *Impact modelling versus systemic modelling*

Usually, in disciplinary studies on climate change, some urban impacts are quantified using a number of models. The description of the city for which they are calculated is provided through scenarios (see Figure S.1a), which are constructed from the expert knowledge of urban planners and scientists (who can include some modelling results within their design) and/or from people who have influence or interests in the local area. This approach requires significant resources and human expertise, so it is likely to provide a limited number of scenarios, focusing on a limited area over a limited time horizon. The vision of urban planners is linked to urban regulations and operations, which typically make provisions for up to 20 years ahead.

The BRIDGE project (Chrysoulakis et al., 2013) comes into this category, as the energy atmospheric models were fed by alternative scenarios of localized urban planning interventions on the five European cities tested.

In some other works, the scenarios of the cities are even simpler in that their description is constant in time. This can be because the authors wish to evaluate the impact of climate change or a few parameters alone. However, this strongly limits the range of urban adaptation strategies that can be tested; for example, Krayenhoff and Voogt (2010) present a review of the modelling of the impact of white roofs on air temperature. Alternatively, the researchers do not expect that the cities under study will grow, even by the end of the century. Kusaka, Hara, and Takane (2012) explain that Japanese cities are not likely to grow any further because they are already very large and the population of Japan is decreasing. As a consequence, the descriptions of the three cities examined were kept constant for the period studied (2010–2070).

To deal more accurately with the question of adaptation of cities to climate change, it is necessary to consider a time-scale of a century or more, as well as a much broader range of disciplines.

The systemic modelling strategy used here is therefore much more ambitious than classical impact modelling in terms of the processes simulated and the perspectives employed to quantify different strategies for adapting cities to climate change. To implement this approach a strong, broad interdisciplinary panel of researchers is needed. However, the crucial difference between the impact and systemic modelling approaches is that the latter

allows the city to evolve using simulations that consider long-term trends, which affects its development, rather than using prescribed scenarios.

Systemic modelling offers several advantages over the alternative. Firstly, it ensures that processes driving the evolution of a city are consistent from an interdisciplinary perspective. Secondly, it permits many more projections of the city to be simulated (allowing sensitivity to be analysed and uncertainties to be quantified), some of which may not have been considered at the outset. For example, a large peak in oil prices will lead to a strong increase in energy costs in the short term (2030–2040), but may not have so much impact in the long term (2100) because economic pressure induces the development of alternative technologies (Viguié, Hallegatte, and Rozenberg, 2014). In this case, city expansion in the future may be much less constrained by oil prices than is usually believed. The systemic modelling of the city simulates an outcome that is internally consistent with both the scenarios developed and the processes embodied by the equations in the linked models.

3.2 *Overview*

The systemic modelling approach combines prospective scenarios (Godet, 1986) and spatially-explicit models (Houet et al., 2010). It can be summarized as follows (Figure s.1b):

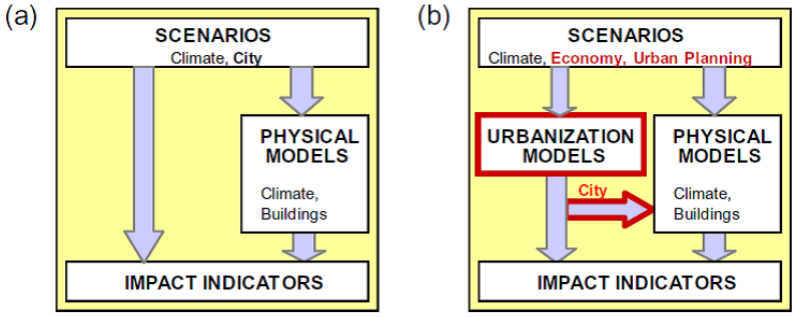


Figure s.1: Approach for (a) impact modeling; (b) systemic modeling.

First, interdisciplinary scenarios are defined. Marchadier, Houet, and Bretagne (2012), considered scenarios based on the IPCC projections, global economy developments including energy costs and per capita income (see Viguié, Hallegatte, and Rozenberg (2014) for details), changes to the local economy (for example, is the city in crisis or not compared to the rest of the country?), technological innovations (in buildings or transport), lifestyle changes (e.g. use of air conditioning), and urban planning initiatives (green city, dense city, etc.). These scenarios do not claim to guess what the city will be like but they do allow us to explore possible city evolutions. Moreover, they can be used in two distinct ways: to forecast based on the existing urban character and; to backcast by illustrating what we would (not) like the city to be. Depending on the other factors (mainly previous history of the city, demography and economy), these urban planning options will have more or less effect on the final shape of the city.

Second, city models are used to simulate long-term urban expansion. The broad shape of the city expansion can be simulated by a socio-economic model (NEDUM is used here), which is driven by general and robust economic laws. This model can be coupled with a geographical model (SLEUTH

is used here; see Clarke (2008), Clarke and Gaydos (1998), and Clarke, Hoppen, and Gaydos (1997)) to provide greater spatial detail and incorporate urban planning decisions more explicitly. Similarly, this geographical model can be coupled to an architectural model that describes outcomes at a fine resolution. Here, we employ an Urban Climate Zone classification to describe how the urban form of each city block will evolve in response.

Third, the impacts (meteorological and others) are simulated by physical models. A building energy model is included in an urban canopy scheme that is coupled to the conceptual or full atmospheric models to take both climate forcing and UHI reciprocal action on the city (energy consumption, comfort, etc.) into account.

Finally, indicators quantifying the adaptation strategy (for each scenario) are calculated and compared.

4 BRIEF PRESENTATION OF THE MODELS

4.1 *The urban expansion models*

The main criterion for the choice of the urban expansion model is to have a model that can produce projections of the city structure over the very long term for varying scenarios that may include a significant change in the environmental context, such as an oil crisis. The urban models used by urban planning agencies (such as TRANUS, De la Barra (2005)) often use rules based on the extrapolation of past trends, which may be valid for a short period into the future (20–30 years). Here, we have selected the Non-Equilibrium-Dynamical Urban Model (NEDUM) to simulate the expansion of the city over long periods; it is driven by economic considerations and general laws that make the model robust and suitable for long-term simulations. However, the model will lack some small-scale details (e.g. urban concentration due to local amenities). In order to be confident in its pertinence for the century to come, NEDUM has been validated on the past 100 years (Viguié, Hallegatte, and Rozenberg, 2014).

The model is based on three key mechanisms:

1. Households choose their accommodation location and size by making a trade-off between transport time to work and the price of real estate.

2. Real estate developers optimize profit by constructing tall buildings where land is expensive and houses further from the city centre.

3. Variable time scales for different processes, for example rents adjust quickly but building construction is slower to external forces. Numerous databases that describe the actual city are needed for the simulation including the transport network and some economic data (e.g. per capita income). Other important data required by the NEDUM model are the areas where building is not permitted (e.g. rivers, parks, protected zones). The simulation results generate a great deal of economic data but the crucial data that are used further in our modelling chain are:

    - A map of the quantity of floor area built for residential housing,
    - A price map for rentals and,
    - The total newly urbanized surface area (including roads, gardens, car parks, etc.).

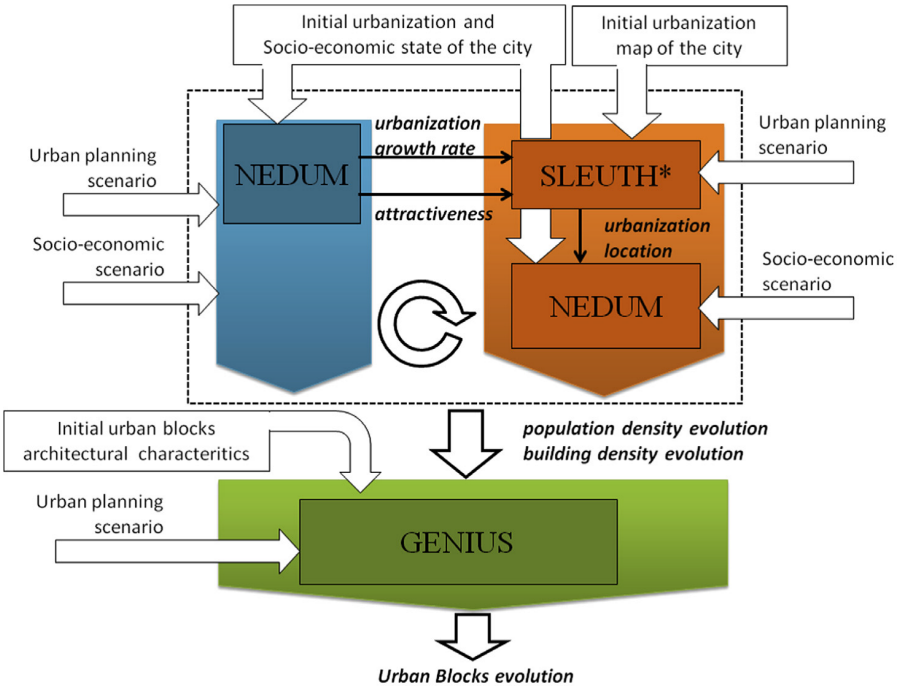


Figure s.2: Strategy for coupling economic expansion model (NEDUM), geographical model (SLEUTH modified) and architectural model (GENIUS). Models are integrated and coupled together every 10 years with the Open-PALM coupler.

These data are generated at 10-year intervals.

In order to refine the spatial allocation of the urbanized areas at small scale, a geographic cellular automata urban growth model was modified (called hereafter SLEUTH* – Doukari, Aguejdad, and Houet (2013)) so that it could be coupled to NEDUM (Figure s.2) and simulate the scenarios for 2100. Instead of estimating the urbanization growth rate from previous urban maps (hence extrapolating past tendencies), SLEUTH* becomes a scenario-dependent model, i.e. it does not require any calibration steps but depends strongly on user (urban planning preferences) defined parameters. It now takes a given amount of urbanization (that is provided by NEDUM every 10 years) into account and relocates it by considering geographical amenities (slopes) and urban planning preferences. The latter includes whether construction is to occur near already built-up areas and roads or disseminated in the countryside or what parts of the landscape are to be protected from urban development. The allocation of new urban areas is also influenced by integrating a map generated by NEDUM that describes the attractiveness of the area under study based on the cost of transport and the price of land.

NEDUM and SLEUTH* were coupled using PALM software[5] and applied to the city of Toulouse. Independently, these two models have limitations for simulating urban development (Aguejdad et al., 2012) but together they complement each other and the coupling offers mutual benefits.

5 http://www.cerfacs.fr/globc/PALM_WEB/.

4.2 *The architectural model*

Once the location of the new urban areas and the quantity of building to take place there is simulated, we still need to know what type of construction is likely to take place. Even in older urbanized areas, population increases can induce a densification of the urban fabric and a destruction/reconstruction process. In order to reproduce these effects, a new architectural program, GENIUS (the GENerator of Interactive Urban blockS) has been specifically developed in the framework of our projects.

The strategy underlying to the development of GENIUS is based on identifying the main characteristics of urban morphology at the block scale (typically 250 m by 250 m), which allow typical urban forms to be identified. This urban block method can be compared to the Local Climate Zones (LCZ) (Oke, 2008; Stewart and Oke, 2012) approach used in urban climatology (Table s.1). In GENIUS, we have adopted the LCZ descriptors most relevant for European cities (according to the nomenclature and numbering of Stewart and Oke (2012)) and applied them to the urban block scale. For our purposes, an additional LCZ class (monuments), is added to allow a better architectural description and other LCZ classes are merged.

Each block then is categorised into an LCZ and is characterised by about 60 indicators. These variables describe urban form (fraction of vegetation, of buildings, height of buildings, etc.), architectural features (e.g. the date of construction of the buildings, majority type of heating equipment, etc.) and social characteristics (for example, residential, offices, commercial, industrial or agricultural use). All these indicators are crucial in our modelling suite, as they make the link between the urbanization and the characteristics of the buildings for the building energy model.

To derive these data, an analysis of the existing 3D building databases was made in order to express the real city in the form of a map of block-scale LCZs (cf Figure s.3). The evolution of these LCZs in the future is driven by the flux of construction of floor area (m^2) in each block at ten year intervals. The way the indicators vary as a function of the others is shown in Figure s.4. Note that some information on urban planning scenarios can also influence the future urban forms in the city so that, for a given built floor density, one type of building or another that typify an LCZ type may be favoured.

4.3 *The urban climate and energy consumption model*

The final step is to simulate energy consumption that accounts for the UHI and all other driving factors (such as climate change or city evolution). However, while detailed building models (such as Energy +) represent the details of the buildings very well (in terms of both interior and envelope architecture), they do not consider the impact of buildings on the outside weather, so the effect of the UHI is neglected. Typically, the meteorological conditions that represent ambient conditions for these models come from an airport meteorological station outside the city.

Taking the urban and global climate changes into account presents two challenges: (1) how to account for urban scale effects like the UHI and (2) how to include climate change scenarios from a climate model to the city scale.

The first issue is solved here by introducing a building energy model (BEM) (Bueno et al., 2012; Bueno et al., 2012; Pigeon et al., 2014) into the Town Energy Balance (TEB) model (Masson, 2000). This BEM works within the

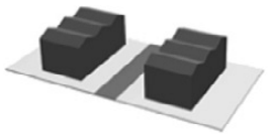
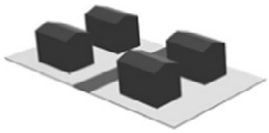
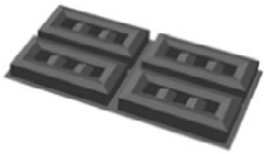
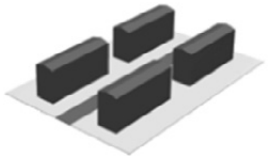
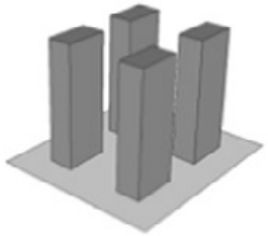
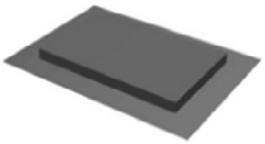
Selected LCZ		Correspondence with Steward and Oke LCZ
Continuous pavilion		(3) 'Compact low rise'
Discontinuous pavilion		(6) 'Open low rise' and (9) 'Sparsely built'
Continuous block		(1) 'Compact high rise'
Discontinuous block		(5) 'Open mid rise'
High-rise tower		(4) 'Open high rise'
Ancient center		(2) 'Compact mid rise'
Industrial building		(8) 'Large low-rise' and (10) 'Heavy industry'

Table s.1: The seven typical blocks.

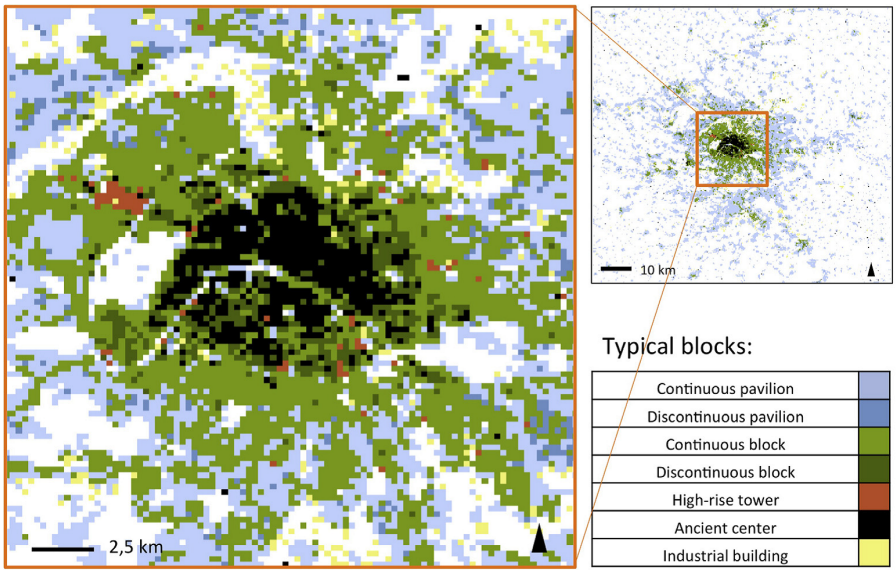


Figure s.3: Description of Paris (year 2008) in terms of Local Climate Zones. Grid mesh is 250 m.

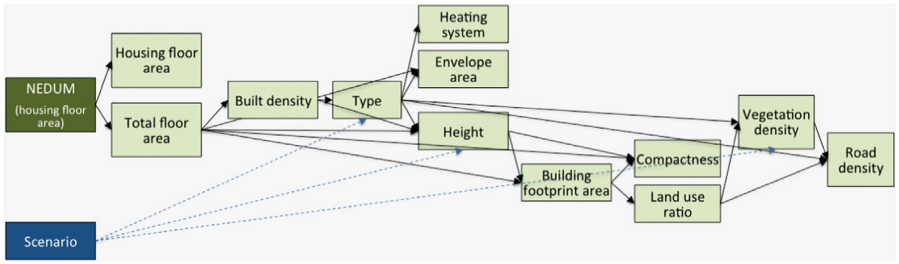


Figure s.4: Causal relations for evolution of indicators in GENIUS architectural model.

relatively simplified urban geometry of TEB but all the important processes are taken into account: internal mass, internal energy balance, windows and solar radiation, shading devices, internal gains, heating/cooling devices (including waste release to the atmosphere) and infiltration/ventilation, and some uses are simulated (shading device use, natural ventilation strategy). In addition, in order to be able to assess some adaptation strategies based on urban vegetation and fine urban structure, gardens are now represented (with the Interface-Soil-Biosphere–Atmosphere ISBA scheme, Noilhan and Planton (1989)) within the canyons themselves, canyons that can now have a specific orientation in TEB (Lemonsu et al., 2012), and a greenroof module (also based on ISBA) is implemented (De Munck et al., 2013).

The second issue is more difficult to address. How can we best represent the impact of cities (typically the UHI) in the context of long-term climate studies? Current global climate models lack two key elements to be able to simulate the UHI. First they do not have the physics dedicated to urban surfaces (such as TEB). Second, their resolution is of several tens of kilometres at best, even for regional climate models. So cities and their climate effects cannot be represented explicitly. Very recently, studies have been made of climate change over several decades at a regional scale (3-km resolution) using climate models (such as the COSMO model with TEB in Berlin Trusilova et al. (2013)) but such models cannot be used to create long-term scenarios yet. This is an acknowledged problem with existing climate change scenarios; see

for example the UK Met Office (UKCP09 web portal[6]) or Météo-France (Drias web portal[7]). The former states that 'UKCP09 does not include the process by which urban areas store and generate heat, creating a local climate which has significant implications under climate change'. As a result, down-scaling of the simulations from climate models to urban scale is necessary.

Here, two down-scaling approaches were considered. The first is to couple the surface with a full atmospheric model. Kusaka, Hara, and Takane (2012) simulate the UHI of Tokyo, Osaka and Nagoya at 3-km resolution for the month of August in 2070. Similarly, Masson et al. (2013) and De Munck et al. (2013) simulate heat-wave days over Paris at 500 m and 250 m of resolution. However, such simulations are extremely expensive in CPU time, especially if a detailed description of the city is included. One means of overcoming this issue is to coupling the surface and the atmosphere at different resolutions (typically 250 m for the city and 1–2 km for the atmosphere). This allows a better physical representation of the atmosphere than in the first approach, but still at a cost of more simulation time. The second approach, which is faster and provides longer simulations, is to couple TEB (and ISBA for urban vegetation and in the countryside) within a simplified model of the atmospheric boundary layer (typically 1 km high by day and 200 m by night) that is driven by the surface-atmosphere energy fluxes (Bueno et al., 2013). Then, the simulation is driven on the countryside either by observations (for present climate) or climate scenarios (climate models represent the countryside as only water and vegetated surfaces, not cities). This is done following the methodology described in Hidalgo, Masson, and Baehr (2014). This is the approach taken in this paper.

Now that our atmospheric models have the adequate physics, the final task is to link these to the city characteristics (as described by the block-scale LCZs), which are generated by the urban development models. This is mainly done through the GENIUS architectural model that links the LCZ parameters to the TEB model. Some of the important data (such as geometry and land cover) are directly associated with each grid cell and its LCZ characteristics. Other data is acquired from architectural expertise that connects built parameters to LCZ class based on current building type, date of construction and likely renovation and future building norms. For example, zinc roofs are associated with old buildings (construction date before 1900) in Paris and non-industrial brick walls are associated with old buildings in Toulouse. Some experimental measurements have documented the radiative properties of these surfaces (Seow et al., 2012), which can have a significant impact on energy consumption.

5 VALIDATION OF THE MODELS IN THE PAST

Before using the coupled models to quantify the benefits/limits of different adaptation strategies, two validation procedures were implemented in the aim of determining whether the model was able to simulate expected changes (scenarios). The first consisted of sensitivity tests to check that each function performed correctly and the second assessed how well the model simulated changes in the past and up to the present. This was done in several steps, first with each model alone and then with several models coupled.

The economic model NEDUM has been validated by comparison with the observed expansion of the Paris (Viguié, Hallegatte, and Rozenberg,

[6] http://www.metoffice.gov.uk/services/climate-services/uk/ukcp.
[7] http://www.drias-climat.fr.

2014) and Toulouse urban areas for the past century. The validation on Paris started from 1900 (with all the difficulties this supposes in gathering the necessary data for such a long time ago). The model was able to reproduce the expansion of the city (size and also pattern) at several stages in the 20th century, and also its socio-economic characteristics (rents, population density, housing density, dwelling size, etc.).

The geographical model SLEUTH* was tested through a set of sensitivity tests and on Toulouse metropolitan area over a period of 16 years (1990 – 2006) (Doukari, Aguejdad, and Houet, 2013). This time span is pertinent because the model is not designed to reproduce the long term evolution itself (this is the role of NEDUM) but to refine the allocation of a known amount of urbanization. Note that, for SLEUTH*, a calibration is performed on the past of the parameters of the model in order to accurately simulate several spatial indicators of the urban extension of the city and also to derive suitable values for a future 'business as usual' scenario. Other scenarios are then defined as variations from this one. The model assessment proved the ability of SLEUTH* to handle the simulation of several urban structures that reflect urban planning strategies. The model could then be used for forecasting.

NEDUM and SLEUTH coupled together were intensively tested on the city of Toulouse. Sensitivity tests assessed the capacity of each of the models to integrate the temporary data produced by the other at an annual time step. Figure s.5 and Table s.2 show an example of coupled NEDUM–SLEUTH model performance in simulating a plausible urban pattern compared to 2006.

Verifying the ability of the architectural model GENIUS to reproduce the evolution of urban forms at block scale was more difficult because of the lack of building data over a lengthy period (50 years or longer). However, as buildings have a long lifetime in European cities, we could use information on existing buildings (for which date of construction was known) to check if GENIUS was able to simulate their construction. The evolution of the density of construction, in terms of floor area, was not available but that of the population was well known (with good spatial resolution) and was used as a proxy. The GENIUS model was able to reproduce the construction of 91% of the LCZ types adequately; the construction date of these LCZ was acceptable, with 66% of buildings built at the right time, i.e. correctly within the ranges 1962–1974, 1975–1989 or 1990 onwards. Given that there are uncertainties on the construction dates from the census data itself, we consider this a good result.

The simplified urban boundary layer model following Bueno et al. (2013) was improved to work in 2D instead of only in 1D. The rural conditions needed to force this simplified model came from Toussus airport, located 20 km from Paris but nevertheless in a non-urbanized area. We carried out the validation on Paris against both observation data and a high-resolution atmospheric model. The validation against the observations ran from 1998 to 2011, for minimum and maximum temperatures. There are 5 observation stations in the historical centre of Paris and its dense suburbs (by far the largest number of routine meteorological observations in a French city). We also extended the validation by comparing the simple weather generator to a complete high resolution atmospheric simulation (MesoNH model) performed over the Paris region at 2-km resolution during 2011 (Lac et al., 2013).

The statistical scores of the simple weather generator against both observations and the high-resolution atmospheric model are presented, by season,

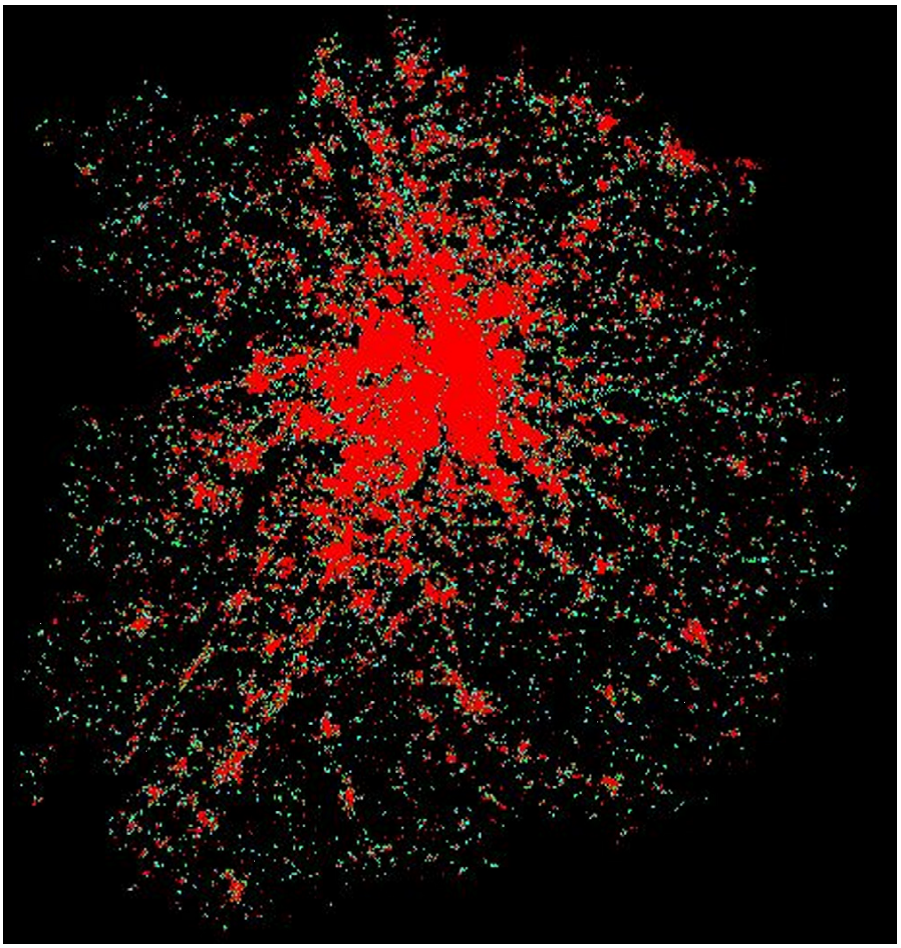


Figure 5.5: Comparison of 2006 urban map with 2006 map simulated using coupled NEDUM–SLEUTH model. The model correctly predicts urban growth (in red), but although the amount of urban extension is correct, its allocation (light blue) does not match the observed situation in 2006 (light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Urban map in 2006	Area	NP	PD	C
Observed	59,527	4257	0.5404	97.77
Simulated	60,460	4267	0.5391	98.26

Table 5.2: comparison of urban structure of the simulated map to the observed one with landscape metrics (Urban area in ha -Area-, Number of urban patches -NP-, Patch density -PD-, Mean distance between patches -MdP-, Cohesion -C-).

	MesoNH/ observations	Simple weather generator/ observations	Without urban weather generator/ observations
Summer	−0.15 K	0.04 K	−1.15 K
Autumn	−0.22 K	0.60 K	−0.55 K
Winter	−0.21 K	0.91 K	−0.33 K
Spring	−0.67 K	0.16 K	−1.58 K

Table s.3: Comparison to the observations of the seasonally averaged 2 m air temperatures simulated over Paris centre for (a) the MesoNH atmospheric model (including TEB) (b) TEB with the urban weather generator, (c) TEB without the urban weather generator.

in Table s.3. While the simplified urban boundary layer model does not perform as well as the high-resolution atmospheric model, it still reproduces the UHI well, especially in spring and summer (when the UHI is the largest) even though, in winter, the UHI seems overestimated. Overall, this validation shows the improvement brought by the use of a weather generator (instead of nothing) to spatialize the UHI for further energy and comfort studies.

Finally, the TEB was also validated in terms of energy consumption at city scale. At a building scale TEB–BEM has been shown to be capable of estimating the heating and cooling demands for 5 different types of buildings and 2 different climates (Paris and Cordoba) with an accuracy of 5 kWh/m^2/year for heating and 3 kWh/m^2/year for cooling (Pigeon et al., 2014).

The validation at city scale raised a problem of accessibility to energy consumption data, which are commercially sensitive and not generally available. However, some broad-scale statistics are available at the French ministry of ecology. They are available for certain sectors, including residential and office buildings taken together (which is the quantity we aim to simulate) annually for the administrative region that contains the Paris urban area. Given that no other significant town is present in this region, we assumed that these data were representative of Paris and its suburbs. Furthermore, the energy data contains not only statistics for heating and air-conditioning, but also for lighting, hot water and specific electricity use. These are not computed by the model and have to be estimated from the observations. In order to obtain data comparable to TEB–BEM energy consumption, we followed an ADEME (French energy agency) rule of thumb that lighting, hot water and specific electricity use represent approximately 20% of total final energy consumption.

The TEB simulation is initialized, in terms of surface characteristics, from the interpretation of building and urban parameters in the LCZs (map in Figure s.3). Two simulations were run: one without UHI, forced by a rural meteorological station, and one forced by the same station but including the representation of the UHI by the conceptual boundary layer model of Bueno et al. (2012). We simulated heating (cf Figure s.6) in residential and office buildings (including commercial buildings and hotels). We assumed that in Paris, located in the North of France, air conditioning was only present in office buildings and not in houses or collective buildings (unlike in

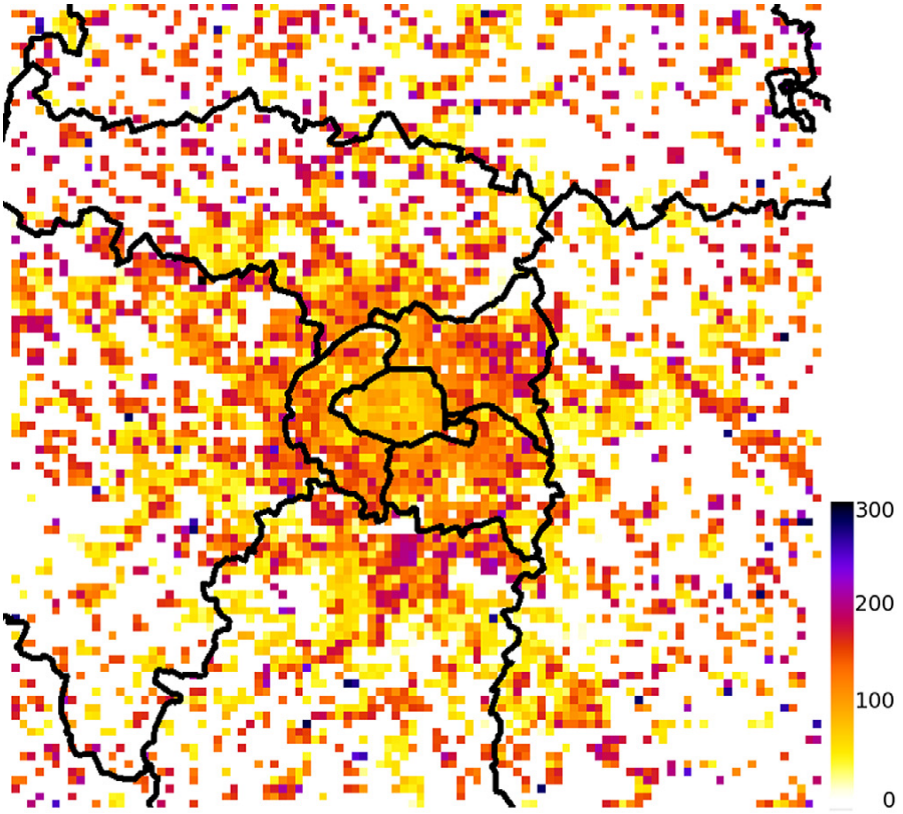


Figure s.6: Energy consumption due to domestic heating in Paris (2008) simulated by TEB. Black lines are administrative boundaries. Inner black line is historic, intra-muros Paris. Resolution is 1 km.

other regions in the world). As energy consumption in industrial buildings depends on many more factors (e.g. a warehouse can be unheated, while a factory can need a lot of energy for its machinery), their energy consumption was not simulated here. This means that no heating or air-conditioning was computed for grid meshes where usage was industrial.

The simulations covered 11 years (from 1998 to 2008) and were compared to data when these were available. TEB, used here at 1-km spatial scale, was able to simulate the energy consumption of the Paris urban area with an error of 5% (using realistic target temperatures for heating (21 °C) and cooling, if any (23 °C)). More importantly, it was able to reproduce the year to year variation of energy consumption (Figure s.7) that was purely due to the response of the system to weather variations. However, the drop for years of low energy consumption seemed overestimated by the model; these were warm years, with less consumption for heating but potentially more for air conditioning. Neglecting all air conditioning in residential areas may explain part of this difference. Unfortunately, there are no data for the 2003 heat wave. While we are aware that there may have been some compensation for errors, this still validates the ability of the model to simulate the energy consumption with the correct order of magnitude and we are confident in its use to assess the relative impacts of different factors or adaptation strategies.

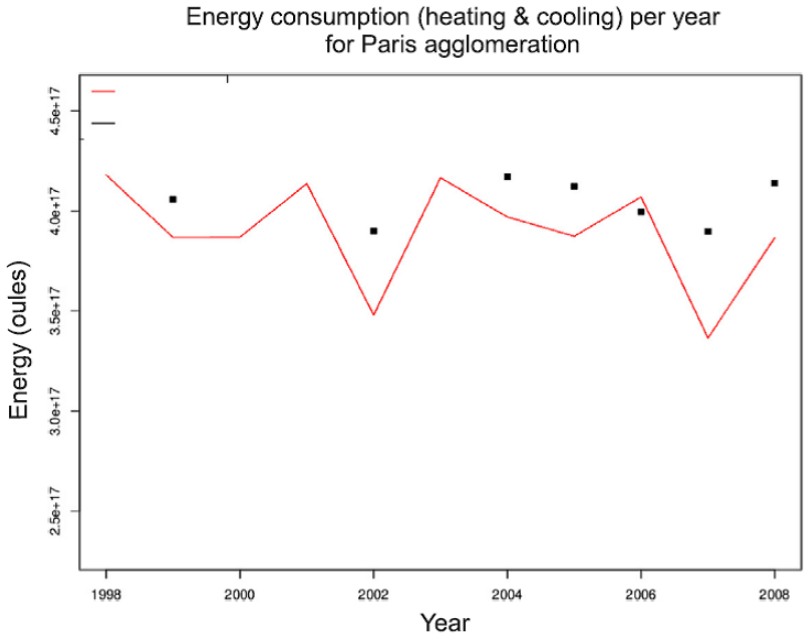


Figure s.7: Energy consumption for buildings (heating and cooling) in Paris urban area.

6 IMPACT ASSESSMENT

The interdisciplinary approach used here allows a wide range of evolution paths and impacts to be considered and assessed. The indicators used for assessment are based on both the data provided to create the scenarios (results from the participatory approach and data necessary as input to the models) and data simulated by the different models. Some indicators may be a mix of these two. The following subsections present some of the major indicators that we estimated for each adaptation strategy and climate warming scenario.

6.1 *Economic and socio-economic indicators*

First, a few indicators describing the socio-economic environment of the city are crucial for interpreting the evolution and expansion (or not) of the built-up area. These are derived from the data required to run the models rather than generated by the model simulations. However these data, which are interpreted from other sources (models, expert analyses), must fit the scenarios used to force our models. There are many such indicators but the main ones that impact city development are:

- The population of the city. This depends partly, but not solely, on the projections of future evolution of the population in this part of the world (nation or continent). It is also strongly dependent on scenarios concerning the welfare of the city in the future: will the city continue to be attractive or will it be in economic crisis (due to over-specialization of local industry, for example). This was implemented in our scenarios by analysing (in the past) the relative difference from the mean national demographic evolution for cities in crisis and attractive

cities in France. We then applied the relative difference to derive several future demographic trends.

- The mean revenue of the people in the city. This is linked to the economic context, both national (from global economic models) and local (using a methodology similar to that for the population).
- The intensity and duration of high oil prices (see discussion in Section 3.1).
- The existence (or not) of a global climatic policy among nations. This can influence the price of energy.

Second, there are indicators that describe the way the city will evolve in the future. These are computed from the NEDUM model and include:

- Spatial distribution of the density of population in the urban area: this information is typically at 1-km or even 500-m resolution. It allows the impacts of urban planning strategies on the choice of localization of the inhabitants to be assessed.
- Spatial distribution of the built density (in terms of floor area built). It is at the same resolution as the density of population and allows the size of dwellings to be estimated per occupant. It also is a direct driving factor for the architectural model GENIUS.
- Spatial distribution of the levels of rents. This has a strong influence on (and is influenced by) the choice of the inhabitants to live near the city centre (where dwelling costs are generally higher).
- Time spent and distance travelled in the transport network (public transport or private cars). This is a major urban indicator for urban planners. The modal share of public transport relative to private cars is also an interesting indicator to improve the overall efficiency of the public transport in the city depending on contrasted urban planning strategies.
- Energy and CO_2 emissions by transports in the city. This indicator integrates the information above with scenario-dependent information on technology (vehicle efficiency, proportion of electric vehicles).

6.2 *Urban form indicators*

The urban expansion models (NEDUM and NEDUM–SLEUTH*) provide indicators on the shape of the city (e.g. for fragmented vs. compact city), while the architectural model GENIUS generates indicators concerning the types of buildings being built in the city. A key indicator is

- The extent and spatial distribution of the urbanized area, which informs us of the overall urban growth.

Other integrated spatial indicators provides measure on the nature of the urban development, such as:

- The number and size of urban patches. This indicates whether the city is dense (small number of large patches of connected urbanization) or fragmented (numerous small patches).

- The type of houses or buildings being built (spatial distribution and integrated values). These are of interest to indicate whether strategies of densification are efficient or not, given the economic environment for example.
- The spatial distribution of the building fraction (as seen from above), of the height of buildings (and its variability in each grid mesh), and of other morphological parameters (e.g. contiguity).
- The spatial distribution of density of vegetation and gardens. Additional indicators, such as the number of inhabitants having a private garden or the number of m^2 of urban vegetation per inhabitant are also useful for urban planners.

6.3 *Micro-climate and comfort indices*

Our integrated model also estimates weather-related indicators, through TEB. These mainly focus on the Urban Heat Island and human thermal comfort and include:

- UHI intensity (difference between temperature of the city centre and the surrounding countryside at night). It can be averaged over different periods of time (e.g. the season). The daytime UHI is also available.
- The fraction of the population affected by a UHI of at least 1 °C (this threshold is not fixed), which allows us to consider not only the physical parameter but also how many people it affects.
- Human comfort, as assessed by the Universal Thermal Climate Index[8]. This takes account not only of temperature but also of humidity, wind, radiation (both solar, if any, and longwave). The radiation reflected or emitted from surfaces (walls, roads, gardens) is also considered in the index computation. The UTCI has been computed for three types of location: indoors, outdoors in shade and outdoors in direct sunlight.
- The number of hours per day the population spends over a given warm threshold (or under a given cold threshold) of UTCI; this estimates the vulnerability of the population to heat stress, which can then be related to physiological indices (not done here).
- The water needed for watering gardens, parks and greenroofs is also estimated, and related to the runoff of these surfaces. This can give information on the necessity to develop local water storage systems to collect water in winter and irrigate in summer. Roads can also be watered during heat waves (such a strategy is being evaluated experimentally in several cities, for example in Japan and France).

6.4 *Energy consumption indicators*

TEB–BEM is able to compute energy consumption indicators for heating and air-conditioning including:

- The total energy consumption in the city, or aggregated by building type, or by type of building use (residential, office, commercial).

[8] http://www.utci.org.

- The peak power needed. This indicator is important for energy distribution companies, as it helps with the sizing of the energy network and to avoid blackouts.

- The emissions of CO_2 due to residential, office and commercial buildings. The type of energy used, especially for heating, and also how electricity is produced are necessary for this estimate. This information comes from the description of the city and the scenarios. This indicator gives information on the ability to reduce the energy consumption so as to mitigate climate change.

- The variation of energy consumption in winter and summer relative to climate warming and city evolution (in terms of expansion, technology of building and insulation, and behaviour of occupants).

7 CASE OF TOULOUSE IN 2100: SIMULATIONS AND DISCUSSION

The objective in this section is to outline the value of the systemic modelling approach we have developed. Here, we focus on the city of Toulouse using several urban planning scenarios leading to different urban expansions up to 2100 and simple climate warming scenarios: present climate plus 2 °C, 4 °C or 6 °C. We do not present model uncertainty and scenario variability ranges, nor do we provide a full or even partial analysis of strategies for adapting to climate change; this will be done in forthcoming papers. However, the results are instructive and allow some preliminary conclusions to be drawn.

7.1 *Scenarios*

Seven systemic scenarios have been simulated. Each describes a pathway for the overall economy, population statistics and attractiveness of the urban area, urban planning, architecture, technology (building and transport), renovation of old buildings, building use and energy use by occupants. Providing the details of all these scenarios, as well as all the simulations and impacts, is beyond the scope of this general paper on the methodology. In the following, we present some results and discuss their links with the relevant aspects of the scenarios. These results have been structured through a collective interdisciplinary analysis by several researchers (from different fields) and the urban planners involved.

7.2 *Impacts and discussion*

7.2.1 *Impact of an economic crisis on population localization within the city*

The expansion of the city and the evolution of the density of population between today and 2100 are presented in Figure s.8 for two scenarios. Each scenario follows the same urban planning strategy (business as usual, i.e. with no strong constraint on urbanization), but for two contrasting economic and demographic environments. In one case, the city of Toulouse is still growing and attractive whereas, in the second, a crisis around 2040 tends to stop the arrival of new inhabitants. The crisis scenario leads to a less extended city (as expected). However, the crisis also has an impact on the location of the people within the city: people move from the centre towards the suburbs, because of the excessive price of dwellings in the centre compared to their

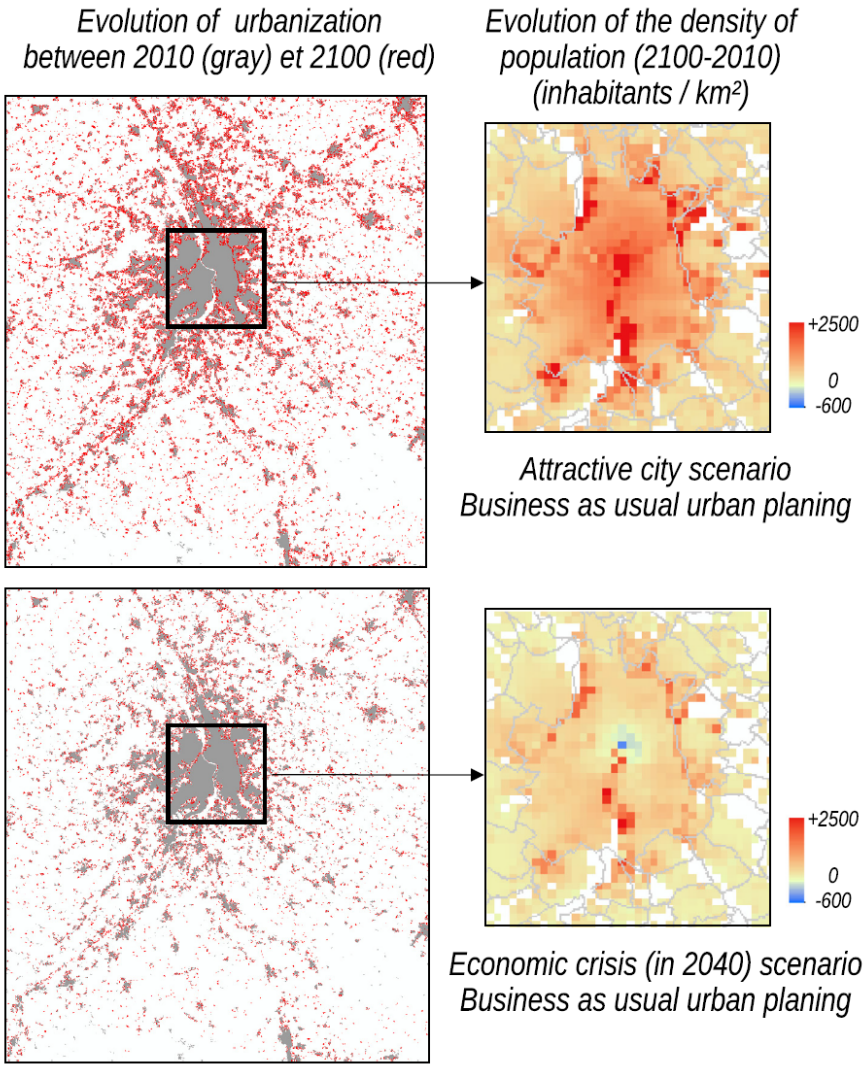


Figure s.8: Possible situation in 2100 of Toulouse urbanization (left) and population density in the city centre (right) following a 'business as usual' urban planning strategy in a scenario of an economically attractive city (top) or a scenario of economic crisis (bottom).

income. Conversely, in the attractive city case, the city centre is one of the most attractive places.

7.2.2 *Impact of an urban planning strategy on city expansion and unexpected effects*

Our systemic modelling approach also simulates the influence of different urban planning strategies. For example, a strategy that is employed to reduce energy consumption (especially from transport) is to promote a compact city (or densify an existing city). One way to achieve this is to implement a 'green belt' around the existing city, where it will not be possible to build so that the city extent becomes constrained.

One such green belt scenario was simulated and compared to the 'business as usual' urban planning scenario for which the city sprawls without many constraints. During the first half of the century, the green belt has the

expected effect; the city becomes more densely occupied and travel times reduce within the city compared to the sprawl case. But what happens after 2050 if the population continues to grow? The cost of housing inside the green belt becomes so high that people prefer to live outside it ('leapfrogging' effect), at the cost of increased travel time. By 2100, for the same population increase, the distance between home and work within the city increases by 122% compared with today for the green belt case, while it increases by 'only' 93% for the sprawled city. The green belt policy, if left unchanged for 100 years, has had a counter-productive effect. This does not mean that a green belt policy should not be implemented now but it does suggest that, if a city continues to be attractive and grow, it should be adapted, and maybe become even more binding, in the future. This would require even more coordination among the planning authorities within the area.

The systemic approach explores the limits of some policies in the very long term, and can shed some light on when they could appear depending on population scenarios.

7.2.3 *Urban forms: the need for anticipation*

Two scenarios with the same population evolution and same policy for overall urban planning were simulated. They differ only in the choice of the type of local urban form (expressed in the LZC class) that was favoured. In one scenario (scenario 2 in Figure s.9) small collective buildings are built from now for intermediate built densities, while in the other (scenario 1) this is the case only after 2040, individual houses still being built until then. Then, in both scenarios, a major crisis occurs in 2040, limiting the population growth. The collective buildings policy proves to be inefficient when taken after 2040, because the renewal of buildings is too slow after the crisis.

7.2.4 *Urban Heat Island*

As is well known, the magnitude of the Urban Heat Island is correlated with the city's population size. This relationship is captured by our simulations; the UHI of the attractive city with 'business as usual' urban planning and technology scenarios increases by up to 1.5 °C on average in summer compared to today's city (950,000 households instead of 550,000 today).

However, other effects seem to modulate this. Renovation of buildings and modification of insulation practices (with insulation on the outside of the wall instead of inside) limits the heat that can be stored in the urban fabric by day. Also, the use of lighter coloured paints for roofs reduces solar energy absorption. Together, these building modifications reduce the UHI by 0.5 °C for Toulouse. The habits of the population also influence the UHI. Measures to decrease the heating target temperature by 2 °C decrease the UHI by a couple of tenths of a degree. The greening of available spaces within the city (for example open spaces, pavements, and car parks) decreases the UHI further, especially in summer, but not necessarily everywhere. As the city centre of Toulouse is already very dense, there is very little room for vegetation and the UHI is not attenuated so much as in the suburbs (almost 1 °C cooler in summer than for a mineral city).

7.2.5 *Energy consumption and climate warming*

Energy consumption simulations are performed by TEB, which interacts with the simulated city scale UHI. Here, we present only those results relative

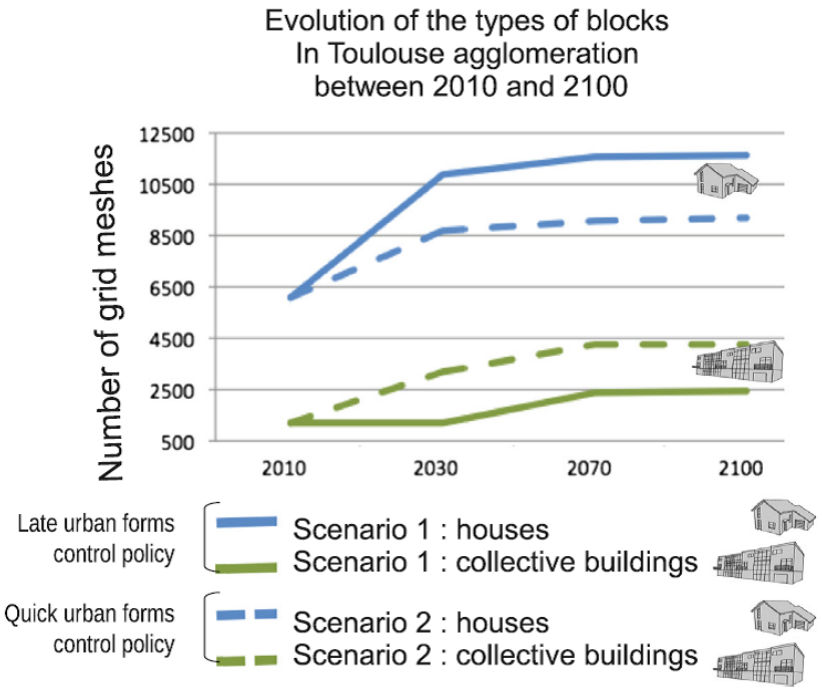


Figure s.9: Possible evolution during the 21st Century of two types of buildings (houses and collective buildings) for scenarios with a rapidly implemented or delayed urban forms control policy.

to the present city case, in order to highlight broad tendencies on a few indicators. The energy values have been normalized by floor area (per square metre) per year for both heating and cooling, to remove the effect of number of inhabitants (or equivalently the total built area of floors) (Figure s.10).

The first important conclusion about energy is that the main levers to decrease the (normalized) energy consumption are renovation of the buildings and, even more, the way of life of the inhabitants in their homes or the way companies use their offices.

The scenario without any renovation does not permit significant energy reduction, as the many efficient buildings built in the future (between now and 2100) will not be able to mask the energy waste in older buildings. When buildings are moderately renovated (1.5% of buildings renovated per year, i.e. the current rate), heating energy use is approximately halved. By contrast, the cooling demand does not change much, as it is primarily driven by incoming solar radiation in homes and offices.

When people adopt more virtuous ways of using their homes (heating to 19 °C instead of 21 °C, cooling to 26 °C instead of 23 °C), then the heating demand is reduced by 30% and the cooling demand is reduced by 66%.

The different urban adaptation strategies and faster renovation rates may not seem to impact the normalized energy consumption significantly (although they modify the UHI). However, this is probably an artefact due to the scenarios chosen, each of which prescribe well insulated buildings and virtuous uses by 2100. Because of this, the buildings are less sensitive to the weather outside (and heating is less necessary). For shorter time horizons (to 2030 or 2050), the urban forms may have more impact as buildings will not all have been renovated. Also, people may never adopt virtuous energy

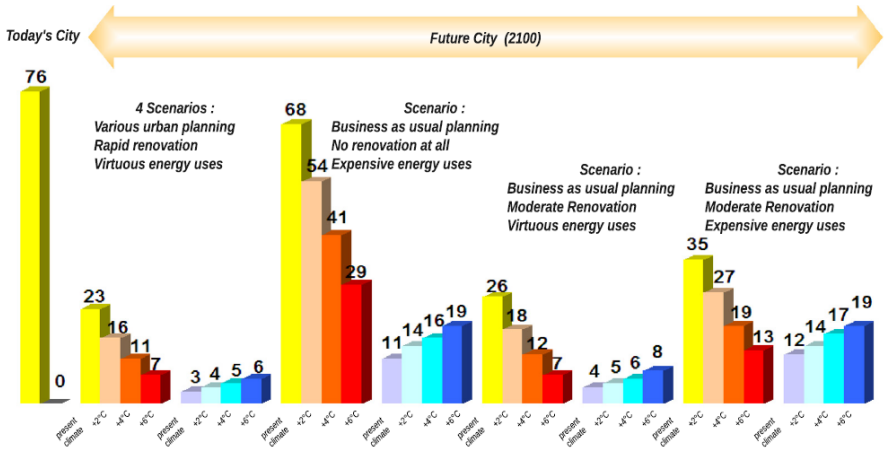


Figure 8.10: Normalized energy consumption (in kWh/m^2 of floor/year) for domestic heating (warm colours) and air-conditioning (cold colours) for present-day urban area of Toulouse (left) and several projections for the evolution of Toulouse depending on different scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

uses in their dwellings. So further work is needed (and ongoing) in order to analyse the impact of urban forms more finely for shorter time horizons.

The second conclusion is that, for a city in a temperate climate like Toulouse, climate warming will lead to an overall decrease the total energy consumption due to buildings. This comes from the more rapid decrease in the need for heating than the increase in need for air conditioning. However, this will have to be discussed in terms of what type of energy is used. While heating can be provided by electricity, fuel oil, gas or wood, air-conditioning needs electricity. So, the peak of electricity distribution may appear in summer instead of winter for even small to moderate climate warming. For some scenarios, even the total amount of energy used may be larger in summer than in winter; this may require a reconfiguration of the electricity production system over the long term.

8 CONCLUSIONS

The complexity of the urban system seems extreme. This leads to difficulties in anticipating the benefits or costs and drawbacks of present and future adaptation strategies to climate warming. However, we have shown here that some of this complexity can be taken into account if an interdisciplinary approach is followed. Furthermore, as the interactions between processes are many and not always intuitive, numerical modelling is well suited to the task.

In this work, we have coupled socio-economic, geographical, architectural, building energetics, urban climate and atmospheric models. The architectural model was specifically developed for this study. Coupling these models not only allows us to provide a better description of the processes that link elements of the urban system, but also permits an interdisciplinary analysis of the impacts for a very broad range of topics (monetary costs, population distribution in the city, architectural forms, energy, micro-climate, anticipation of side effects of adaptation measures, definition of the requirements to ensure adaptation measures achieve the expected performance levels, and so on).

One of the preliminary findings of this paper is that, even for similar impacts (total or instantaneous energy demand) the relative influences of city evolution and climate change varies depending on the specific impact we focus on. Another finding is that it is important to consider the UHI if the energy demand is to be accurately reproduced in cities and to take it into account in the operational estimation of building energy demands.

Our next step will be to evaluate a large number of strategies for adapting to climate change using the systemic modelling approach. This will require the development of mixed backcasting and forecasting scenarios within a prospective approach (Houet et al., 2010; Marchadier, Houet, and Bretagne, 2012) that force or constrain the various models. Different climate change scenarios will also be used. These further studies will allow each adaptation strategy to be assessed in a context of uncertainty (not only climatic but also economic and technological), using numerous indicators and allocating estimations of uncertainties to them. The systemic modelling approach draws advantage from the methodological interactions between the creation of the scenarios and the definition of the coupled modelling platform. As a result, it allows the exploration of a wider diversity of urban futures than exclusive model-driven approaches can.

Moreover, this approach may favour the participation of those most concerned by the results in defining new scenarios according to land system theory (Dearing et al., 2010; Kok, Verburg, and Veldkamp, 2007; Turner, Lambin, and Reenberg, 2007; Van Der Leeuw et al., 2011). For example, it appears that some urban planning strategies, such as green belts, can be efficient and achieve their goals in the short term (the next few decades) but produce counter-intuitive and opposite impacts in the long term if the city continues to grow. So, while such strategies could be implemented now, this underlines the need to prepare others for the future. The decision and urban policy making systems may need to be modified in order to be able to create and set in motion more binding policies if necessary. Anticipation is also necessary, as what will be built in the next decades may still be unchanged by the end of the century.

Changes to energy demand in the future may lead to issues for energy production units that are less efficient in summer, such as nuclear or gas power plants, or wind turbines. However, this issue could be anticipated, using urban forms that can be more efficient at producing renewable energy, for example solar energy. This will also be tested in our scenarios and modelling in forthcoming studies.

Some adaptation measures do impact the urban landscape. The massive installation of solar collectors, the implementation of wind turbines, the modification of the radiative properties of walls, roofs and street surfaces, and the development of green areas change people's perception of the city. The acceptability of such modifications by citizens and by tourists has to be addressed. This is one of the elements to be taken into account by decision makers, together with economic, technical and maintenance considerations. A measure that would be efficient from a technical point of view but that would decrease the attractiveness of a city could be counterproductive for the local economy. A measure with lower effectiveness but that would enhance attractiveness could be positively assessed.

Changes in human behaviour seem to be a very potent lever for adaptation in cities. In addition to the elements presented above, the way people behave in terms of energy use, and of their dwelling or office in general, may strongly modify the energy consumption in the city. People may set different, more

virtuous, target temperatures for heating and air-conditioning. They may even use features of their house to avoid or limit the need for air-conditioning. However, these types of behaviour will probably differ according to age or socio-economic status. Building renovation is also a key trigger, and often depends of the will of the occupants to carry out adequate work in their house or apartment.

Future work will also have to focus on such questions. Dealing with these questions reinforces the need for the interdisciplinary approach we advocate here.

REFERENCES

Aguejdad, Rahim, J. Hidalgo, O. Doukari, Valéry Masson, and Thomas Houet (2012). "Assessing the influence of long-term urban growth and climate change scenarios on urban climate." In: Leipzig, Germany.

Balaras, Constantinos A., Gershon Grossman, Hans-Martin Henning, Carlos A. Infante Ferreira, Erich Podesser, Lei Wang, and Edo Wiemken (2007). "Solar air conditioning in Europe—an overview." In: *Renewable and Sustainable Energy Reviews* 11.2, pp. 299–314. ISSN: 13640321. DOI: 10.1016/j.rser.2005.02.003.

Bell, Michelle L., Richard Goldberg, Christian Hogrefe, Patrick L. Kinney, Kim Knowlton, Barry Lynn, Joyce Rosenthal, Cynthia Rosenzweig, and Jonathan A. Patz (2007). "Climate change, ambient ozone, and health in 50 US cities." In: *Climatic Change* 82.1-2, pp. 61–76. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-006-9166-7.

Billen, G., S. Barles, P. Chatzimpiros, and J. Garnier (2012). "Grain, meat and vegetables to feed Paris: where did and do they come from? Localising Paris food supply areas from the eighteenth to the twenty-first century." In: *Regional Environmental Change* 12.2, pp. 325–335. ISSN: 1436-3798, 1436-378X. DOI: 10.1007/s10113-011-0244-7.

Bjerke, Tore, Torbjørn Østdahl, Christer Thrane, and Einar Strumse (2006). "Vegetation density of urban parks and perceived appropriateness for recreation." In: *Urban Forestry & Urban Greening* 5.1, pp. 35–44. ISSN: 16188667. DOI: 10.1016/j.ufug.2006.01.006.

Brasington, David M. and Diane Hite (2005). "Demand for environmental quality: a spatial hedonic analysis." In: *Regional Science and Urban Economics* 35.1, pp. 57–82. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2003.09.001.

Bueno, Bruno, Julia Hidalgo, Grégoire Pigeon, Leslie Norford, and Valéry Masson (2013). "Calculation of Air Temperatures above the Urban Canopy Layer from Measurements at a Rural Operational Weather Station." In: *Journal of Applied Meteorology and Climatology* 52.2, pp. 472–483. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/JAMC-D-12-083.1.

Bueno, Bruno, Leslie Norford, Grégoire Pigeon, and Rex Britter (2012). "A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate." In: *Building and Environment* 54, pp. 116–125. ISSN: 03601323. DOI: 10.1016/j.buildenv.2012.01.023.

Bueno, Bruno, Grégoire Pigeon, Leslie Norford, Karim Zibouche, and Colette Marchadier (2012). "Development and evaluation of a building energy model integrated in the TEB scheme." In: *Geoscientific Model Development* 5.2, pp. 433–448. ISSN: 1991-9603. DOI: 10.5194/gmd-5-433-2012.

Chrysoulakis, Nektarios et al. (2013). "Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project." In: *Landscape and Urban Planning* 112, pp. 100–117. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2012.12.005.

Clarke, Keith C. (2008). "A decade of cellular urban modeling with SLEUTH: Unresolved issues and problems Chapter 3." In: *Planning Support Systems for Cities and Regions*. Ed. by RK Brail. Cambridge, MA: Lincoln Institute of Land Policy, pp. 47–60.

Clarke, Keith C. and Leonard J. Gaydos (1998). "Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore." In: *International Journal of Geographical Information Science* 12.7, pp. 699–714. ISSN: 1365-8816, 1362-3087. DOI: 10.1080/136588198241617.

Clarke, Keith C., S. Hoppen, and Leonard J. Gaydos (1997). "A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area." In: *Environment and Planning B: Planning and Design* 24.2, pp. 247–261. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b240247.

De la Barra, Tomas (2005). *Integrated land use and transport modelling. Decision chains and hierarchies*. Cambridge University Press. ISBN: 0-521-24318-1.

De Munck, Cécile, Grégoire Pigeon, Valéry Masson, Francis Meunier, Pierre Bousquet, Brice Tréméac, Michèle Merchat, Pierre Poeuf, and Colette Marchadier (2013). "How much can air conditioning increase air temperatures for a city like Paris, France?" In: *International Journal of Climatology* 33.1, pp. 210–227. ISSN: 08998418. DOI: 10.1002/joc.3415.

De Roo, Ad, Jose Barredo, Carlo Lavalle, Katalin Bodis, and Rado Bonk (2007). "Potential Flood Hazard and Risk Mapping at Pan-European Scale." In: *Digital Terrain Modelling*. Ed. by William Cartwright, Georg Gartner, Liqiu Meng, Michael P. Peterson, Robert Joseph Peckham, and Gyozo Jordan. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 183–202. ISBN: 978-3-540-36730-7 978-3-540-36731-4. DOI: 10.1007/978-3-540-36731-4_8.

Dearing, John, Ademola Braimoh, Anette Reenberg, Billie Turner, and Sander Van der Leeuw (2010). "Complex land systems: the need for long time perspectives to assess their future." In: *Ecology and Society* 15.4.

Dessai, Suraje (2003). "Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change." In: *International Journal of Biometeorology* 48.1, pp. 37–44. ISSN: 0020-7128, 1432-1254. DOI: 10.1007/s00484-003-0180-4.

Doukari, O., Rahim Aguejdad, and Thomas Houet (2013). "SLEUTH*: a scenario-based version of SLEUTH for simulating breaking trends urban sprawl futures." In: *Comput. Environ. Urban Syst.(submitted)*.

Gabriel, Katharina M.A. and Wilfried R. Endlicher (2011). "Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany." In: *Environmental Pollution* 159.8-9, pp. 2044–2050. ISSN: 02697491. DOI: 10.1016/j.envpol.2011.01.016.

Godet, Michel (1986). "Introduction to la prospective." In: *Futures* 18.2, pp. 134–157. ISSN: 00163287. DOI: 10.1016/0016-3287(86)90094-7.

Grazi, Fabio and Jeroen C.J.M. van den Bergh (2008). "Spatial organization, transport, and climate change: Comparing instruments of spatial planning and policy." In: *Ecological Economics* 67.4, pp. 630–639. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2008.01.014.

Grazi, Fabio, Jeroen C.J.M. van den Bergh, and Jos N. van Ommeren (2008). "An Empirical Analysis of Urban Form, Transport, and Global Warming." In: *The Energy Journal* 29.4.

Gusdorf, François, Stéphane Hallegatte, and Alain Lahellec (2008). "Time and space matter: How urban transitions create inequality." In: *Global Environmental Change* 18.4, pp. 708–719. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2008.06.005.

Hamilton, Stuart E. and Ash Morgan (2010). "Integrating lidar, GIS and hedonic price modeling to measure amenity values in urban beach residential property markets." In: *Computers, Environment and Urban Systems* 34.2, pp. 133–141. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2009.10.007.

Hidalgo, Julia, Valéry Masson, and Christophe Baehr (2014). "From daily climatic scenarios to hourly atmospheric forcing fields to force Soil-Vegetation-Atmosphere transfer models." In: *Frontiers in Environmental Science* 2. ISSN: 2296-665X. DOI: 10.3389/fenvs.2014.00040.

Houet, Thomas, Thomas R. Loveland, Laurence Hubert-Moy, Cédric Gaucherel, Darrell Napton, Christopher A. Barnes, and Kristi Sayler (2010). "Exploring subtle land use and land cover changes: a framework for future landscape studies." In: *Landscape Ecology* 25.2, pp. 249–266. ISSN: 0921-2973, 1572-9761. DOI: 10.1007/s10980-009-9362-8.

IPCC (2007). *Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

— (2013). *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Johnson, Daniel P. and Jeffrey S. Wilson (2009). "The socio-spatial dynamics of extreme urban heat events: The case of heat-related deaths in Philadelphia." In: *Applied Geography* 29.3, pp. 419–434. ISSN: 01436228. DOI: 10.1016/j.apgeog.2008.11.004.

Knowlton, Kim, Barry Lynn, Richard A. Goldberg, Cynthia Rosenzweig, Christian Hogrefe, Joyce Klein Rosenthal, and Patrick L. Kinney (2007). "Projecting Heat-Related Mortality Impacts Under a Changing Climate in the New York City Region." In: *American Journal of Public Health* 97.11, pp. 2028–2034. ISSN: 0090-0036, 1541-0048. DOI: 10.2105/AJPH.2006.102947.

Kok, Kasper, Peter H. Verburg, and Tom (A.) Veldkamp (2007). "Integrated Assessment of the land system: The future of land use." In: *Land Use Policy* 24.3, pp. 517–520. ISSN: 02648377. DOI: 10.1016/j.landusepol.2006.04.007.

Krayenhoff, E. Scott and James A. Voogt (2010). "Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time Scales: Model Results and Synthesis of Previous Work." In: *Journal of Applied Meteorology and Climatology* 49.8, pp. 1634–1648. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/2010JAMC2356.1.

Kusaka, Hiroyuki, Masayuki Hara, and Yuya Takane (2012). "Urban Climate Projection by the WRF Model at 3-Km Horizontal Grid Increment: Dynamical Downscaling and Predicting Heat Stress in the 2070's August for Tokyo, Osaka, and Nagoya Metropolises." In: *Journal of the Meteorological Society of Japan. Ser. II* 90B.0, pp. 47–63. ISSN: 2186-9057, 0026-1165. DOI: 10.2151/jmsj.2012-B04.

Lac, C., R. P. Donnelly, Valéry Masson, S. Pal, S. Riette, S. Donier, S. Queguiner, G. Tanguy, L. Ammoura, and I. Xueref-Remy (2013). "CO2 dispersion modelling over Paris region within the CO2-MEGAPARIS

project." In: *Atmospheric Chemistry & Physics* 13.9. ISSN: 1680-7324. DOI: 10.5194/acp-13-4941-2013.

Lemonsu, Aude, Raphaëlle Kounkou-Arnaud, Julien Desplat, Jean-Luc Salagnac, and Valéry Masson (2013). "Evolution of the Parisian urban climate under a global changing climate." In: *Climatic Change* 116.3-4, pp. 679–692. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-012-0521-6.

Lemonsu, Aude, Valéry Masson, L. Shashua-Bar, E. Erell, and D. Pearlmutter (2012). "Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas." In: *Geoscientific Model Development* 5.6, pp. 1377–1393. ISSN: 1991-9603. DOI: 10.5194/gmd-5-1377-2012.

Marchadier, C., Thomas Houet, and G. Bretagne (2012). "How to define and assess city adaptation strategies." In: *8th International Conference on Urban Climate, Dublin*. Vol. 2012.

Masson, Valéry (2000). "A Physically-Based Scheme For The Urban Energy Budget In Atmospheric Models." In: *Boundary-Layer Meteorology* 94.3, pp. 357–397. ISSN: 0006-8314, 1573-1472. DOI: 10.1023/A:1002463829265.

Masson, Valéry, Y. Lion, A. Peter, G. Pigeon, J. Buyck, and E. Brun (2013). ""Grand Paris": regional landscape change to adapt city to climate warming." In: *Climatic Change* 117.4, pp. 769–782. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-012-0579-1.

Noilhan, J. and S. Planton (1989). "A simple parameterization of land surface processes for meteorological models." In: *Monthly weather review* 117.3, pp. 536–549.

Oke, T. R. (2008). "Urban observations. Guide to meteorological instruments and methods of observation, Part II of Observing Systems, WMO-No. 8." In: *World Meteorological Organization, II-11-1–II-11-25*.

Pigeon, Grégoire, Karim Zibouche, Bruno Bueno, J Le Bras, and Valéry Masson (2014). "Evaluation of building energy simulations with the TEB model against EnergyPlus for a set of representative buildings in Paris." In: *Build. Environ* 76, pp. 1–14.

Rosenzweig, Cynthia, David C. Major, Kate Demong, Christina Stanton, Radley Horton, and Melissa Stults (2007). "Managing climate change risks in New York City's water system: assessment and adaptation planning." In: *Mitigation and Adaptation Strategies for Global Change* 12.8, pp. 1391–1409. ISSN: 1381-2386, 1573-1596. DOI: 10.1007/s11027-006-9070-5.

Rosenzweig, Cynthia et al. (2011). "Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies." In: *Climatic Change* 106.1, pp. 93–127. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-010-0002-8.

Seow, K. L., M. Doya, Xavier Briottet, R. Ceolato, N. Riviere, and S. K. Pang (2012). "Spectral BRDF of common urban materials." In: *2012 4th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)*. IEEE, pp. 1–4. ISBN: 1-4799-3406-2.

Solomon, Susan (2007). "The physical science basis: Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change." In: *Intergovernmental Panel on Climate Change (IPCC), Climate change 2007* 996.

Stewart, I. D. and T. R. Oke (2012). "Local Climate Zones for Urban Temperature Studies." In: *Bulletin of the American Meteorological Society* 93.12, pp. 1879–1900. ISSN: 0003-0007, 1520-0477. DOI: 10.1175/BAMS-D-11-00019.1.

Tremeac, Brice, Pierre Bousquet, Cecile de Munck, Grégoire Pigeon, Valéry Masson, Colette Marchadier, Michele Merchat, Pierre Poeuf, and Francis Meunier (2012). "Influence of air conditioning management on heat island in Paris air street temperatures." In: *Applied Energy* 95, pp. 102–110. ISSN: 03062619. DOI: 10.1016/j.apenergy.2012.02.015.

Trusilova, Kristina, Barbara Früh, Susanne Brienen, Andreas Walter, Valéry Masson, Grégoire Pigeon, and Paul Becker (2013). "Implementation of an Urban Parameterization Scheme into the Regional Climate Model COSMO-CLM." In: *Journal of Applied Meteorology and Climatology* 52.10, pp. 2296–2311. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/JAMC-D-12-0209.1.

Turner, B. L., E. F. Lambin, and A. Reenberg (2007). "The emergence of land change science for global environmental change and sustainability." In: *Proceedings of the National Academy of Sciences* 104.52, pp. 20666–20671. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.0704119104.

Van Der Leeuw, Sander et al. (2011). "Toward an Integrated History to Guide the Future." In: *Ecology and Society* 16.4, art2. ISSN: 1708-3087. DOI: 10.5751/ES-04341-160402.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

3

WHEN TAXING CONSTRUCTION LEADS TO MORE CONSTRUCTION: MODELLING THE IMPACT OF A LAND VALUE TAX ON LOW DENSITY[1]

> *« C'est sous son propre poids que l'empire va s'écraser », pense Kublai et dans ses rêves maintenant apparaissent des villes légères comme des cerfs-volants, des villes ajourées comme des dentelles, des villes transparentes comme des moustiquaires, des villes nervures de feuilles, des villes lignes de la main, des villes filigranes à voir au travers d'une épaisseur opaque et leurrante. »*
>
> Calvino, Italo. 2013. *Les Villes Invisibles*. Gallimard.

3.1 INTRODUCTION

In the United States, developed areas grew at an annual rate of 2.5% between 1976 and 1992, reaching a total increase of 48% (Burchfield et al., 2006). In Europe the diagnosis is similar albeit less extreme in more recent times as during the 1990-2000 decade, urban areas have increased by more than 8 000km^2 (+5.4%) which corresponds to the entire land area of Luxemburg (EEA, 2006). Since the mid-1950s urban areas in Europe have increased by 78% whilst population has only increased by 33%. This disconnection between the increase in population and built-up areas translates into falling urban densities and urban sprawl.

The main causes of urban sprawl[2] are well documented. Wheaton (1974), Brueckner (2001) and other scholars identified demographic growth, increase in incomes, and fall in commuting costs as factors influencing urban expansion of cities in the standard monocentric framework. Other factors, such as the desire to "live in the woods" and benefits from green sceneries, can also play a role but are more difficult to measure and will vary with individuals preferences.

Urban sprawl entails or is suspected of entailing a number of negative consequences (Transportation Research Board - NRC, 2002) such as impacts on landscapes, on ecosystems and biodiversity, local noise and pollution because of increased car use, greenhouse gas emissions and higher costs of providing infrastructure services in more dispersed settlements (especially gas, water, sanitation, electricity).

While some degree of urban expansion appears to be a rational and efficient response to changed socio-economic conditions, the question that needs to be answered is: Is it excessive[3]? It will be considered excessive if

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[2] We use the terms urban sprawl or urban expansion indiscriminately although the case has been made that sprawl carries a pejorative connotation (Brueckner and Kim, 2003).

[3] Brueckner (2001) defines sprawl this way: "spatial growth of cities that is excessive relative to what is socially desirable".

the costs, listed above, it imposes on the rest of society are not accounted for through market mechanisms. This gives rise to negative externalities, which public intervention should seek to correct. A number of potential market failures have been identified in the literature: failure to account for the social costs of congestion, failure to account for the social value of open space and failure to account for the costs of infrastructure provision (Brueckner, 2001; Nechyba and Walsh, 2004). In the presence of negative externalities, the consumption of land for urban residential purposes will be excessive. Whereas the existence of these market failures is debated (Glaeser and Kahn, 2004), its possibility has motivated scholars to look into policy options to correct them. Among these, Bento, Franco, and Kaffine (2006) noticeably investigated the relative efficiency of development taxes, urban growth boundaries, property taxes and gasoline taxes to limit the spatial footprint of cities.

We wish to pursue in this direction by investigating yet a different device. We wish to assess the impact of land value taxes whose rate depends on local housing construction (or improvement) density. This tool exists in French law since 2012 and is termed Payment for Insufficient Density (PID). It allows for land value taxation upon land development when new constructions do not reach a certain housing density threshold. This policy option which aims to limit urban sprawl seems an interesting avenue for investigation but is to the best of our knowledge undocumented.

The purpose of this paper is to assess the implications of a PID for the main determinants of the urban form. We pursue this goal through a case study on the urban area of Paris using a dynamic numerical land use model – NEDUM-2D – which reproduces the mechanisms of urban economic theory. Whilst conducting this study we essentially tried to answer three questions that are interesting both from theoretical and policy guidance perspectives.

The first question that calls for an answer is: "is the PID device effective in limiting urban sprawl"? The policy's objective is to reduce urban land consumption, so it is crucial to understand if it can contribute to this goal and by how much. Secondly, the spatial extent of a city is only one among its many features so the second question is to what extent the PID will influence other major city characteristics. In particular, France is currently characterized by localised housing crises in some of its most dynamic regions (including the urban area of Paris). In these areas, a number of factors contribute to a limited and expensive housing production which results in low residential mobility and high housing effort rates for households. In this context, introducing a new land value tax has been questioned, with fears that it will have a detrimental impact on housing affordability, another important policy objective for local officials. Finally, the third question is related to the fact that, beyond urban sprawl and housing affordability, local decision-makers have multiple objectives that interact closely, such as local economic development and quality of life. All policies must therefore be evaluated along multiple indicators corresponding to these multiple goals. In urban environments where policies have strong interactions, the classical approach of introducing one instrument for each policy objectives is likely to reveal suboptimal. These questions structure this article.

We first present the main results from the literature on the links between urban sprawl and both property and land taxation. We then describe in some details the Payment for Insufficient Density device and show why it is a very specific land value taxation scheme. In section 3.4 we briefly present the method and the model we use to evaluate the PID's impacts on the Paris

region. In section 3.5, we review qualitatively the main mechanisms and effects that can be expected from the Payment for Insufficient Density, using a stylized (axi-symmetric) city. In sections 3.6 and 3.7 we show modelling results using a realistic transport network. We use these results to debate in particular the effectiveness of the PID in limiting urban sprawl and to shed light on its effects on rents and construction. Finally, we discuss how the PID should be implemented, as a function of various policy objectives. Section 3.8 provides orders of magnitude of the revenues that the PID could generate, section 3.9 presents and discusses feedbacks from communes that implemented the PID and finally section 3.10 concludes.

We derive three important messages from our analysis. First, this land value tax conditional on housing density can be effective in limiting urban sprawl. Second, tackling urban sprawl is not necessarily detrimental in terms of housing affordability. We show here that the PID lowers housing costs and improves households' utility. Third, depending on the pursued policy objective, the PID needs to be implemented in different manners in order to gain maximum efficiency.

3.2 LITERATURE REVIEW: IMPACTS OF PROPERTY AND LAND VALUE TAXES ON URBAN SPRAWL

A number of exercises have been conducted to specifically assess the link between land value or property taxes and urban sprawl. A property tax which taxes at equal rates both improvements and land has two effects. By decreasing the return on investment of improvements it discourages high density buildings and thus lowers population densities implying a tendency towards an increase in urban sprawl. But there exists a countervailing effect from property taxation. Property taxes are partly shifted towards consumers leading to higher housing prices and lower dwelling sizes a consequence of which is higher population densities. The improvement intensity and the dwelling size effect have opposite impacts and the consequence of a property tax on the spatial extent of cities is a priori ambiguous. Brueckner and Kim (2003) show that for CES utility functions which display an elasticity of substitution between housing services and a composite good that is equal or higher than one, then the dwelling size effect dominates, entailing a reduction in city size subsequent to the introduction of a property tax. This result has been confirmed both theoretically for log-linear utility functions (still with an elasticity of substitution superior to one) and empirically for more than 440 urbanized areas in the US (Song and Zenou, 2006).

While these results linking the property tax to the size of cities have been derived in a static framework, the temporal aspect is key in assessing the impact of land value taxes on urban sprawl. In a static setting where land supply is essentially fixed, a land value tax is neutral with respect to city size[4]. Although it reduces landowners' profit, it carries no incentive to modify the capital/land ratio and as a consequence does not affect the urban equilibrium that would emerge in the absence of the tax (Oates and Schwab, 1997). In a dynamic setting however, the neutrality of land taxes is less clear. In fact it depends crucially upon the definition of land value. Two definitions have been used which have different implications for the neutrality of land

[4] This result is true in the standard mono-centric urban economic framework with absentee landowners. If this latter hypothesis is relaxed, the decrease in aggregate rents redistributed to the urban population will depress the demand for housing services and will lead to spatial shrinkage of cities.

taxes: "residual site value" and "raw site value" (Arnott, 2005). "Residual site value" is defined as property value minus the depreciated construction costs. It is equivalent to the current site value given that it is already committed to a determined use. "Raw site value" is the value of a site independently of what is currently built upon it. As such it is the value of land assessed on the basis of its "highest and best possible use" (Oates and Schwab, 1997). When competing projects requiring land have different income generating time profiles, the introduction of a tax on "residual site value" will distort land use favouring the project that has the earliest payoff income streams (Bentick, 1979; Mills, 1981). This may discourage building projects that require large capital amounts and display longer payoffs. As such it would tend to favour lower density, sprawled out cities. Tideman (1982) has opposed this view on the basis that land value cannot be defined as depending on what is actually built upon the lot of land. Conversely he defines land value as "the highest present value of streams of return that begin with bare land today". In this case, as the amount of the tax is independent of how the site is used, the land value tax is neutral (Tideman, 1982; Wildasin, 1982) and urban form is unaffected.

This short literature review has provided insights into the influence of property and land value taxes on urban form. However all of these exercises have looked into the consequences of homogeneous tax rates. To the best of our knowledge only one paper has investigated the impact of differences in property taxes within cities on urban sprawl (Song and Zenou, 2009). The paper by Song and Zenou presents a model of a duo-centric city with lower property taxes in the suburb business district than in the city centre. Although the theoretical model has no clear prediction of the consequences on the spatial extent of the city, an empirical test concludes that heterogeneous property taxes may increase urban sprawl.

In the next section we will describe the PID, a land value taxation device which varies in rate depending on construction decisions, and which has never been studied before in the literature, to the authors' knowledge.

3.3 INTRODUCING THE PAYMENT FOR INSUFFICIENT DENSITY (PID)

Since mid-2012, French law allows communes[5] and communities of communes to tax any building permit holder whose real estate project does not reach the Minimum Density Threshold (MDT) decided in the local urbanism plan (PLU in French). This device, called Payment for Insufficient Density (PID)[6] was adopted on the 30th of January 2011. The aim is to limit urban sprawl by increasing the construction costs of buildings that do not reach a sufficient density. This policy is not compulsory: mayors have the choice to implement it or not. In the rest of this paper, to analyze the potential effects of such a policy we will however consider that the PID is mandatory, and uniformly implemented.

In the areas where a MDT has been defined, new construction permit holders (private individuals, real estate or building companies) have to pay a PID when the construction density of their real estate project is below the MDT. The tax is calculated according to the following formula:

$$\text{PID} = \frac{\text{land value}}{2} \times \frac{S_{\text{MDT}} - S}{S_{\text{MDT}}} \tag{3.1}$$

[5] French administrative level roughly equivalent to a town; a mayor is elected in each "commune".
[6] The French term is Versement pour Sous-Densité (VSD)

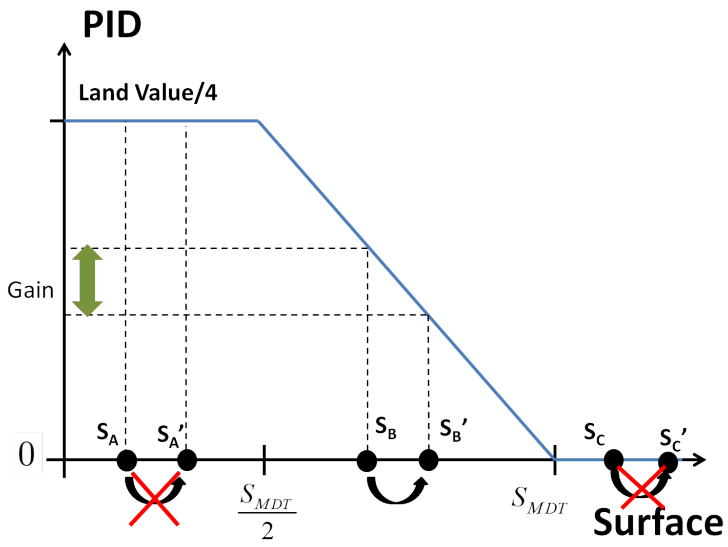

Figure 3.1: The impact of a PID on the built floor areas.

Where S_{MDT} represents the built floor space area which would correspond to a construction density of MDT, and where S is the actual built floor space area. A limit is however set by law: the PID cannot exceed 25% of the land value. The resolution of a simple equation shows that such a situation occurs when the built floor area is equal to half S_{MDT}. We can thus rewrite the formula presented above as:

$$PID = \begin{cases} \frac{\text{land value}}{2} \times \frac{S_{\text{MDT}} - S}{S_{\text{MDT}}} & \text{if } \frac{S_{\text{MDT}}}{2} < S < S_{\text{MDT}} \\ \frac{\text{land value}}{4} & \text{if } S \leq \frac{S_{\text{MDT}}}{2} \end{cases} \tag{3.2}$$

A tangible example will illustrate the functioning of the PID better, so let us imagine a landowner who possesses 700m^2 of land estimated at 150 000€. Let us also imagine that the local planning documents establish that the plot of land is situated in an area where the MDT is 0.5. In this case, the floor space area that should be built in order to comply with the minimum density criteria (S_{MDT}) and thus to avoid paying any PID is 700m^2 $\times$ 0.5 = 350m^2.

Let us suppose that two developers (A and B) are interested in buying this plot of land in order to build housing. The first developer wishes to build a house with a floor space S_A of 135m^2 and the second developer a surface S_B of 210m^2. The Payments for Insufficient Density associated to these two projects are 150 000/4 = 37 500€ for promoter A (because 135m^2 $<$ 175m^2 = $S_{\text{MDT}}/2$) and (150 000/2) $\times$ (1 $-$ 210m^2/350m^2) = 30 000€ for promoter B.

Now let us suppose that the developers wish to marginally modify their projects in order to decrease the amount of PID they have to settle.

For developer A, if he adds 20m^2 to the initial project (graphically he moves from S_A to S'_A), thus building 155m^2 instead of 135m^2, he will still have to pay the same amount of PID (150 000/4 = 37 500€). Indeed, the resulting housing surface is still lower than $S_{\text{MDT}}/2$ = 175m^2 and the tax amount remains equal to its possible maximum value. A marginal change in the building project is not sufficient to lower the amount of PID. In order to do so, he would have to change his plans more substantially by adding at least 40m^2 (= 175m^2 $-$ 135m^2). For developer B however, adding 20m^2 of housing surface to the initial project (moving from S_B = 210m^2 to S$'_B$ = 230m^2),

would lower the PID to $(150\,000€/2) \times (1 - 230m^2/350m^2) = 25\,714€$ which represents 4 286€ in savings.

It is now easy to understand that the PID will only increase built surfaces in areas where the initial projects are not too far from the floor area which would result from the PID cap, as illustrated on Figure 3.1. Indeed, when the projects are too far from that level, then the supplementary construction costs will outweigh the decrease in PID that such an operation will entail. It would then be rational to pay the maximum PID, without building more. In the opposite case, however, it is possible that the increase in construction costs will be more than compensated by a lower PID. Finally, developer C who had planned to build a housing surface S_C larger than S_{MDT} has no incentive to modify his project.

3.4 MODELLING THE IMPACTS OF THE PAYMENT FOR INSUFFICIENT DENSITY

A theoretical framework that reflects the interplay between households' locational decisions, project developers' construction decisions and real estate prices is required to evaluate the impacts of PID on an urban area. The NEDUM-2D model (Non Equilibrium Dynamic Urban Model) developed in CIRED (Viguié and Hallegatte, 2012) is well suited to conduct such a study. It is comprehensively described in Chapter 1, including its assumptions, and we refer the reader to that chapter for modelling details. Although a very simple description of the analytical framework used to express these mechanisms can be found in the Appendix in section 3.11.1. Below we will only highlight the specific choices made for this study and make some important clarifications.

In this model version, landowners are assumed to live outside the city, which means that land rents are not recycled into the local economy as income.

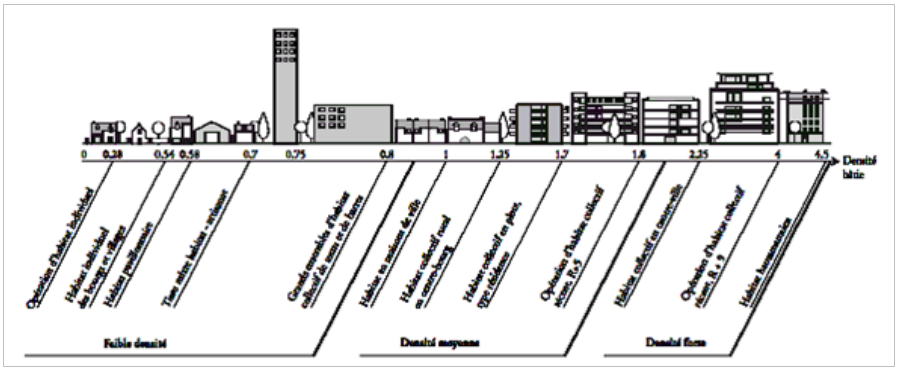

Figure 3.2: Housing density and urban forms in France, according to the Institut d'Aménagement et d'Urbanisme de la Région Île-de-France (Moulinié and Naudin-Adam, 2005). The figures indicate the floor-area ratios that are typically associated to different building types.

Although it does not concern an assumption 'per se', an important clarification needs to be introduced at this point. The model exclusively studies residential behaviour and as a consequence does not provide any information on buildings for other purposes such as leisure (museums, cinemas), shopping or working (offices). This simplification introduces a discrepancy between the Floor Area ratios (FAR) that are simulated by the model and the ones that are observed in practice. This discrepancy

is reinforced because the FARs that are produced by NEDUM-2D do not account for residential building space used for corridors and lobbies or even courtyards. By way of comparison, in the centre of Paris, typical "Haussmanian" buildings usually have 6 floors which corresponds to a FAR of approximately 4 (because 75% of ground area is used[7]). However, when we only account for living space, the maximum "living space FAR" measured as (maximum population density)x(dwelling sizes)/(urbanizable land) is 1.5. NEDUM-2D typically produces what we called above "living space FAR". Figure 3.2 shows how different urban forms and building types lead to different densities. In this figure and in line with the discussion above, the housing densities that are used in Figure 3.2 are not directly comparable to the FARs or housing densities produced by NEDUM-2D. According to our calibration these housing densities are higher than ours by approximately a factor 2 (see Appendix in section 3.11.3). In the context of this paper where we look into the PID's ability to favour denser, less sprawled cities, the choice of the MDT will have an impact on landscapes and urban lifestyles. A MDT of 0.5 in NEDUM-2D, for example, would correspond to a real housing density of 1, and would favour the construction type on the right-hand side of the unit density in Figure 3.2. It would therefore encourage the construction of multi-family buildings with two or more floors.

We will use housing densities values such as produced by NEDUM-2D throughout this paper. The reader should be aware that to relate to FARs such as they are used in urbanism documents a simple multiplication by approximately 2 needs to be applied.

3.5 THE PAYMENT FOR INSUFFICIENT DENSITY IN AN IDEALISED CITY

In the absence of any housing or land value taxation, real estate developers seek to maximize the following profit function which corresponds to the value of land per m^2 derived from housing:

$$\pi = RH - (\rho + \delta) K \tag{3.3}$$

Where R is the rent per m^2 of housing space, H is the amount of built housing space per m^2 of land (or building height), K is the amount of invested capital per m^2 of land. We assume absentee landowners, so that the land rent is not recycled in the local economy. The parameter ρ represents the rate of capital depreciation and δ the interest rate or capital cost.

The introduction of the PID in the model consists in modifying equation (3.3) as follows:

$$\pi = [\mathrm{RH} - (\rho + \delta) K] \begin{cases} \times 1 & \text{if } H \geq H_{\min} \\ \left(1 - \frac{(H_{\min} - H)}{2H_{\min}}\right) & \text{if } H_p \leq H < H_{\min} \\ \times 0.75 & \text{if } H < H_p \end{cases} \tag{3.4}$$

Where $H_{\min}$ is the built housing surface per m^2 (housing density) of land corresponding to the MDT and H_p is the built housing density that corresponds to the cap of PID (i.e. 25% of the land's value). It is possible to determine H_p.

[7] http://www.iau-idf.fr/fileadmin/Etudes/etude_213/nr_384_Apprehender_la_densite_3.pdf

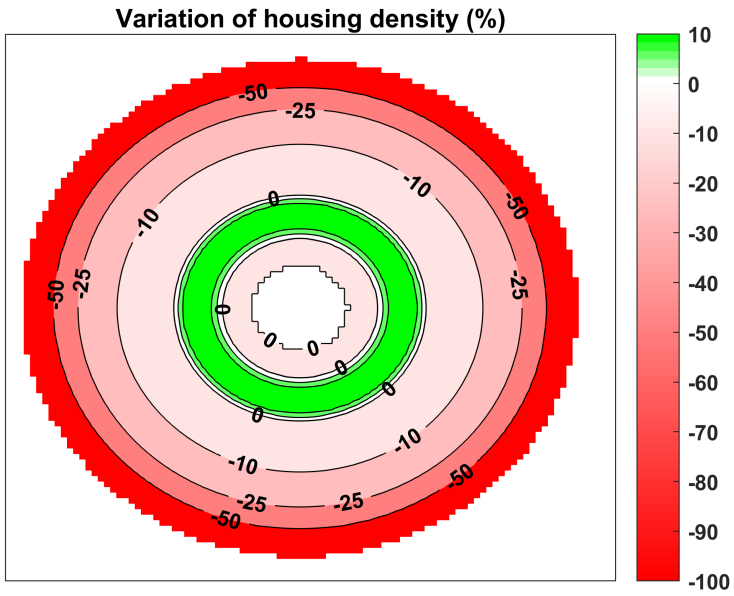

Figure 3.3: Variation of the housing density caused by the introduction of PID with respect to a situation with no PID in a circular schematic city. In the red and pink zones, constructions decrease with respect to the reference case, whereas they increase in the green area.

$$\begin{aligned} 0,25 \times \pi &= \pi \frac{H_{\min} - H_p}{2H_{\min}} \\ \Leftrightarrow H_p &= 0,5 H_{\min} \end{aligned} \tag{3.5}$$

The housing density that corresponds to the cap of the PID is H_p half the housing density that avoids paying any PID.

Before presenting the detailed results on the Paris region, it is useful to show what would result from the implementation of a PID on a schematic city where transport costs are a linear function of the distance to the centre (Figure 3.3). We also assume that there is a height limit in the middle of the city, which reproduces building height regulations in downtown Paris.

In Figure 3.3 we compare the housing density in a scenario where a uniform PID has been introduced a few years beforehand, and the housing density in the same scenario (same demographic evolution, same transport policies, etc...) without PID.

Four concentric rings appear (Figure 3.3 and Figure 3.4). Moving from the outskirt to the centre we find:

- A peripheral ring, in which we observe a decrease in construction. This ring corresponds to areas where the 25% cap on PID applies. In this ring, the PID is a tax on construction that is proportional to land value, independently of the housing density.

- An intermediate ring (appearing on Figure 3.3 in green), closer to the city centre. This zone corresponds to the areas where the introduction of the PID has encouraged project developers to build more. This is a zone where housing density is lower than the MDT but still higher than the threshold corresponding to the 25% cap.

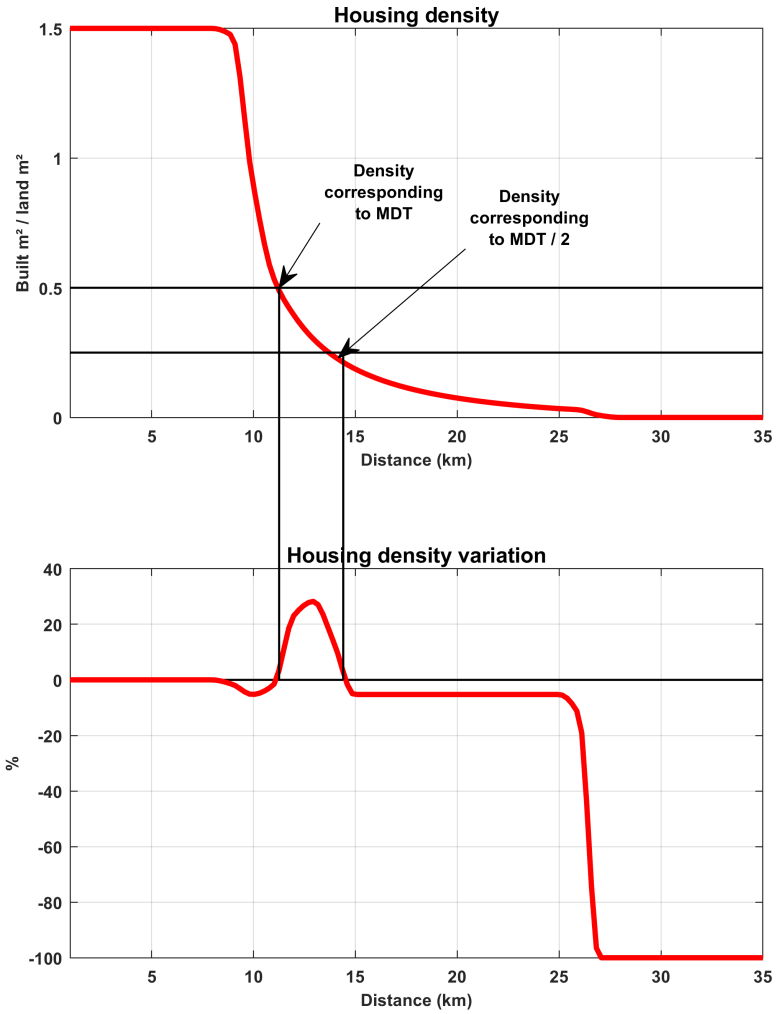

Figure 3.4: Cross section view of the previous map.

- A central zone outside downtown Paris, where density has only slightly decreased (light pink colour), which corresponds to areas where housing density is above the Minimum Density Threshold in the reference scenario and therefore where no PID is settled anyway.
- An area in central Paris (in white) where constructions are constrained by urbanism rules (height limit) and density remains unchanged. In this location, the constraint on the number of floors is the only factor driving density. The marginal incentives created by the PID have no impact.

The second ring in green in Figure 3.3 corresponds to zones where the PID has had its expected impact: by taxing low density constructions, it has encouraged developers to build denser than in the reference scenario. The red ring and the central zone (beyond downtown Paris) are zones where, either because of the cap on the PID or because density is above MDT, the PID does not encourage developers to build more. Equations (3.4) and (3.5)

explain why the 25% cap leads to the suppression of incentives to build more in the peripheral ring.

It can appear surprising at first that housing density decreases in these two zones. The explanation is as follows. The total population is the same in the scenario with PID as in the reference case; the total need for accommodation is thus equally identical. In the green ring the PID encourages construction, i.e. housing supply is larger in this ring. This increase in aggregate housing supply leads to a decrease in aggregate rent and an increase in average dwelling sizes. Outside the second ring, the PID does not create an incentive to build more housing, and the subsequent decrease in aggregate rent reduces the incentive to build there. And this in turns leads to a decrease in built-area density. The increase in dwelling size leads to further population density decrease.

In the ring in downtown Paris that appears unchanged (white), construction is constrained by density limits, and housing supply is lower than demand. There is no decrease of construction in this zone because, even if housing demand decreases slightly, as in the two red and pink rings, housing supply remains lower than demand and constrained by the height limit.

To summarize, there is a redeployment of population and constructions throughout the city towards certain zones where housing density has increased. This redeployment is most visible in lower density areas. Zones where the housing density increases depend on the MDT and correspond to areas where the initial density (before construction) is close to the Minimum Density Threshold.

3.6 THE IMPACTS OF THE PAYMENT FOR INSUFFICIENT DENSITY ON THE PARIS URBAN AREA

In order to study the impacts of the introduction of a PID on the Paris area, we conduct a prospective study between 2015 and 2040. Doing so requires "boundary conditions" regarding socio-economic trends, for instance for population, GDP, and oil and gasoline prices. We selected a scenario for the global economy produced by IMACLIM-R (Rozenberg et al., 2010; Waisman et al., 2012) that extends the trends observed over the last twenty years to supply NEDUM-2D with the inputs that are necessary (income, population and transport prices). The coupling of global variables with an agglomeration-scale model is explained in more details in Viguié, Hallegatte, and Rozenberg (2014).[8]

The use of a scenario is indispensable to conduct this prospective study. However, the actual choice of the scenario is not of the uppermost importance. Indeed, the objective of this paper is to compare a baseline scenario to a scenario in which a PID is implemented, keeping all other inputs unchanged. The absolute values of the different variables have less importance in this exercise.

In the simulations with PID, we introduce the tax in 2015. For reasons of clarity and simplicity, we chose to implement a uniform and compulsory MDT throughout the urban area: we suppose that for any new construction, paying the tax is required if the density of the new building is under the MDT. We do so also because a PID implementation to limit urban sprawl

[8] The classical urban economic models represent cities at equilibrium, i.e. when all markets clear and the built environment is optimal as a function of income, population size and transport costs. In reality however, cities are characterized by evolution inertia: to take it into account, we suppose that, between 2015 and 2040, at every location, building density can only grow.

should be designed at the agglomeration scale, as discussed in section 3.10. The experiments conducted here are thus illustrative of the potential impact of the PID, but do not predict future impacts of the current law. Indeed, the legal text states that the PID is optional and that the choice of the MDTs is made independently at the communal level (also, the MDT can differ by local area, at a sub-communal level). It is difficult to predict how mayors and local deciders will use this optional tool. It can be expected that many will simply decide not to implement it. And even among those that do choose to use this policy instrument, the Minimum Density Thresholds are likely to differ across and within communes.

The PID impacts real-estate developers' decisions. It increases the generalised construction costs through the form of a land value tax[9]: for a given rent level, when the housing density that corresponds to a promoter's building project is below the MDT, she has taxes to pay and her profit is reduced compared to a situation with no PID. She thus has an incentive to marginally increase the housing density of his building to reduce the PID and increase her profit. Since construction costs increase non-linearly with density, this creates a trade-off between tax payment and construction costs. As a result, there is an optimal increase in housing surfaces that maximises the promoters gain in response to the introduction of the tax.

If we consider a Minimum Density Threshold of 0.5 (which means that for $100m^2$ of land, at least $50m^2$ of living floor space must be built in order to avoid paying the PID[10]), we obtain the map shown in Figure 3.5.

The figure captures the urban area's reorganisation induced by the implementation of a PID for this Minimum Density Threshold. It clarifies in part the mechanisms at stake: general contraction of the urbanised surfaces and partial reallocation of the peripheral constructions towards more central zones where density increases as a consequence. The figure suggests that the tool is able to limit urban sprawl and thus meets its stated objective. However, it does not tell us much on the general effectiveness of the PID tool with respect to this objective.

Furthermore, the figure does not tell us how it facilitates or impairs reaching other policy goals local decision-makers may have. Following the approach in Viguié and Hallegatte (2012), we use a multi-criteria evaluation framework in Table 3.1 and Figure 3.6.

The statistics in Table 3.1 provide main orders of magnitude for various indicators that correspond to three main policy goals: limiting urban sprawl, ensuring housing affordability, and limiting climate change and local pollution. These values all indicate a visible impact of PID. The PID has a non-marginal impact on urban sprawl, and the urbanised area decreases by about 3% in the PID scenario compared to the reference scenario in 2040. In parallel, the mean population density in the urban area increases by about 3%. Considering that Paris is already largely built up and that the housing renewal only happens at a slow pace, this statistic shows an important impact of the PID.

[9] As we consider that land is always committed to its "highest and possible" use we fall within the definition of land value proposed by Tideman (1982), i.e "raw site value". As a consequence, even in a dynamic setting, when faced with a homogenous land value tax, landowners have no incentive a priori to modify their construction decisions. A homogenous land value tax here would be neutral.

[10] The reader should be reminded that the FARs or housing densities produced by NEDUM-2D do not correspond to FARs as they are usually interpreted. A simple multiplication by two needs to be applied as is discussed in sections 3.4 and 3.11.2. Here a MDT of 0.5 would encourage buildings that exhibit FARs of approximately 1 (Figure 3.3).

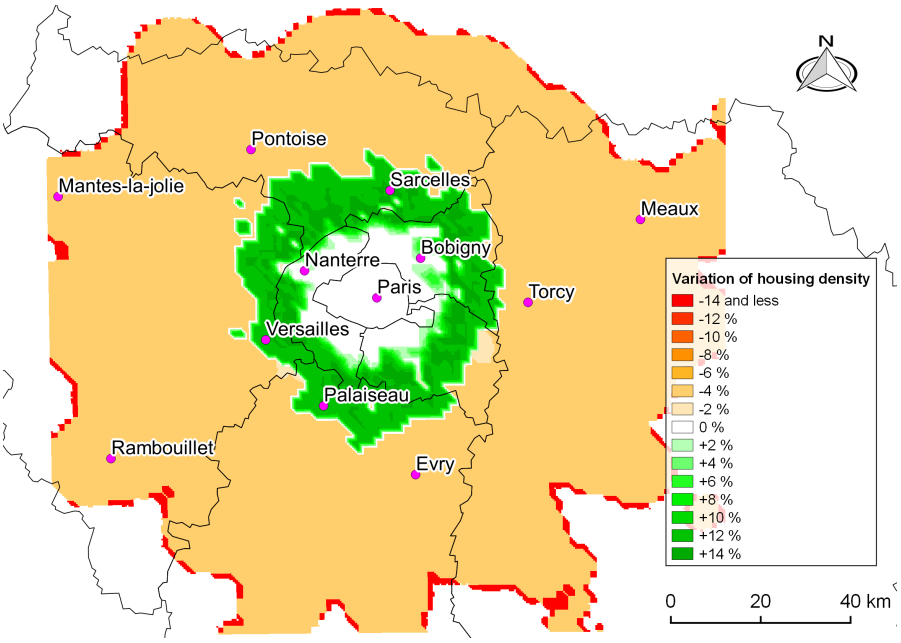

Figure 3.5: Variation in housing density in 2040 caused by the implementation of PID (with a Minimum Density Threshold of 0.5) with respect to a scenario with no PID.

	Initial (2015)	Base (2040)	PID (2040)	Variation
Urban sprawl				
Urbanized area (km^2)	3971	4712	4572	-2.98%
Average density in the urban area (hab/km^2)	1380	1334	1375	3.10%
Average distance to the city center (km)	15.35	17.82	17.13	-3.84%
Housing affordability				
Average monthly rent in the urban area ($euros/m^2$)	16.26	24.88	24.77	-0.41%
Average dwelling size (m^2)	77.3	79.0	79.3	0.36%
Built floor space (km^2)	424	496	498	0.39%
Climate change / CO_2 emissions				
Average annual distance travelled by car (km/year)	5875	7138	6911	-3.17%
Percentage of access to public transport (%)	45.92	41.81	42.82	2.43%

Table 3.1: Impact of the implementation of a PID (MDT: 0.5) on various variables that characterise urban form.

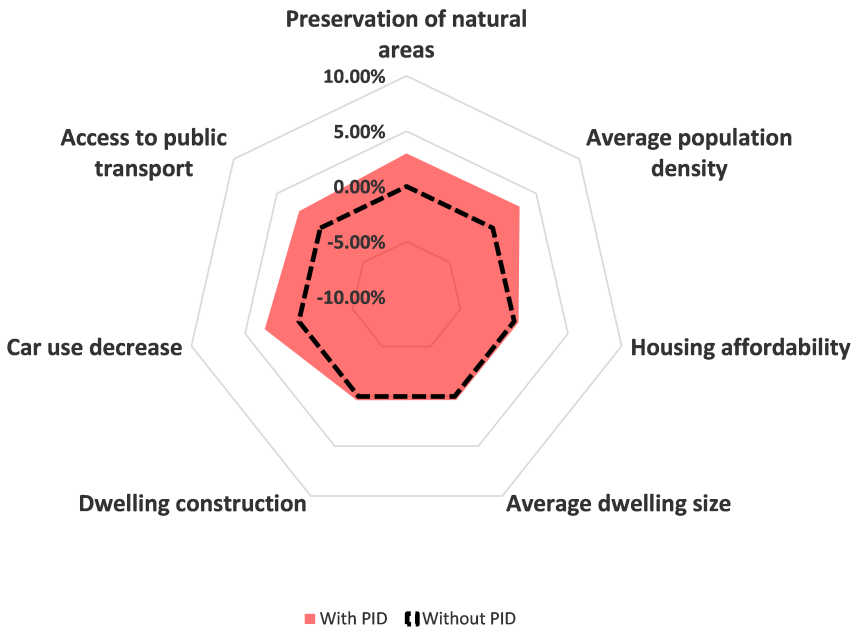

Figure 3.6: Consequences of the PID (MDT: 0.5) on various policy objectives compared to a do-nothing scenario in 2040. Axes orientation is such that directions towards the exterior of the radar plot represent positive outcomes.

These results also partially answer one of our initial questions: "Is it reasonable to tax construction in a context of housing shortage?" Indeed, the built floor space increases in the urban area by around 0.4% in 2040 with PID relatively to a scenario without PID, and the average rent level decreases. So taxing construction here increases construction and can help alleviate housing scarcity.

This surprising result can be explained by the way the tax is designed, with a tax rate that decreases with density. The implementation of a PID modifies the values of land (land rents) and as a consequence building decisions on each plot. As was explained in previous sections, in order to maximise the land rent, the landowners, when confronted to the PID, will be encouraged in certain locations to increase their housing surfaces in order to reduce the PID's amount despite higher construction costs. The result at the level of the urban area is an increase in built housing surfaces. Rents adjust in the NEDUM-2D model in order to ensure the equilibrium between supply and demand for housing space, they therefore diminish. This decrease is not large, but it suggests that the PID would not contribute to the shortage of accommodation and to the current rise in rents.

Furthermore, Figure 3.6 shows that for the three main policy objectives that are listed in Table 3.1 (housing affordability, CO_2 emission mitigation and urban sprawl reduction) which are captured by different indicators, the PID scheme improves the situation in 2040 along all indicators, when compared to a do-nothing scenario.

The PID could contribute substantially to the preservation of natural space and agricultural land in the Paris region. It could equally help to alleviate the housing crisis – by increasing construction – and in the reduction of GHG emissions through the decrease in automobile-travelled distances. The next section examines the determination of an "optimal" value for the MDT.

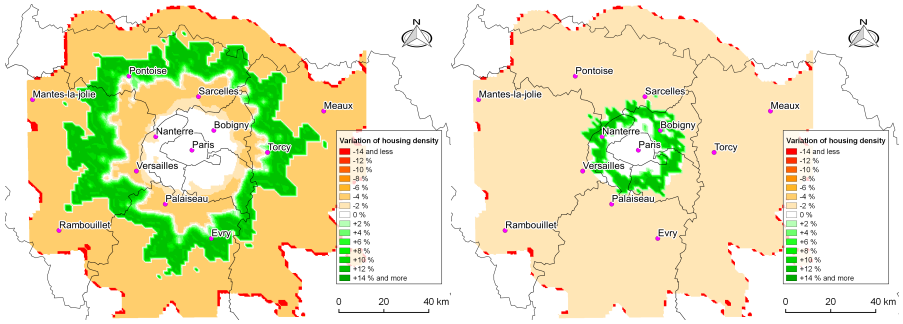

Figure 3.7: Variation of housing density in the Paris region for different MDTs: 0.2 on the left and 0.8 on the right. The shift of the "green ring" position in which the PID increases density appears clearly: the lower the MDT, the more that ring moves away from the centre of the urban area.

3.7 THE CHOICE OF THE MINIMUM DENSITY THRESHOLD CONDITIONS THE EFFICIENCY OF THE PAYMENT FOR INSUFFICIENT DENSITY

Let us adopt the position of an elected official of the Paris region who wishes to implement a PID to mitigate urban sprawl. As previously, we assume that she must choose a unique compulsory MDT for the whole of the urban area.

If she chooses too small a MDT (for example 0.05; which entails to build 50m^2 of floor space area on a land surface of 1000m^2), the densification will be limited as a vast majority of the buildings already complies with this criteria. Furthermore, the outcome can even be negative, as the areas that will attract the extra investment and thus more tenants will be situated in the periphery, thus contributing further to urban sprawl.

Conversely, if she adopts a MDT that is too high, a significant share of developers will prefer to pay the maximum PID rate instead of investing to build more, and the 25% cap will be met over a very large area. As a result, the incentive to build more will only hold for a limited number of the new dwellings. Here are two graphical examples of these situations where a very low MDT is chosen in one case (0.2) and a very high one in the other (0.8).

The four rings detailed above appear neatly in the two simulations; however their locations are very different. The lower the MDT, the further the ring in which the densification happens moves away from the city centre.

The choice of an optimal MDT to reduce urban sprawl differs from the classical issue of optimal taxation because the aim is to change behaviours and not to maximise utility or revenues. We have selected here a number of criteria to measure the efficiency of the PID depending on the chosen MDT. The first ones that spring to mind when considering urban sprawl and climate change are the total urbanised area and the mean distance travelled by car. In order to appreciate the capacity of the PID to influence the trajectory of urban evolution other indicators can be selected. Indeed, one of the most discussed consequences of urban sprawl is the decrease of public transport's modal shares for commuting purposes. This decrease results from the high cost and difficulty of providing sufficiently attractive infrastructure patterns of buses and railways in sprawled and diffuse territories (Kenworthy and Laube, 1999). We hereby estimate the evolution of the accessibility to the public transport network of 2015, as a function of the chosen Minimum Density Thresholds. Bertaud (2002) indicates that public transport is only competitive if a station is situated within 800 metres of households' place

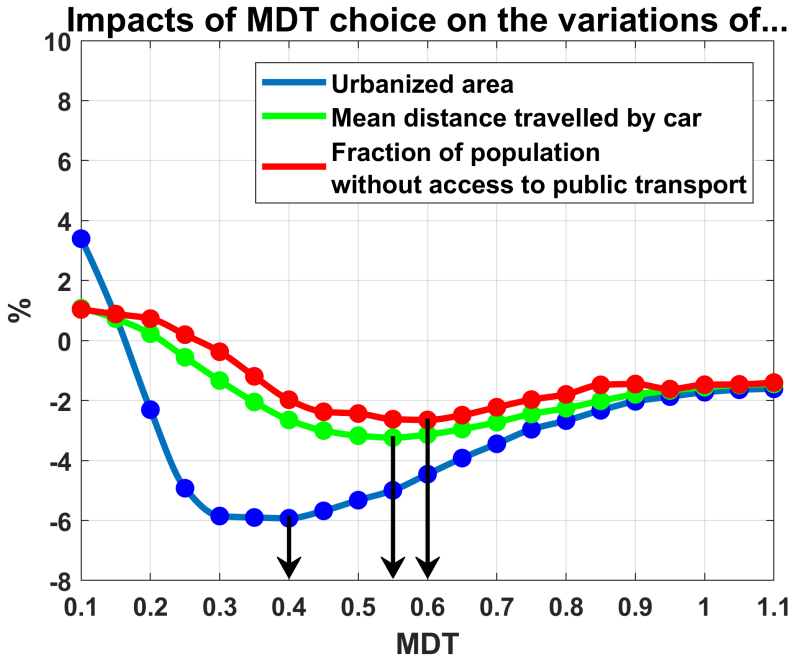

Figure 3.8: Impact of the MDT choice on the evolution of the urbanised area, the mean annual distance travelled by car and the accessibility to public transport with respect to a situation with no PID. The maximum reduction for each of these three variables is obtained for different values of the MDT (they are indicated by the black arrows).

of residence.[11] Altogether, these three variables capture different aspects of the spatial reorganisation induced by the implementation of a PID and Figure 3.8 represents their evolution as a function of the chosen MDT.

For MDTs that are too low, the implementation of a PID can lead to counter-productive results. For a MDT of 0.2, the fraction of population without access to public transport will increase by more than 1 % with respect to a no PID situation, because this tool will encourage construction mostly in low density areas. Even if it increases density in these low-density locations, the aggregate impact is to lower average density.

The three indicators above present U shaped evolutions when the MDT varies, however the maximum beneficial impacts are obtained for different MDTs. If one wishes to minimise the urbanised area in 2040, then the model suggests choosing 0.4 as a threshold. However, if the objective is to decrease the distances travelled by car as much as possible, then an MDT of 0.55 is more efficient. Finally the Minimum Density Threshold that maximizes access to public transport is 0.6.

An important aspect of the question is thus that the optimal implementation of the PID depends on the efficiency criteria chosen and that there is a trade-off across different objectives. Such work requires a political discussion and goes beyond the ambition of this paper. However, our model and approach seem to be able to inform the decision by quantifying the impacts of different PID implementation choices. And these preliminary

[11] Bertaud justified this hypothesis by explaining that on average no one accepts to walk for more than 10 minutes in order to ride by bus or metro. With an average speed of 4.5km/hour, this length of time indicates that one must reside within 800m meters of a station or bus stop in order to consider public transport as an option.

Minimum Density Thresholds	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Evolution of household utility	0.09%	0.18%	0.22%	0.22%	0.20%	0.17%	0.13%	0.10%	0.08%	0.06%
Evolution of aggregate land value	−4.7%	−9.5%	−11.9%	−12.4%	−11.8%	−10.6%	−9.2%	−8.0%	−7.0%	−6.5%

Table 3.2: Evolution of households' average utility and aggregate land value in the urban area relatively to an unconstrained baseline in 2040.

results are encouraging: even though "optimal" MDTs differ, there is a range of MDTs that lead to positive outcomes across the policy goals investigated here (Figure 3.8).

We have focused here on various indicators that capture some important features of the evolution of the urban area as a result of the implementation of the PID. These show that it is possible to create synergies across various policy goals. If we now turn to household utility, which is derived in the urban economic framework we use from housing services and a composite good, we expect an amelioration as average housing size has increased. Conversely, as the PID is a tax on land value conditional on housing densities we expect a decrease in land values which will worsen the landowners' situation. Table 3.2 provides figures that show how both utility and aggregate land value evolve as a result of PID implementation relatively to an unconstrained baseline (no PID).

Aggregate land value in the agglomeration decreases as the result of PID implementation. As mentioned above, this does not come as a surprise as PID is a tax on land value (although a specific one). It is however interesting to have orders of magnitude of the decrease in aggregate land value. These are far from being negligible as they can reach 12% for the whole of the urban area. Although we do not address political economy issues here we can acknowledge that this is likely to render the PID a politically sensitive tool were it to be made compulsory.

Average household utility on the other hand is positively affected by the introduction of the PID. Caution is required when looking at this table as the two indicators are not directly comparable. Aggregate land rents are expressed in monetary terms whilst utility has an undefined unit. These two variables cannot be compared without expressing utility in monetary terms and we do not attempt a social welfare analysis of the PID here. This goes beyond the scope of this paper but will be investigated in a future piece where the assumption of absentee landowners will be lifted.

From Table 3.2 we can also see that utility evolution, as the other indicators discussed above, presents a U-shape. It reaches a maximum when the MDT is 0.4 and decreases after.

3.8 REVENUES EXPECTED FROM THE PAYMENT FOR INSUFFICIENT DENSITY

What can we expect from the PID in terms of fiscal revenues? This question is probably the most complicated to answer for two main sets of reasons.

First, there are numerous uncertainties on the rhythm of housing construction/destruction. Indeed, only new buildings are taxed, whereas in practice there is always the possibility of refurbishing existing buildings

MDT	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Revenues from the PID in 2020 (billion euros)	5.4	7.2	3.4	3.0	3.4	3.0	2.7	13.0	25.2	30.7

Table 3.3: Annual revenues expected from the PID in 2020 in the simulations as a function of the MDTs. We used a discount rate of 5% to express future revenues into present values.

by adding floors rather than destroying and rebuilding them. Over the short-term, the PID could have a significant impact on the choice between retrofitting and enlarging on the one hand, and complete reconstruction on the other hand. These uncertainties have no impact on the final equilibrium result – in terms of population density and urbanisation in the long term – but they are crucial to calculate the revenues that can be expected from the tax every year. NEDUM-2D considers that any new built m^2 corresponds to a new building and does not account for the possibility of enlarging existing buildings (through for example the addition of an extra floor on an existing construction). This simplification however currently remains realistic Buzy-Cazaux (2012)).

Second, it is hard to calibrate the model so as to reproduce observed land values. Whereas, housing rents historically display a strong regularity when compared to average incomes, real estate prices have varied strongly in recent times in France and elsewhere (Friggit, 2010). This tends to support the idea that real estate and land have a value reserve function and that their prices do not adjust solely in reaction to tensions on the housing market (Timbeau, 2013). In addition, there are regulatory mechanisms that contribute to low availability of land for new construction and therefore fuel high land values (Charmes, 2007). As NEDUM-2D does not capture the impacts of financial markets on land development and construction decisions, nor does it account for organized land scarcity, it misses in part some fundamentals of land values.

With these limits stated, here is a table that provides estimates for annual expected revenues in 2020 in our simulations:

For the Paris region (Île de France), the revenues of property and housing taxation schemes are respectively 7 and 4 billion (DGFiP, 2010). By comparison, the revenues calculated for the PID are of similar magnitude. A recycling of these revenues into infrastructure provision projects such as transport or sanitation would be an interesting idea. Indeed, the increased densities in the zones where the PID is effective could create some bottleneck issues that would need to be addressed by local authorities through transportation infrastructure provision for example.

3.9 FEEDBACKS FROM COMMUNES THAT IMPLEMENTED A PID

In July 2013, the number of communes that chose to implement a PID stood at 33. We were able to gather initial feedback from 19 of them.

The questions covered the reasons for implementing this optional tax, the methodology used to define the MDT, the reactions of various stakeholders to this policy, the actual impact in terms of construction and revenues as well as the impression of the mayor's team of the performance of the tool in limiting sprawl. Among the 19 communes, two of them, although they initially agreed on the implementation of the PID, cancelled it very rapidly. We therefore have feedbacks for 17 communes. Another commune equally

Alba-la-Romaine	Morangis	Boussy-Saint-Antoine	Médan	Saint-Ouen
Bermerain	Rieulay	Cauroir	Orchamps-Vennes	Xirocourt
Bugarach	Sète	Chaumes-en-Brie	Phalsbourg	Chéroy
Cattenières	Taverny	La Côte-d'Aime	Saint-Blaise-du-Buis	Montbartier
Gonfaron	Tonnoy	La Talaudière	Sainte-Feyre	Noyelles-Godault
Mas-Saintes-Puelles	Valdahon	Latour-de-Carol	Sainte-Honorine-du-Fay	
Montfort-sur-Argens	Volonne	Lunel-Viel	Saint-Jean-d'Arvey	

Table 3.4: Communes having implemented a PID on July 24 2013.

cancelled the PID but after some test time, thereby constituting an interesting case study.

Table 3.4 lists the communes that had implemented a PID on part of their territory by July 24 2013. In orange, you have the communes that implemented a PID but that we were not able to reach; in green those that had an active PID and provided some feedback. In blue the communes of Chéroy and Montbartier cancelled the PID nearly immediately after implementing it. Finally the commune of Noyelles-Godault in grey in the table, implemented a PID and subsequently cancelled it but only after some testing time. Apart from Morangis, Sète and Taverny, all communes house less than 10,000 people and 10 are mainly rural and have lower than 1,000 population counts.

3.9.1 *Multiple reasons for implementing a Payment for Insufficient Density*

The motivations of the communes for implementing the PID are mainly linked to the desire to orient urban development, avoid leapfrogging and densify certain areas considered as priority zones. Others insist more (one does not exclude the other) on the financial expectations they have from this tool, either to increase revenues or to avoid excess spending on infrastructure tied to urban sprawl (see Figure 3.9).

Two cases deserve attention. One commune explains that the objective of limiting urban sprawl should be tackled through the local urban plans (PLU): this commune thinks of the PID not as a tool to incentivize density (which would therefore be duplicative) but able to generate supplementary fiscal revenues. Finally one commune used the PID in a surprising way: in order to equip an already developable zone in road network and public spaces, it resorted to the PID to enforce a certain density that would allow it to apply an equipment tax rate increased by 20%. The PID does not directly finance the public works here, but betting on the fact that it will enforce density, it will justify the application of higher density-tied equipment tax rates, the proceeds of which will cover a large share of the infrastructure spending.

3.9.2 *The difficult choice of the Minimum Density Threshold*

The town councils determined the MDTs mainly through internal discussion within the municipal council (12 communes), sometimes relying on internal

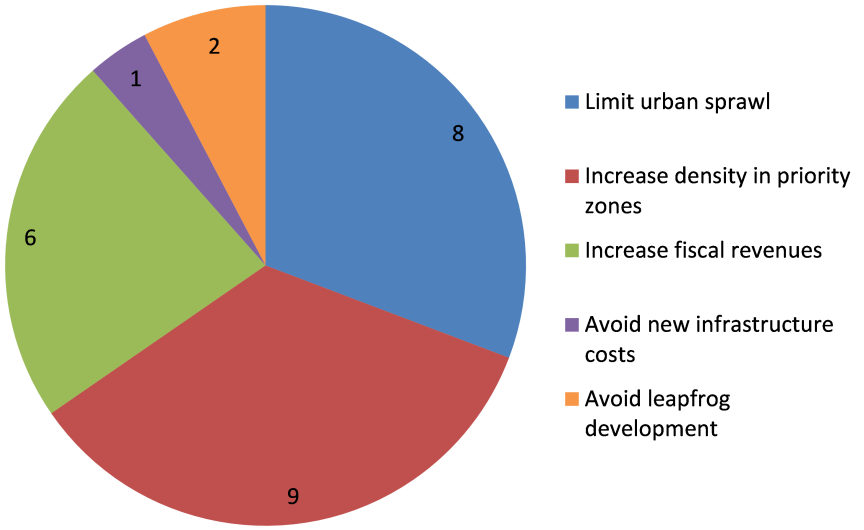

Figure 3.9: Reasons for implementing a PID for 17 communes.

impact studies (7 responses). Only three communes resorted to external consulting companies to determine the MDTs.

Of the 19 studied communes, two indicated having initially badly calibrated the MDTs. One of the two subsequently canceled the PID on the basis of excessively heavy fiscal burdens which was badly accepted by local residents. The second commune drastically decreased the MDT threshold from 0.5 to 0.05.

A strong local opposition to the PID took place in 4 communes only: the two previously mentioned and two others. The unhappiness of landowners found its root in two main reasons: 1/ the PID created a supplementary tax for projects that had been planned in its absence and 2/ the PID was likely to discourage future landowners from purchasing land. In the 13 remaining communes however there was no strong opposition to the PID, either because the PID implementation went unnoticed (12 responses) or because its implementation was accompanied by careful pedagogical explanations (1 response).

3.9.3 *The mixed impacts of the Payment for Insufficient Density*

When discussing the impact of PID on constructions, 8 communes claim they cannot conclude because no construction was initiated in the zones where the PID was implemented without it being possible to hold the PID responsible for the lack of activity. Conversely, one commune in this situation clearly concludes that the PID stalled construction after the abandonment of a project it was aware of. One commune observed that the Floor Area Ratio (FAR) increased as a result of denser buildings following the implementation of the PID. Finally, 5 communes claim that the PID has modified the behavior of land purchasers: they observed that these were buying smaller than usual lots. In order to avoid paying the PID, the main mechanism seems not to be

larger or taller buildings but the size of the land plots they are developed on. This way of avoiding the payment of the PID would be the main cause of the increase in price per sq. meter of smaller sized plots according to one commune.

None of the communes contacted had available information on the revenues from the PID. And none had produced any estimates before the implementation of the policy.

In the end, they are 12 out of 17 to believe that the PID is an interesting tool to orient urban development, either to reduce sprawl or to achieve higher densities in specific areas. Two communes view the PID as a very good tool to produce fiscal revenues but are skeptical as to its capacity to curb urban sprawl. And finally two communes regret the PID being an obstacle to construction.

3.10 CONCLUSIONS

The PID appears to be an interesting tool to limit urban sprawl and to promote an efficient use of land. If the threshold is chosen appropriately, it encourages more construction in dense areas and the construction of denser housing. Its aggregate impact is to increase construction in the urban area. Contrarily to uniform property taxes (Brueckner and Kim, 2003; Song and Zenou, 2006) the PID can mitigate urban sprawl without decreasing housing services for the inhabitants of the urban area. As such, and with the hypothesis of absentee landowners, it is a utility improving device. As other urban-environmental policies (Viguié and Hallegatte, 2012), the PID therefore creates a synergy with other housing policies and leads to a global reduction in housing costs: because of its calculation method, the PID increases construction by taxing it.

Furthermore, this measure would help reduce greenhouse gas emissions in a way that is more socially and politically acceptable than a carbon tax, because it does not affect people that already live in low density areas but only newcomers and developers (Rozenberg, Vogt-Schilb, and Hallegatte, 2013).

The efficiency of this tool however strongly depends on the MDTs that are chosen at the local level. The simulations presented here highlight the counter-productive consequences[12] of too low MDTs, but also the decreasing returns when thresholds are too high.

At the time of the interviews, only 33 communes had implemented a PID and among them 3 had abandoned it and 8 had not experienced any constructions in areas targeted by the policy. The feedback gathered from 19 communes is therefore limited and does not allow for an in-depth evaluation of the policy. However, these feedback do provide some insights into the motivations of the communes to implement this optional tool and into the early impacts of the PID. Two sets of motivation appear: the will to better control urban development and increase density on one hand and the possibility of increasing fiscal revenues on the other hand. Whereas it is difficult to measure the impact of the PID in practice based on such limited data, it seems to be able to increase density by reducing the average size of land plots purchased for the construction of structures.

[12] Again this assumes the existence of a housing density threshold below which zones are no longer urbanized. This threshold can lead to urban sprawl for low MDTs. But even without this threshold, the purpose of the PID is not to attract populations in zones that are situated at the urban fringe, therefore low MDTs can lead to counter-productive results.

Our modelling results are based on a number of simplifying assumptions that it is useful to review and discuss. First, we supposed homogeneous MDTs that would apply to the whole of the Paris region. The introduction of a MDT for each "commune" (which is a likely probability) would yield very different results and could prove totally counter-productive in order to mitigate urban sprawl. As often, see for example Przylusky and Hallegatte (2012) on flood risk management, the analysis suggests that the urbanization process needs to be managed at the urban area scale, the division between small size "communes" causing strong negative impacts.

Second, we conducted our analysis, assuming absentee landowners and concluded to a utility improving impact of PID. It would be interesting to relax this assumption and investigate the social welfare impact of the PID in a fully closed city in the presence of landowners. This constitutes a promising avenue for future research.

Third, despite additions to the traditional urban economic framework aimed at improving the realism of city representation, we still rely on a mono-centric approach. In a poly-centric model, we might expect land use for housing purposes to intensify around each Business District. We believe it likely that in aggregate we would reach similar conclusions, but this remains an open empirical question at the present time. Therefore, while it is not obvious how polycentrism would change our results, we believe it to be an equally interesting area for future research.

Fourth, we also assume identical households earning the same income throughout the urban area. However, different income groups live in different places which can display different housing densities. It is again not obvious how the introduction of different income groups in the model would modify our results, but we cannot rule out the fact that this would have redistributive impacts that we do not currently document.

Finally, although we have introduced realistic transport infrastructures in the model, we have also assumed that no new networks will be built between now and 2040. However, there is currently a plan to build the "Grand Paris Express", a massive transportation infrastructure that would connect suburban residential locations in the Paris region to economic opportunities both in the centre of Paris and in the suburbs. It would be interesting to investigate how this would affect the map of higher/lower density zones in the future. It would also provide useful insights to look into how the PID could help finance such a large transportation plan.

3.11 APPENDIX

3.11.1 *Analytical framework*

The mechanisms that describe households' and real estate developers' behaviors can be expressed mathematically in a quantitative manner. We introduce the following utility function to represent the trade-off that households face

$$U = Z^{\alpha} q^{\beta} \tag{3.6}$$

Where α and β are coefficients $(\alpha + \beta = 1)$, q represents each household's accommodation size and Z the quantity of composite good (goods other than housing) that can be acquired once the rent has been paid. This functional form is coherent with the fact that the share of income spent on housing is reasonably constant, on average, across urban areas (Davis and Ortalo-

Magné, 2011) and over time. The budgetary constraint of each household can be expressed as follows:

$$Y = \mathrm{Rq} + Z + t_r \tag{3.7}$$

Where Y represents the average income of a household, R the rent per m^2 and t_r the transport costs. The real estate developers seek to maximize the following profit function:

$$\pi = \mathrm{RH} - (\rho + \delta) K \tag{3.8}$$

Where H is the amount of built housing space and K is the amount of invested capital. We assume absentee landowners, so that the land rent is not recycled in the local economy. The parameter ρ represents the rate of capital depreciation and δ the interest rate or capital cost.

The housing space production function can be expressed classically as follows (Muth, 1969; Thorsnes, 1997):

$$H = AK^b L^a \tag{3.9}$$

Where a and b are coefficients such as $(a + b) = 1$ and L is the land surface occupied by buildings. This functional form expresses the fact that generalized costs of construction increase with density (Castel, 2007).

With exogenous information on households' average income Y, on generalised transport costs (both time and monetary costs) t_r for each location in the urban area, on the total population, on the construction costs (coefficients A and b) and finally on the structure of households' expenditure (α and β), it is possible to characterize the internal structure of an urban area. The other variables such as the rents R, the invested capital K, the built housing surfaces H, or the size of accommodations q are determined endogenously in this model.

3.11.2 *Comparing real and simulated land prices*

Comparison between observed and simulated land values is made difficult by the fact that data describes land plots which have been serviced and are ready to be built upon. The reported values therefore account for the fact that servicing costs have already been paid. Servicing land includes providing roads, gas, electricity and water infrastructures, as well as potential administrative costs to open the plots of land to construction. In the framework that we have just described, the price of land, given by π, real estate developers profit, represent land values before servicing is done.

In order to be able to represent land values net of servicing costs, we have to decompose real estate developers' actions into two actions: first land servicing, and, then, building construction. Let us suppose therefore that two types of actors are involved in housing construction. First, land developers service land, and, then, sell serviced plots to housing developers who build upon the plots and rent the buildings to the city inhabitants. In each city districts, land developers can choose the fraction F of land that can be serviced, and on each serviced plot, housing developers choose the type of building that they want to build. The type of building is characterized by its floor-area ratio, h.

The profit of land developers reads:

$$\pi_L = F \cdot P_T - C(F) \tag{3.10}$$

Where P_T is the price to which each serviced plot will be sold to real estate developers, and $C(F)$ is the price of servicing a fraction F of the land of the district.

The profit of housing developers reads:

$$\pi_l = R \cdot h - (\rho + \delta) \cdot k_0(h) - \delta \cdot P_T \tag{3.11}$$

Where h is the amount of built housing space, R the rent per m^2 and $k_0(h)$ the amount of invested capital. We assume absentee landowners, so that the land rent is not recycled in the local economy. The parameter ρ represents the rate of capital depreciation and δ the interest rate or capital cost.

We suppose that housing developers are in perfect competition, whereas land developers can freely choose the price to which they will sell serviced plots. To maximize their profits, land developers will therefore choose serviced land prices P_T so that housing developers profit is equal to zero, and we have:

$$P_T = \left(\frac{1}{\delta}\right) \cdot \max[R \cdot h - (\rho + \delta) \cdot k_0(h)] \tag{3.12}$$

The gross floor-area ratio H, i.e. the number of built square meters divided by the entire district land surface, reads $H = h \cdot F$. In average over one district, total invested capital K per district land unit is the sum of the capital invested to service land and of the capital invested to build the buildings:

$$K = F \cdot k_0(h) + C(F) \tag{3.13}$$

To keep relationship (3.9) between K and H, we can express $C(F)$ and $k_0(h)$ the following way:

$$\begin{cases} k_0(h) = \left(\frac{h}{A}\right)^{1/b} - \left(\frac{h_{\lim}}{A}\right)^{1/b} + K_{\lim} \\ C(F) = \left(\frac{F \cdot h_{\lim}}{A}\right)^{1/b} - K_{\lim} \cdot F \end{cases} \tag{3.14}$$

Where $h_{\lim}$ and $K_{\lim}$ are two constants.

We choose these functional forms because they lead to simple analytical results. Indeed it can be easily shown that, under this choice, when $H > h_{\lim}$ then we have $F = 1$ and $H = h$. This means that when gross floor area ratio in a district is larger than the threshold $h_{\lim}$, then the district is fully serviced, and all buildings have a floor area ratio equal to H. Conversely, when $H < h_{\lim}$, then we have $F < 1$ and $h = h_{\lim}$. This means that when gross floor area ratio H in a district is lower than the threshold $h_{\lim}$, the district is no longer fully serviced, but on each serviced plot the local floor area ratio of buildings is equal to the limit $h_{\lim}$. $K_{\lim}$ is finally simply the cost of building a structure with floor-area ratio $h_{\lim}$.

Under these choices, the price of serviced land, P_T, will be given by

$$P_T = \left(\frac{1}{\delta}\right) \cdot \max\left[R \cdot h - (\rho+\delta) \cdot \left(\frac{h}{A}\right)^{1/b} + (\rho+\delta) \cdot \left(\frac{h_{\lim}}{A}\right)^{1/b} - (\rho+\delta) \cdot K_{\lim}\right] \tag{3.15}$$

Figure 3.10 shows a comparison of observed land prices in Paris metropolitan areas and of simulated values, using the formula above. Land price data is scarce, as it is only available in places where unbuilt land has been sold. There is for instance no data point close to the center of the metropolitan area. Model and data seem to match well overall, even if local differences can be large.

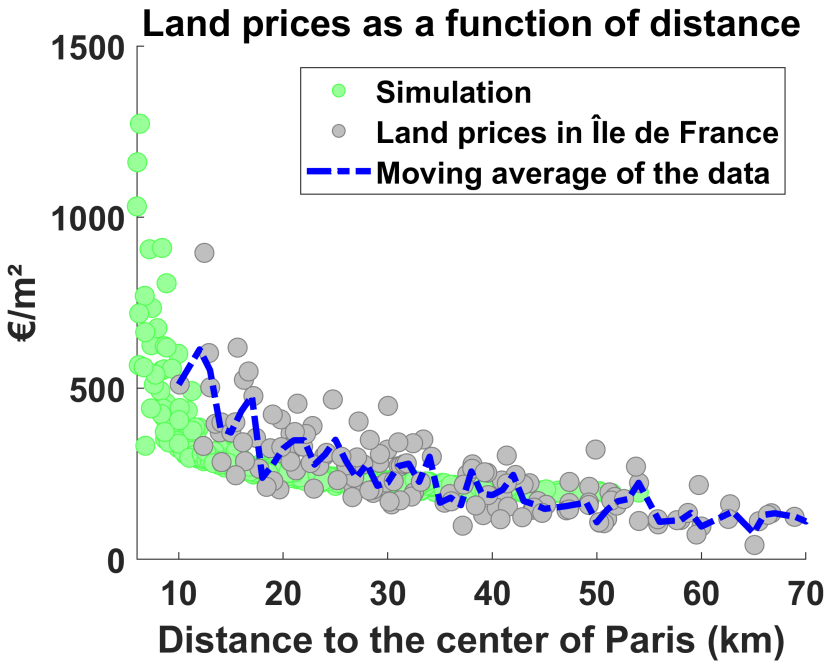

Figure 3.10: Comparison of land prices per m^2 as observed and simulated by NEDUM-2D as a function of the distance to the center of Paris, for year 2012 (Data source: EPTB database from the French ministry of sustainable development).

3.11.3 *Comparing real and simulated FAR (housing densities)*

There is a discrepancy between observed and simulated FARs. This discrepancy can be explained by the fact that NEDUM-2D only simulates residential behaviors. As a consequence it does not account for building for purposes of shopping, work or leisure. It equally only considers building space for living purposes and disregards lobbies, corridors and courtyards. It is useful to see how the FARs that are modeled by NEDUM-2D relate to those that are observed in practice.

To deal with this issue, we compare FARs simulated by the model to actual FARs, through two methods.

First we look at places in the study area where NEDUM-2D population density simulation is consistent with actual population density. Population density data are available at the "commune"[13], and we choose all simulation grid points corresponding to communes where simulated and actual population density differ by less than 20%. In comparing simulated and observed FARs with this method we find an approximate constant ratio of 2 between NEDUM FARs and observed FARs.

The method employed above only uses a handful of observations, where the model performs well in simulating local population densities. We therefore also go beyond this exercise and use a second method, this time looking at all communes of the Île de France area. To approximate actual FAR, we use the MOS database, a precise map of neighborhood types in Île de France created by Île de France urbanism institute.[14] We then use a scale proposed by this institute, and which compares FAR with neighborhood type. Figure 3.11 shows a comparison between estimated FARs and FARs simulated

[13] Data source: 2006 population census, INSEE: http://www.insee.fr/fr/recensement-2006.htm.
[14] http://www.iau-idf.fr/cartes/mode-doccupation-du-sol-mos.html

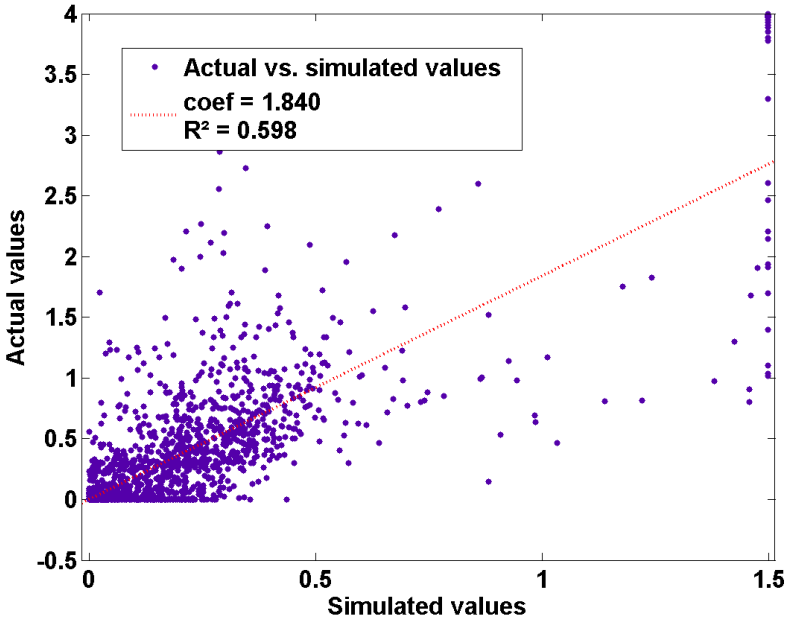

Figure 3.11: Comparison between simulated and observed FARs (data sources: MOS database, IAURIF).

by NEDUM-2D. The ratio we find between simulated and observed FARs is slightly lower than with the previous method, 1.84 instead of 2 but both are close enough that we can use the ratio of 2 between simulated and observed FARs as a simplification.

REFERENCES

Arnott, Richard (2005). "Neutral Property Taxation." In: *Journal of Public Economic Theory* 7.1, pp. 27–50. ISSN: 1467-9779. DOI: 10.1111/j.1467-9779.2005.00192.x.

Bentick, Brian L. (1979). "The Impact of Taxation and Valuation Practices on the Timing and Efficiency of Land Use." In: *Journal of Political Economy* 87.4, pp. 859–868. ISSN: 0022-3808.

Bento, Antonio M., Sofia F. Franco, and Daniel Kaffine (2006). "The efficiency and distributional impacts of alternative anti-sprawl policies." In: *Journal of Urban Economics* 59.1, pp. 121–141. ISSN: 0094-1190. DOI: 10.1016/j.jue.2005.09.004.

Bertaud, Alain (2002). "The spatial organization of cities: Deliberate outcome or unforeseen consequence?" In: *World Development Report 2003, background paper*.

Brueckner, Jan K. (2001). "Urban Sprawl: Lessons from Urban Economics [with Comments]." In: *Brookings-Wharton Papers on Urban Affairs*, pp. 65–97. ISSN: 15287084.

Brueckner, Jan K. and Hyun-A. Kim (2003). "Urban sprawl and the property tax." In: *International Tax and Public Finance* 10.1, pp. 5–23.

Burchfield, Marcy, Henry G. Overman, Diego Puga, and Matthew A. Turner (2006). "Causes of Sprawl: A Portrait from Space." In: *The Quarterly Journal of Economics* 121.2, pp. 587–633. ISSN: 0033-5533, 1531-4650. DOI: 10.1162/qjec.2006.121.2.587.

Buzy-Cazaux, Henry (2012). *Augmentation des droits à construire : une mesure d'optique - Blogs Immobilier*.

Castel, J. C (2007). "Coûts immobiliers et arbitrages des opérateurs: un facteur explicatif de la ville diffuse." In: *Annales de la recherche urbaine* 102.

Charmes, Eric (2007). "Le malthusianisme foncier." In: *Etudes foncières* 125, pp. 12–16.

Davis, Morris A. and François Ortalo-Magné (2011). "Household expenditures, wages, rents." In: *Review of Economic Dynamics* 14.2, pp. 248–261. ISSN: 10942025. DOI: 10.1016/j.red.2009.12.003.

DGFiP (2010). *L'annuaire statistique des impôts 2010*. Tech. rep. Direction Générale des Finances Publiques.

EEA (2006). *Urban sprawl in Europe–the ignored challenge*. No. 10. EEA, Copenhagen, Denmark.

Friggit, J. (2010). "Le prix des logements sur le long terme." In: *Structure* 3, p. 1.

Glaeser, Edward L. and Matthew E. Kahn (2004). "Sprawl and urban growth." In: *Handbook of Regional and Urban Economics*. Ed. by J. Vernon Henderson and Jacques-François Thisse. Vol. Volume 4. Cities and Geography. Elsevier, pp. 2481–2527. ISBN: 1574-0080.

Kenworthy, J. R. and F. B. Laube (1999). "Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy." In: *Transportation Research Part A: Policy and Practice* 33.7, pp. 691–723.

Mills, David E. (1981). "The Non-Neutrality of Land Value Taxation." In: *National Tax Journal* 34.1, pp. 125–129. ISSN: 00280283.

Moulinié, Claire and Muriel Naudin-Adam (2005). *Appréhender la densité 3. "Formes urbaines et densités"*. Note Rapide sur l'Occupation des sols 384. Paris: Institut d'Aménagement Urbain de la Région Ile de France.

Muth, Richard F. (1969). *Cities and housing; the spatial pattern of urban residential land use*. Chicago: University of Chicago Press.

Nechyba, Thomas J. and Randall P. Walsh (2004). "Urban Sprawl." In: *The Journal of Economic Perspectives* 18.4, pp. 177–200. ISSN: 0895-3309.

Oates, Wallace E. and Robert M. Schwab (1997). "The impact of urban land taxation: The Pittsburgh experience." In: *National Tax Journal* 50.1, pp. 1–21.

Przylusky, Valentin and Stéphane Hallegatte (2012). *Gestion des risques naturels : leçons de la tempête Xynthia*. Matière à débattre et décider. Versailles Cedex: Quae. ISBN: 978-2-7592-1820-2 2-7592-1820-1.

Rozenberg, Julie, Stéphane Hallegatte, Adrien Vogt-Schilb, Olivier Sassi, Céline Guivarch, Henri Waisman, and Jean-Charles Hourcade (2010). "Climate policies as a hedge against the uncertainty on future oil supply." In: *Climatic Change* 101.3, pp. 663–668. ISSN: 0165-0009. DOI: 10.1007/s10584-010-9868-8.

Rozenberg, Julie, Adrien Vogt-Schilb, and Stéphane Hallegatte (2013). "How Capital-Based Instruments Facilitate the Transition Toward a Low-Carbon Economy." In: *World Bank Policy Research Working Paper* n°6609.

Song, Yan and Yves Zenou (2006). "Property tax and urban sprawl: Theory and implications for US cities." In: *Journal of Urban Economics* 60.3, pp. 519–534. ISSN: 0094-1190. DOI: doi:DOI:10.1016/j.jue.2006.05.001.

— (2009). "How do differences in property taxes within cities affect urban sprawl?" In: *Journal of Regional Science* 49.5, pp. 801–831. ISSN: 00224146, 14679787. DOI: 10.1111/j.1467-9787.2009.00616.x.

Thorsnes, Paul (1997). "Consistent Estimates of the Elasticity of Substitution between Land and Non-Land Inputs in the Production of Housing." In: *Journal of Urban Economics* 42.1, pp. 98–108. ISSN: 0094-1190. DOI: 10.1006/juec.1996.2015.

Tideman, T. Nicolaus (1982). "A Tax on Land Value Is Neutral." In: *National Tax Journal* 35.1, pp. 109–111. ISSN: 00280283.

Timbeau, Xavier (2013). "Les bulles «robustes»." In: *Revue de l'OFCE* 2, pp. 277–313.

Transportation Research Board - NRC (2002). *Costs of sprawl – 2002*. TCRP Report 74. Washington, D.C.: National Academy Press. ISBN: 1073-4872.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

Waisman, Henri, Céline Guivarch, Fabio Grazi, and Jean-Charles Hourcade (2012). "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." In: *Climatic Change* 114.1, pp. 101–120. ISSN: 0165-0009. DOI: 10.1007/s10584-011-0387-z.

Wheaton, William C. (1974). "A comparative static analysis of urban spatial structure." In: *Journal of Economic Theory* 9.2, pp. 223–237. ISSN: 0022-0531. DOI: doi:DOI:10.1016/0022-0531(74)90068-4.

Wildasin, David E. (1982). "More on the Neutrality of Land Taxation." In: *National Tax Journal* 35.1, pp. 105–108. ISSN: 00280283.

4

BUSES, HOUSES OR CASH? SOCIO-ECONOMIC, SPATIAL AND ENVIRONMENTAL CONSEQUENCES OF REFORMING PUBLIC TRANSPORT SUBSIDIES IN BUENOS AIRES[1]

> *« The squats we used to party in are flats we can't afford.*
> *The dumps we did our dancing in have all been restored.*
> *Pints are up two quid, the staff are beautiful and bored.*
> *You think it's coming up round here? It's falling on its sword.*
> *It don't feel like home no more. I don't speak the lingo.*
> *Since when was this a winery? It used to be the bingo.*
> *I've walked these streets for all my life. They know me like no other.*
> *But the streets have changed, I no longer feel them shudder. »*
>
> Tempest, Kate. 2017. *Let Them Eat Chaos*. First U.S. edition. New York: Bloomsbury.

4.1 INTRODUCTION

Public transport is highly subsidized in the urban area of Buenos Aires. The fares paid by the users only cover around a third of the cost of the trips with total transit subsidies amounting to more than US$ 5 billion for the urban area of Buenos Aires alone in 2012. This level of subsidization is in line with what is found in developed country cities but is high for a developing country. In light of these figures, the transit subsidies have been challenged first on a financial and fiscal basis[2]. Is this the best use of scarce public resources? Or could alternative policy and interventions lead to better welfare outcomes? Commentators have focused on many potential weaknesses of the subsidy – including the impact of diverting resources originally earmarked for system maintenance and investment both of which have been inadequate in the last decade; issues of financial management; as well as the lack of transparency or incentives to foster efficiency in the allocation mechanism.

There is also a debate on the impact of the low fare on the aggregate modal share of public transport in the metropolitan area. On one hand, all else equal, low fares make for more competitive public transport. But the evidence also suggests that for most riders of choice, quality trumps fare, so that when transit subsidies come at the expense of quality of service (comfort, reliability, passenger information systems), as is the case in the Buenos Aires urban area, the public transport ridership balance is unclear. In particular, Gwilliam (2017) reports evidence from London that reductions in public transport fares are less likely to bring about mode share changes in favor of transit than service quality improvements.

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[2] In April 2016, fare increases were introduced with the minimum bus fare doubling from AR$ 3 in 2014 to AR$ 6. This study assumes subsidies and fares before their revision in 2016.

There are also a number of other dimensions along which the subsidies need to be assessed. First there are concerns that these artificially low public transport prices have fueled urban sprawl and related negative externalities such as excessive loss of farmland, or the need for costly infrastructure (sewage systems, roads, etc.). Second, the transit subsidy has an impact on commuting-related energy expenditures and CO_2 emissions. This is closely linked to the impact of lower fares on both transit ridership – which is less carbon-intensive than travel by private cars – and in parallel on location decisions of households in the Buenos Aires urban area. Whereas higher public transport mode shares would tend to decrease emissions, lower transport costs would also enable households to settle further from job centers, thereby lengthening commuting distances and increasing CO_2 emissions. The net effect is a priori ambiguous.

Finally, transit subsidies are generally believed to be pro-poor, enabling the poor to maintain a reasonable level of accessibility to jobs. Evidence however suggests that in Buenos Aires Metropolitan area, transit subsidies disproportionately benefit the middle income class rather than the poor (Bondorevsky, 2007). If the aim of the transit subsidy is to provide the poor with urban transport options then the targeting is inefficient, resulting in both bad resource use and low accessibility for the poor.

In this context this paper examines the spatial development, welfare, redistributive and environmental impact of cost recovery fares under a range of different policy scenarios that could potentially cushion the impact of fare increases. The scenarios that we scrutinize are the uncompensated removal of the public transport subsidy, its replacement by a lump sum transfer, and its replacement by two different construction subsidy schemes. The first construction subsidy device assumes that a fixed share of the construction costs is subsidized wherever construction occurs, while the second device targets specific zones that benefit from high transit accessibility within the urban area. Special attention is paid to the lump sum transfer counterfactual as it is theoretically optimal and because there is a rich history of cash transfers in Argentina, in particular following the 2001 crisis. The outcomes of counterfactual scenarios are compared to the baseline and the results are assessed along four dimensions: 1/ the aggregate welfare or efficiency impact on residents, 2/ the impact on the internal structure of the urban area and on sprawl, 3/ the impact on commuting related CO_2 emissions and 4/ the redistributive impact of each policy scenario with a focus on the poorest households in the urban area of Buenos Aires.

To investigate the respective impacts of cost recovery fares associated with compensatory policy options along the efficiency, spatial, environmental and redistributive dimensions, we use a simple land-use transport interaction model calibrated for the urban area of Buenos Aires, NEDUM-2D (Viguié and Hallegatte, 2012), which can account for all these dimensions. Many land use–transport integrated models (LUTI) exist and the applied research community has made great progress on these in the past decades. No single LUTI model however is perfect and the choice of the most appropriate model is very dependent on the research question and the degree of detail/simplicity which is expected. A number of criteria explain the choice of NEDUM-2D: 1/ it is a simple and understandable model – not a black box; 2/ it is one of the only ones that describes the housing and land market with micro-economically founded behaviors; 3/ it is not a data greedy model which makes it usable in data scarce situations and 4/ it is a dynamic model which can capture the impacts of shocks and transitions, including adjustment costs. As we

will see below, however, the model is not able to capture all the mechanisms that would be required to answer all questions, and we explore options for further developments.

A series of results emerge from our exercises which paint a complex picture of transit subsidies and alternative cost-recovery options in the urban area of Buenos Aires. First, there are efficiency/welfare gains associated with replacing the transit subsidy by a lump sum transfer. These are non-negligible when subsidization rates are high. In the case of Buenos Aires, the average gains would correspond to an extra US$ 325 per household when expressed in equivalent income or 1.75% of the average household's annual budget in 2014. Our definition of welfare includes only consumption of housing space and other goods. For example, we do not explicitly account for distributional impacts or various externalities such as the access of the poorest to economic opportunities and the associated benefits of social inclusion. Nor do we feature specific preferences such as preferences for low density housing. For these reasons we will refer to consumption-related welfare in the rest of the paper.

Second, the removal of the transit subsidies leads to moderate reductions in urbanization over time. This indicates that the argument that low transit fares could fuel large amounts of sprawl in the future and associated infrastructure costs are likely to be overplayed. The changes in the internal structure of the urban area of Buenos Aires are much larger however with higher densities close to jobs and a decrease in the average distance to jobs triggered by the removal of the subsidy, which in turn reduces commuting distances. So, although public transport ridership decreases in the medium to long term as a result of the fare increase, the increase in commuting related CO_2 emissions is expected to remain limited. In fact, if the transit subsidy is replaced by a targeted construction subsidy, the model predicts a net reduction in emissions by 0.7%. The most CO_2 intensive policy alternative is the lump transfer with emissions increasing by more than 5% in 2050.

Thirdly, whereas some efficiency gains are to be expected from replacing the transit subsidy by a lump sum transfer, these will come at the expense of short term harsh redistributive impacts for the heaviest users of public transport. These negative redistributive impacts are stronger as the distance to the city center increases. For tenants, they will be partially mitigated over the medium term by land and housing markets mechanisms whereby the hardest hit areas of the urban area will see a decrease in housing rents reflecting lower accessibility. This adjustment in housing prices will benefit tenants and newcomers to the urban area but will penalize homeowners residing in these areas as they will face both higher commuting costs and lower resale values of their dwellings. The high rate of home ownership, across all income groups in Buenos Aires, including the poor, increases the negative impact of higher transit prices.

The remainder of this paper is structured as follows. Section 4.2 provides a literature review of the welfare, spatial, environmental and distributional impacts of transport and construction subsidies. Section 4.3 describes the history and functioning of transit subsidies in Argentina and Buenos Aires in particular. Section 4.4 investigates the welfare impacts of a public transport subsidy in a very simplified urban economics framework and describes the mechanisms at play. Section 4.5 describes the principles and mechanisms of the land use – transport modeling framework, NEDUM-2D, used in the remainder of the paper to assess the impacts of the transit subsidy in Buenos Aires and of alternative policy options. It also shows how simulations compare to

data which serves to validate the use of the model. Section 4.6 describes the various cost-recovery options studied and how they affect the extent of the urban area and the CO_2 emissions from commuting as well as households' welfare. Section 4.7 investigates the distributional impacts of removing the public transit subsidy and replacing it by a lump sum transfer for all income groups in the urban area of Buenos Aires. Finally, section 4.8 concludes.

4.2 LITERATURE REVIEW

There is a relatively well established literature focusing on the link between welfare and transport subsidies starting with Mohring (1972). This seminal paper argued that in the presence of scale economies in public transport provision (for example because a train or a bus is indivisible), marginal cost pricing schemes would lead to low public transport ridership which in turn would result in low frequencies and long (and sub-optimal) waiting times for users. This Mohring effect would warrant public transport subsidies so as to reduce waiting times and increase welfare. The magnitude and even the existence of the Mohring effect is however debated (Estupiñán et al., 2007). Gwilliam (2017) in his recent review on transport pricing emphasizes that if urban transport can be considered as a "merit good", i.e. a good which is undervalued by its consumer and the consumption of which generates positive externalities, this would provide a theoretical basis for subsidization. There are reasons to argue that urban transport indeed is a "merit good" as the accessibility for example to an increased number of jobs generates positive externalities through larger and more integrated labor markets (Rosenthal and Strange, 2004). Other scholars (Basso and Silva, 2014; Parry and Small, 2009; Parry and Timilsina, 2010) have built models and frameworks which aim at identifying optimal transportation policies in urban settings in the presence of externalities such as congestion, CO_2 emissions contributing to climate change, air pollution and road fatalities. All these papers find positive welfare effects associated with transit subsidies. But they argue that transit subsidies are only a second best and are dominated by policies which affect congestion (the main negative externality) more directly such as congestion tolls, gasoline taxes or dedicated bus lanes. However, these models are non-spatial in essence and although they are evaluated in urban settings they do not represent households' locational decisions explicitly. This means that they miss the tradeoff between housing and transport costs and may underestimate the benefits that policies which decrease transport costs may bring (because they can also decrease housing costs for residents) and conversely overestimate the benefits of policies that increase transport costs such as congestion tolls.

The reliance on non-spatial models also means that it is not possible to shed light on the urban expansion consequences of transit subsidies and their associated costs. To fill this gap, scholars have resorted to the classic urban economics framework based on the pioneering works of Alonso (1964), Mills (1967) and Muth (1969). In urban economic theory, a decrease in transport costs tends to flatten the land and housing rent curves thereby encouraging residents to settle further away from the city center and displacing the urban area's boundary outwards (see for example Fujita (1989)). Whether transport subsidies lead to urban sprawl when the decrease in transport costs is financed through income taxation is however not as trivial. Brueckner (2005) tackles this issue and shows that despite the higher tax burden needed to finance a transport subsidy, the transport cost reduction dominates the tax burden effect and leads to urban sprawl. He also concludes that if the

transport system displays constant returns to scale, the subsidy is welfare reducing. Building on Brueckner's work, Su and DeSalvo (2008) develop a monocentric model with two modes, cars and transit, which are characterized by different fixed and marginal costs as in LeRoy and Sonstelie (1983). The authors also employ empirical methods. They find that car subsidies tend to increase the size of urban areas while transit subsidies would reduce sprawl. In both cases the effects are limited in magnitude. Conversely, while they do not directly assess the spatial impact of any transport subsidization scheme, Gonzalez-Navarro and Turner (2018) study the impact of subway system construction in 138 cities around the world and conclude that they have caused population decentralization. It is not obvious how to make sense of these contradictory results. There are a number of subtle mechanisms at play, which would push the overall net result in one direction or another: 1/ a higher tax burden to finance the transit subsidy would tend to curb sprawl by reducing available income for housing space consumption; 2/ the lower transport cost would push the urban area's boundaries outwards; and 3/ because public transit is by nature more localized than road (think of bus or urban rail stops for example) we could have a combination of more concentrated population with transit subsidies around transit stops and a larger urban footprint.

Scholars have also investigated the distributional impact of transit subsidies by distinguishing between income groups (Basso and Silva, 2014; Estupiñán et al., 2007) but also between renters and landowners (Borck and Wrede, 2005, 2008). Basso and Silva (2014) find that congestion pricing, dedicated bus lanes and, more importantly for this paper, transit subsidies unambiguously increase the welfare of the poorest. Borck and Wrede (2005, 2008) use a monocentric model with two income classes to study the reasons for popular support to transport subsidy schemes despite clear inefficiencies. Their conclusions are less straightforward. When only one transport mode is available, they show that transport subsidies can benefit all residents in the case of absentee landowners at the expense of the landowners. When conversely all land is owned by residents of the urban area, commuting subsidies lead to a distributional antagonism between central residents and suburbanites. While the rich would benefit at the expense of the poor if they reside in the periphery, benefitting proportionately more from the subsidy, the poor do not necessarily benefit if they live on the outskirts (Borck and Wrede, 2005). Borck and Wrede (2008) then complete their model by introducing two distinct transport modes, cars and public transport. In this case the conclusions are much more subtle as the winners and losers depend not only on their location within the urban area and whether they are landowners or not but also on the commuting mode they use.

Finally, Estupiñán et al. (2007) conduct an in-depth review of real world transit subsidy schemes and focus on whether they are pro-poor. They find that whereas in developed countries transit subsidies mainly benefit the poor, this is mostly not the case in developing countries where transit remains a luxury good. The authors argue that, as the more wealthy urban residents benefit more than the poorest, a lump sum transfer would actually be a better device to reach the poor than a transit subsidy. In particular, they document that the transit subsidy program in the Buenos Aires region disproportionately benefits the middle income class rather than the poor, although subsidized fares are available to all. There are indeed significant errors of exclusion, defined as the share of the poor (the bottom quartile) not benefitting from transit subsidies because they do not use transit. For bus users the error of exclusion was as high as 70% in 2002 and 60% in

2006 (Bondorevsky, 2007). Conversely the errors of inclusion, defined as the share of beneficiaries which are non-poor was 59% in 2002 and 75% for bus users in 2006 (Bondorevsky, 2007). These figures indicate that if the aim of the transit subsidy is to provide the poor with urban transport options then the targeting is inefficient, resulting in both bad resource use and low accessibility for the poor.

To the best of our knowledge, the most comprehensive effort at addressing welfare, spatial, environmental and distributional impacts of transport subsidies is a paper by Tscharaktschiew and Hirte (2012). The authors develop a Computable General Equilibrium model, inspired by Anas and Xu (1999) and Anas and Rhee (2006), which includes many real world features such as congestion, polycentric urban structures, multiple household types, different trip purposes and endogenous labor supply among others. They calibrate their model so as to reproduce the main features of an 'average' German city and test a wide range of urban transport subsidies schemes; one of them being a variant of a transit subsidy in the form of a reduced sales tax rate on public transport fares. The authors find that transit subsidies lead to only low levels of suburbanization, are welfare enhancing (including for landowners) and decrease CO_2 emissions.

The urban economics literature is surprisingly silent on the issue of construction subsidies, despite the acknowledgment that land and housing markets are central to urban development. Construction and buildings have rightfully been investigated because their durability imposes some path dependencies in cities (Duranton and Puga, 2015). Other scholars have focused on the impact of building height regulations on welfare and spatial expansion (Bertaud and Brueckner, 2005) and on environmental externalities such as CO_2 emissions (Borck, 2016). It is however surprising that in a world which faces large housing deficits (estimated to be a billion homes according to UN-Habitat), especially in the rapidly urbanizing developing countries, little attention has been paid to the potential impact of construction subsidies. This is perhaps even more surprising as the compact city concept has gained a lot of attention as a sustainable urban growth trajectory (OECD, 2012). Indeed, whereas compact cities carry the potential to reduce commuting related CO_2 emissions, their critics often argue that they would lead to higher housing costs (Krupp and Acharya, 2014) and the actual densification of an urban area would prove difficult because taller buildings are typically too costly (Castel, 2007). In this respect, construction subsidies – justified by the positive externality of higher densities – seem like an a-priori promising avenue to reduce the housing deficit while enabling the construction of taller building and therefore achieving more compact and sustainable cities without leading to strong housing price increases. As Glaeser (2009) puts it "The best thing that we can do for the planet is build more skyscrapers." A notable exception to this silence is Helsley and Strange (2007) who develop an urban economics model where positive externalities are generated by social interactions. They find that a construction subsidy can increase the housing supply near the city center and lead to a densification of the urban area which would promote social interactions and therefore increase social welfare.

4.3 PUBLIC TRANSPORT SUBSIDIES IN THE METROPOLITAN AREA OF BUENOS AIRES

Following the 2001 crisis and the peso depreciation which led to spiraling inflation in Argentina, public transport fares were frozen (or increases were

restrained) in an attempt to dampen the impact of rising prices and protect the incomes of the poor. In parallel, the costs of operating public transit systems increased strongly in part as oil imports were purchased using a devaluated currency. The government provided direct (supply-side) subsidies to operators in order to maintain public transport service in a post-crisis period. While buses (colectivos), which today account for 87% of the public transport ridership, were not subsidized prior to the 2001 crisis, subsidies now account for over two-thirds (71%) of their operating costs. The average commercial fare of AR$ 3.5 can be compared to the AR$ 12 average fare necessary to achieve cost recovery. On the regional railway and metro (SUBTE) systems subsidization rates today represent respectively 94% and 68% of operating costs. Their passenger market shares are however much lower than for buses at 7% and 6%. In total, the public transport subsidies in the Area Metropolitana de Buenos Aires (AMBA) amount to AR$ 25 billion or around US$ 5.4 billion[3] in 2012 which represents close to 0.7% of Argentina's GDP.

While public transport is subsidized in other metropolitan areas in Argentina, the subsidization rates are lower and the minimum bus fares are higher: AR$ 6 and AR$ 9.15 in Mendoza and Córdoba respectively for example compared to AR$ 3 in AMBA.

The public transit subsidies in Argentina are currently financed by the Treasury (85%) and SISTAU (Sistema Integrado de Transporte Automotor) for the remaining 15%. The SISTAU funds are based on a 18.5% tax on gasoline while the Treasury funds are channeled through the RCC (Régimen de Compensatión Complementaria). Together the Treasury funds and SISTAU finance 72% of the operating costs of public transport systems in AMBA while earnings from travel fares account for the remaining 28%.

How does this compare to other cities worldwide? These public transport subsidization levels are commonplace in developed countries; for example they reach around 70% of operational costs for the largest 20 cities in the United States (Parry and Small, 2009), 55% in London, 70% in Paris (Institut Montaigne, 2012) and the Millennium database reports similar figures for many developed country cities around the world (Kenworthy, Laube, and Vivier, 2001). In developing country cities however, public transport subsidies are very low or non-existent. In this respect, Argentina and above all the Metropolitan area of Buenos Aires are exceptions (Basso and Silva, 2014).

Beyond the general discussions about public transport subsidy merits and potential inefficiencies that are mentioned in the introduction and literature review, there are a couple of specific points that deserve to be reported here. First, public funds have an opportunity cost, meaning that when they are mobilized for financing public transit systems, they are not available for other priorities such as education, health and sanitation for example. While public funds have opportunity costs in all countries and at all times, the necessity to allocate them wisely is arguably more critical in a developing country which is recovering from a major economic crisis as occurred just above a decade ago and where fiscal resources are likely to be scarcer than elsewhere. The need to evaluate whether these resources should be sunk into public transit subsidies or not is even more pressing as Argentina is an exception in the developing world in its choice to instore a transit subsidy scheme.

[3] All monetary values were converted into US$ for data consistency. The exchange rate that is used throughout this exercise is AR$1 = US$0.2198. The conversion factor was retrieved from the web for the month of July 2012.

Second, the design of the scheme is conducive to some inefficiencies and perverse effects. Indeed, the supply side subsidies from the government are calculated so as to cover the deficits of the private transit operators. The latter therefore do not have any incentive to rationalize their operations and seek inefficiencies in their system as this would only result in a reduction of the subsidy level received from the government.

Thirdly, the massive level of subsidies poured into the public transit systems cover only the operational costs and leave very little available fiscal resources for investments and crucial maintenance of the public transport infrastructure. The lack of investment and maintenance has led to a slow degradation of the infrastructure and to the impossibility of keeping pace with urban growth through the addition of new routes or extension of existing ones.

The Argentine government is well aware of these issues and is exploring ways in which to reduce the fiscal burden of public transport subsidies without adversely impacting the poorest 40% of households which crucially rely on transit to reach jobs and other services. In early April 2016, fare increases were implemented with a doubling of the minimum fares for buses and trains (fares for colectivos now stand at min AR$ 6; trains AR$ 4); and recently fares for SUBTE (metro) also increased. Operating subsidies for buses have been reduced to 66%. Alongside this process, the government has also been offering demand-side subsidies to protect the poor from these fare increases. In this study we do no account for the changes in transit fares that took place in 2016 and rely on the subsidization levels and fares prior to these increases.

4.4 WHAT IS THE EFFICIENCY OF PUBLIC TRANSIT SUBSIDIES AND OTHER POLICIES?

To explore the efficiency of transit subsidies in a general case we will compare these to a policy option whereby transit subsidies are removed but a lump sum redistribution of the total initial transit subsidy savings is introduced. Comparing transit subsidies to a lump sum transfer is justified because lump sum transfers are usually deemed to be a more efficient public intervention as they do not distort household choices toward the consumption of a specific good, in this case transport. The comparison of the outcomes of a transit subsidy with that of a lump sum transfer through the measurement of households welfare and landowners' profit in an urban economy aims to provide a benchmark for measuring the (in)efficiency of a transit subsidy (through orders of magnitude). We will focus distinctly on households' and landowners in order to untangle the impacts of removing a public transit subsidy and compensating through lump sum transfers for each group of actors in the urban economy.

4.4.1 *A simple model to compare lump sum transfers to transit subsidies*

To investigate the efficiency of public transport subsidies, we will first focus on a very simple and schematic case. We use a monocentric model based on the works of Alonso (1964), Mills (1967), Muth (1969) and comprehensively described in Fujita (1989). This model displays one city center which is the commuting destination of all households of the urban area (the CBD). There is only one transport mode and we run the model in a static framework, i.e.

at equilibrium with only one time period. In this simple model, residents derive utility from housing space q and a composite good z:

$$\text{Max}_{r,z,q} U(z,q) \quad \text{s.t.} \quad z(r) + R(r)\,q(r) + T(r) \leq Y + \overline{L} \tag{4.1}$$

Each worker has to commute once a day to the CBD, and this commuting entails transportation costs $T(r)$. All households are supposed to earn the same income Y and – at the equilibrium – they have the same level of satisfaction described by a utility function U. The level of rents per square meter (or, equivalently, the annualized real estate price per square meter) is $R(r)$, at each location in the city. Each household maximizes his utility function under the budget constraint described in (4.1) by choosing where to settle in the urban area r, how much housing space q to consume and what to spend on other goods z. The term $\overline{L}$ represents the annual amount accruing from land rents per household which is recycled in the urban economy in the form of increased incomes.

In parallel, developers decide how much floor space to build and where in the city. They do so by choosing the amount of capital to invest at a specific distance to the city center $K(r)$ in order to maximize their profit function which also represents land values.

$$\pi(r) = \left[(R(r) - R_0)\,F(K(r), L(r)) - (i+\rho)K(r)\right] \tag{4.2}$$

The amount of floor space built and the annual land rents depend on an exogenous specific construction technology which displays decreasing returns to capital: $H(r) = F(K(r), L(r))$. These decreasing returns to capital will cap the building heights and as consequence the total amount of residential floor space. Developers will only invest large amounts of capital to build tall buildings when the anticipated rents they expect will offset the extra building costs. The edge of the city is given by a transaction cost R_0 below which it is no longer profitable to build. At the edge of the city (r_f) we therefore have $R\left(r_f\right) = R_0$.

The term $\overline{L}$ found in (4.1) can schematically take on one of two values depending on the type of model used: Closed City model with Absentee landowners (CCA) or Closed City model with Public ownership of land (CCP). In the closed city model with absentee landowners (CCA), landowners are supposed to live outside the urban area which means that land rents are not recycled in the local economy in the form of increased incomes. In this case $\overline{L} = 0$. At the opposite end of the spectra, if all land plots are supposed to be owned by a local government (or by all households in equal shares) then $\overline{L} = \int_0^{r_f} \frac{\pi(r)}{N} \mathrm{d}r$, where N is the number of households in the urban area.

The functional forms used in this paper as well as more details on the construction function can be found in appendix 4.9.1

4.4.2 *Numeric simulations: Aggregate welfare description of results*

4.4.2.1 *Impacts on tenants and landowners of replacing a transport subsidy with a lump sum transfer*

Solving the static model described in 4.4.1 with specific functional forms described in Appendix 4.9.1 in the closed city model with Absentee landowners (CCA), it can be shown that the impacts of replacing a transport subsidy by a lump sum transfer are complex. We run a numerical model with a number of realistic values for key parameters and data values for the model

in 2012 described in Appendix 4.9.2, but with the assumption of a unique transport mode, linear transport costs, no land regulations and with a transaction cost of zero. We also assume, as in Parry and Timilsina (2010), that public transport displays constant returns of scale, meaning that only the variable costs of transport are accounted for and not the fixed costs linked to infrastructure provision. This is a reasonable proxy for buses which constitute the main public transport means. We run simulations for a large range of subsidization/taxation levels: from a 100 percent taxation level to a subsidization level equivalent to two-thirds of the transport costs. Impacts of these transportation policies on tenants' welfare and landowners' aggregate profits are depicted in Figure 4.1 and Figure 4.2.

Figure 4.1 shows that transport taxes/subsidies (transport taxes are the negative values on the x-axis while subsidies are the positive ones) are generally detrimental to tenants' welfare when compared to lump sum transfers. This is visible from the curve representing the ratio between tenants' utility with subsidies and with lump sum transfers mostly being lower than one. However, there are some values of the transport subsidies for which tenant's consumption-related welfare is higher with subsidies. These welfare improving subsidization rates are 9% and 17% with the optimal subsidization rate being 9% and with welfare improving very slightly by 0.03% by comparison to lump sum transfers which makes it visually difficult to discern on Figure 4.1.

The transport subsidy relaxes tenants' budget constraint and allows them to settle further from the city center, thereby consuming more floor space and land at a cheaper unitary rate. As such a transport subsidy transfers rents from landowners to tenants as can be seen in Figure 4.2.

When the subsidization rate is positive, it can be seen that landowners' aggregate profit decreases with the subsidy relative to lump sum transfers in a closed city model with absentee landowners. The opposite is true for transport taxation which increases landowners' profits. The implicit transfer of wealth from landowners' to tenants triggered by the transport subsidy is sufficient to increase tenants' welfare relative to lump sum transfers for specific subsidization rates as documented above (Figure 4.1).

In Buenos Aires urban area, as documented in section 4.3, public transport is subsidized by around two-thirds. We are therefore mainly interested in depicting the impacts of a drastic subsidy of 67%. It can be shown that replacing this level of transit subsidy with a lump sum transfer:

- increases household utility by 5.20%
- increases Aggregate Landowners' Profits by 20%

We can draw two conclusions from this section. First, transport subsidies are not unambiguously negative for tenants in a closed city model with absentee landowners (CCA). In fact, low levels of transport subsidies (between 9% and 16%) can marginally increase tenants' consumption-related welfare relative to lump sum transfers. This impact can be interpreted as a wealth transfer from landowners to tenants and is consistent with findings in Gusdorf and Hallegatte (2007). Second, a transport subsidization rate as high as 2/3 of the transport cost constitutes a less efficient means of improving both welfare and land rents than a lump sum transfer. In particular transport subsidies hurt landowners quite harshly compared to a lump sum transfer.

Household utility and landowners' profits are however difficult to compare because landowners' total profit is measured directly in monetary terms, whereas households' utility level is a convenient yet abstract construction

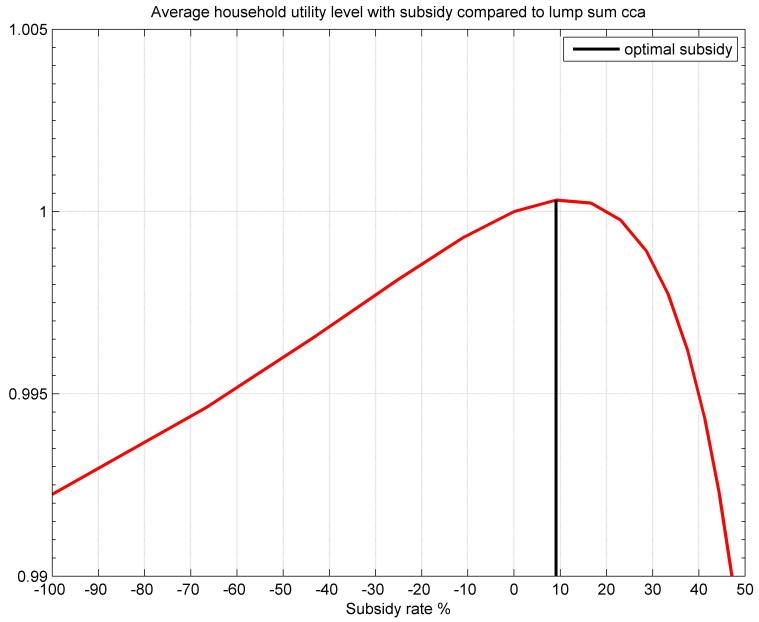

Figure 4.1: Comparison of tenants' consumption-related welfare with transport subsidies and lump sum transfers in a Closed City model with Absentee landowners (CCA).

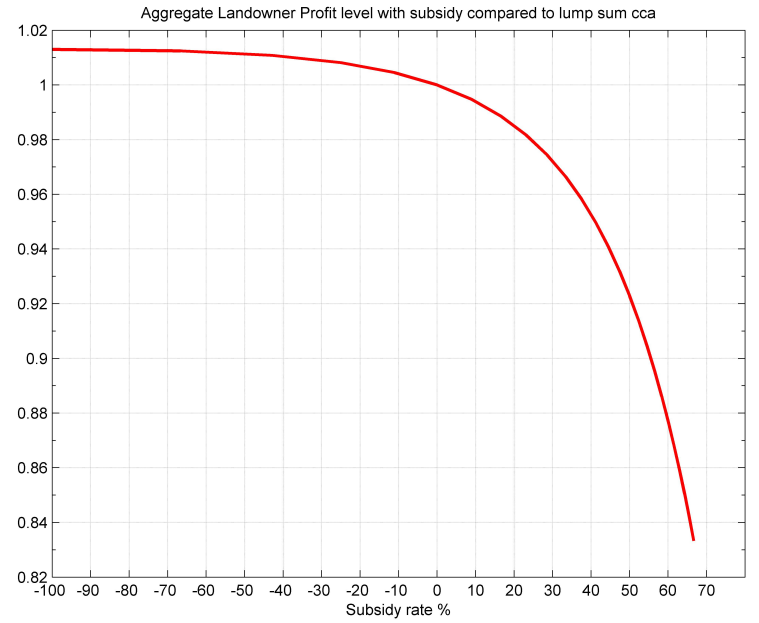

Figure 4.2: Comparison of Aggregate Landowners' profit with transport subsidies and lump sum transfers in a Closed City model with Absentee landowners (CCA).

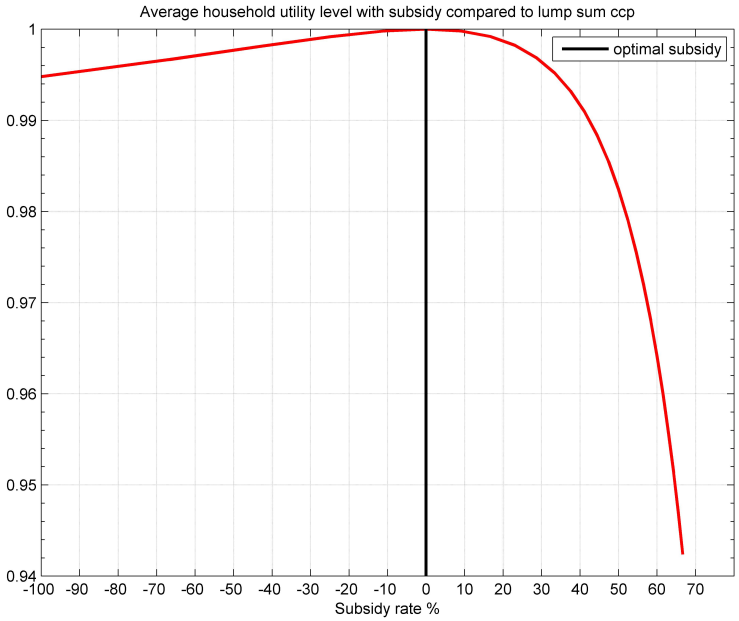

Figure 4.3: Comparison of household consumption-related welfare with transport subsidies and lump sum transfers in a Closed City model with Public ownership of land (CCP).

which cannot be directly translated into a monetary value. We would, however, like to understand how a transit subsidy performs against a lump-sum transfer policy through one unique indicator.

4.4.2.2 *Moving toward a city model with land rents recycling in the local economy*

One way of achieving a unique indicator of the welfare impact of transport subsidy for landowners and households is to incorporate landowners' proceeds into the households' utility function by switching to a Closed City model with Public ownership of land. As detailed above, in such a model, landowners' rents are recycled in the local urban economy through increased household incomes. This corresponds to a case whereby, $\overline{L} = \int_0^{r_f} \frac{\pi(r)}{N} \mathrm{d}r$. This is equivalent to assuming that one dollar has the same value for tenants and for landowners, or that both groups have the same marginal utility of consumption. While this representation is still a simplification, it does make sense for Argentina where the rate of dwelling ownership is very high, close to 80% over all income quintiles (Fay, 2005, pp 93), reported for the early 2000s. It also allows us to take into account the impacts of transit subsidies and lump sum-transfers on land rents in the form of a welfare impact.

With a fully closed city model with public ownership of land, it can be shown that the optimal subsidization/taxation level is zero (Figure 4.3), which is consistent with findings from Brueckner (2005) and Gusdorf and Hallegatte (2007) among others.

While the uncompensated removal of the transit subsidy (equivalent to two-thirds of the transport costs) leads to 22.6% decrease in household utility, the compensation in the form of a lump sum transfer yields a 5.7% increase compared to the baseline scenario with transport subsidies. This result confirms the economic intuition that cash transfers are preferable to

		Transport subsidization rate		
		1/3	1/2	2/3
Share of land rents recycled in the local urban economy	0: Absentee landowners (cca)	0.2%	1.3%	5.2%
	0.2	0.3%	1.4%	5.4%
	0.5	0.4%	1.6%	5.7%
	0.8	0.4%	1.7%	5.9%
	1: Public ownership of land (ccp)	0.5%	1.8%	6.1%

Table 4.1: Consumption-related welfare impacts of replacing a transport subsidy by a lump sum transfer as a function of subsidization rates and ratio of land rents which are recycled into the local urban economy.

subsidies because they allow households to choose how to use them, thereby providing them with a supplementary degree of liberty.

But these results should be interpreted with caution for a number of reasons. First, the increase in consumption-related welfare triggered by switching from a transport subsidy to a lump sum transfer depends on the level of recycling of land rents into the local economy. Second, this increase in welfare depends equally on the rate of subsidization of the transport system. In both cases, welfare improvements from replacing the subsidy by cash transfers are higher when 1/ the ratio of land rents recycling into the local urban economy is high and 2/ the transport subsidization rate is high. Both these effects are depicted in Table 4.1:

Table 4.1 shows that potential welfare gains are large with a lump sum transfer rather than a transport subsidy, especially if subsidization rates are high and land rents are recycled in the local urban economy, which is the case in Buenos Aires. This warrants a more in depth exploration of the welfare impact of transit subsidies in a more realistic model tailored for the urban area of Buenos Aires.

This picture omits two important dimensions of the discussion. The first is the dynamics of urbanization and in particular how each policy influences urban sprawl and its associated infrastructure costs and transport emissions. The second is the re-distributional impacts of each policy. To look into these dimensions we need a model which is spatially explicit so as to capture realistically the urbanization trajectory of the urban area of Buenos Aires and how the poor will be affected by an increase in public transport fares. The next section will present the model that we use in the rest of this paper while sections 4.6 and 4.7 will address the urban sprawl, environmental, welfare and political economy issues involved with public transit subsidies and other alternative policy options.

4.5 DYNAMIC MODEL NEDUM-2D APPLIED TO BUENOS AIRES

A theoretical framework that reflects the interplay between households' localization decisions, project developers' construction decisions and transport costs is required to evaluate the impacts of removing public transport

subsidies in an urban area. The NEDUM-2D model (Non Equilibrium Dynamic Urban Model) developed in CIRED (Viguié and Hallegatte, 2012), and comprehensively described in Chapter 1 is well suited to conduct such a study. The appendices in section 4.9 also provide an in-depth description of NEDUM-2D as it is applied to Buenos Aires, including data sources and modelling choices.

4.5.1 *Geographic scope of the study*

The study area is slightly larger than what the INDEC (Instituto Nacional de Estadística y Censos de la República Argentina) defines as the Gran Buenos Aires (GBA). GBA encompasses 24 fully or partially urbanized partidos and the City of Buenos Aires (CABA). Supplementary to the 24 partidos of GBA, our study area also includes 3 other partidos. Altogether the study area that we will name GBA+ in the rest of this report can be broken down as follows:

- The city of Buenos Aires (CABA)
- 14 fully urbanized partidos that belong to GBA:

Avellaneda	Lanús	San Isidro
General San Martín	Lomas de Zamora	San Miguel
Hurlingham	Malvinas Argentinas	Tres de Febrero
Ituzaingó José C. Paz	Morón Quilmes	Vicente López

- 10 partially urbanized partidos that belong to GBA:

Almirante Brown	Florencio Varela	San Fernando
Berazategui Esteban Echeverría	La Matanza Merlo	Tigre
Berazategui Ezeiza	La Matanza Moreno	Tigre

- 3 partidos that do not belong to GBA

Escobar	Pilar	Presidente Perón

The Gran Buenos Aires covers more than 3,800 km^2 of land and the GBA+ area is close to 4,000 km^2.

4.5.2 *Validation of NEDUM-2D on the urban area of Buenos Aires (GBA+)*

With a limited amount of data describing the size of the population, households' income, the transport system, land use, construction costs, households and developers' behavior, NEDUM-2D can reproduce the structure of an urban area in a fairly accurate way. This section aims at demonstrating this for the Buenos Aires region[4]. Appendix 4.9.2 provides an in-depth description of the data and parameters used in the simulations both for 2012 and for the projections.

[4] The model has been successfully applied to the urban area of Paris (Avner, Rentschler, and Hallegatte, 2014; Viguié and Hallegatte, 2012), London (Viguié, 2012) and Toulouse (Masson et al., 2014).

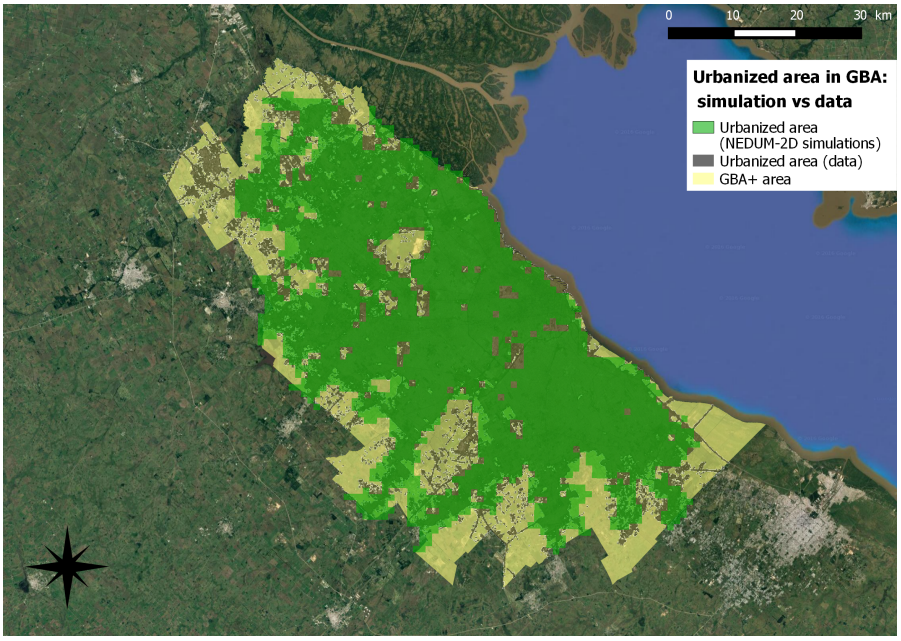

Figure 4.4: The simulated and real urban area of the GBA+ region in 2012. The green shade corresponds to the simulation whilst the black is geographic data. The dark green shade shows areas where the model accurately predicts urbanization. Light green shows areas where the model inaccurately predicts urbanization. Black stands for areas where the model fails to reproduce urbanization. Finally where the map is yellow, there is no urbanization and the model agrees with the data.

The last phase in applying the NEDUM model to a city is to run a calibration procedure. This is done by comparing results (map of urbanized area, real estate/rents, population and housing density) to observed data. Overall, the NEDUM-2D model is very robust as it relies on very simple basic economic behaviors that are likely to remain true both through space and time. As a consequence the calibration process is mostly done through refining the data that are used to inform the model. However, a very limited number of parameters can then be marginally modified so as to minimize the discrepancies between observations and model results.

It can be seen from Figure 4.4 that the simulated and the actual urban area in 2012 coincide quite well within the GBA+ region (which appears in light yellow). The model captures the general size of urbanized area but also its shape and specific urbanization directions along the transportation network. There are however some discrepancies even within the GBA+ boundaries. In particular it can be seen that the map misses some areas towards the North and the North West of the GBA+ region. This can mainly be explained either by the existence of local secondary employment centers that attract settlements or the presence of local amenities.

The shape and size is one among other features of an urban area. Below we compare data with simulations for the distribution of land values and population densities.

Figure 4.5 shows the classic result that land values decline as the distance to the city center increases both in the data and the simulations. It shows land value data represented by grey circles as well as the average of the data (dashed blue line). The green area captures the spread of the simulations for a given distance to the CBD, while the red plotted line represents the average of

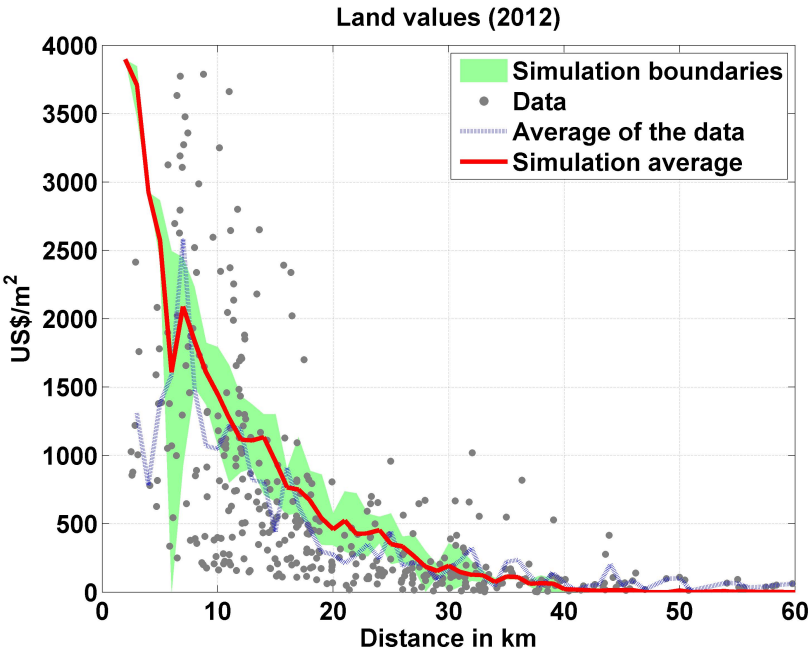

Figure 4.5: Simulated and actual land values as a function of the distance to the city center.

the simulation. The one dimensional R^2 coefficient – comparing the averages of the simulation and the data – is 0.68 meaning that the model can explain 68% of the one dimensional variance in the data. The two-dimensional R^2 coefficient – comparing the each pair of simulation and data points locally – is lower at 34%. As we move closer to the city center, the model tends to either underestimate or overestimate land values. In particular, the model fails to reproduce the spike in land values visible around km 10. There is also quite a lot of dispersion in the data (grey dots) which is only partially captured by the model (simulation boundaries are represented by the light green area). This dispersion in the data is highest in the vicinity to the city center.

This phenomenon is likely to be explained by social segregation processes and the existence of amenities (such as good schools). As the NEDUM-2D version we use in this study only accounts for one average social group it fails to reproduce the segregation mechanisms. More generally land values are in reality not only determined by land developers' behavior. Land is subject to speculation and performs a 'reserve value' function that the model does not account for. Indeed, within the urban economics framework, the value of land is determined only by its value as an input in housing production. It is likely that this partial representation of the value of land leads to some discrepancies as the ones discussed above. For this reason, where they are available (not the case in Buenos Aires), it is better to calibrate land use transport models based on rents rather than land values. They indeed display much more regularity across time and space and are less subject to speculative behaviors.

Figure 4.6 has the same color codes and purpose as Figure 4.5 but looks into whether and to what extent the simulations and the data agree for population densities at the census tract level (households/km^2). A similar conclusion can be drawn from the figure, that there is a general agreement on the shape of the two curves representing the averages of the data and

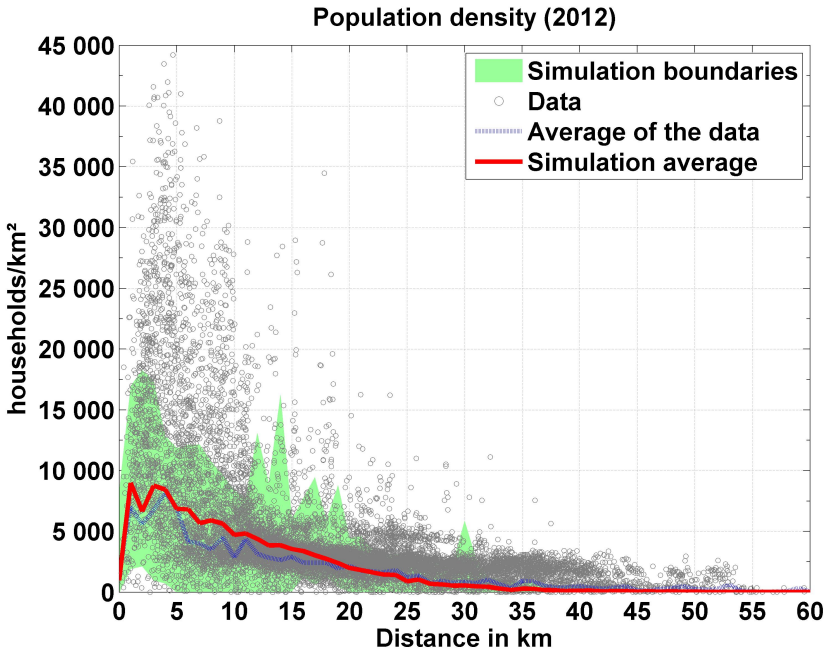

Figure 4.6: Simulated and actual population densities for all radios in GBA+ as a function of the distance to the city center.

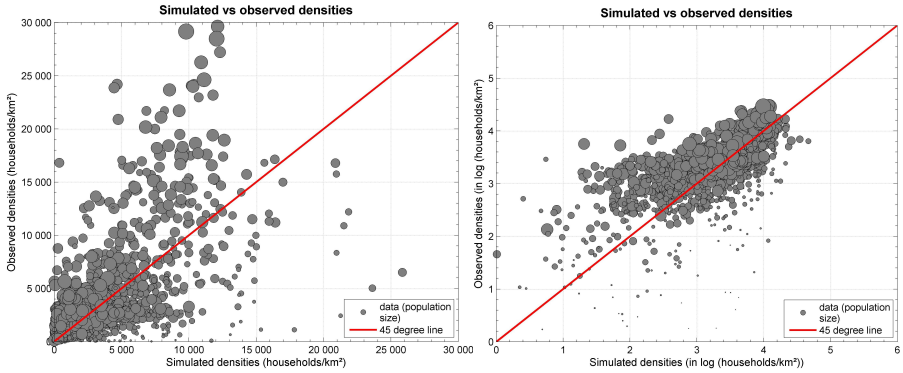

Figure 4.7: Comparison of simulated (on the x-axis) and observed (on the y-axis) population densities (densities on the left and log10 numbers on the right) at the *zonificaciòn* administrative level. The size of the bubbles is proportional to the population in each administrative unit.

the simulations. In particular, toward the city center, both curves display similar spikes and slumps. The model's spread also captures a large share of the data points (grey circles), although there is a greater dispersion in population densities of radios (census tracts) within 10km of the CBD that the model only partially accounts for. The one-dimensional R^2 coefficient is high at 0.95 meaning that the model can explain 95% of the variance between the simulation and data average. The two-dimensional R^2 coefficient comparing data and simulation at the census tract level, and accounting for the population of each census tract, is lower at 0.32.

Figure 4.7 usefully complements Figure 4.6. It shows on a scatter plot the differences and agreement between simulated and observed population densities at the *zonificaciòn* administrative level, which is slightly larger than a census tract. The closer the grey bubbles are to the 45 degree line,

the better the correspondence between simulated and observed densities. Bubbles above the red line indicate that the model underestimates densities while bubbles below indicate overestimation. The left panel of Figure 4.7 shows a clustering of points toward the bottom left quadrant around the 45 degree line, indicating small discrepancies in absolute terms. The model however struggles to reproduce higher densities. It can indeed be seen that as the observed population densities increase beyond 15,000 households per square.km, corresponding simulated densities tend to remain around the 10,000 household per square.km threshold. The right panel of Figure 4.7 shows the same comparison in log format and is a useful complement to the right panel. It shows the clustering of points along the 45 degree line but indicates that, although small in absolute terms, the discrepancies are highest in relative terms for lower densities which the model tends to underestimate. Overall, when excluding areas where population density is low, below 10 households per hectare, in 46% of the census tracts (*radio censales*) and 51% of the slightly larger administrative units (*zonificaciòn)*, the absolute variation between simulated and observed density is below 50%[5].

The model is reasonably accurate (i.e. less than 50% variation) at medium distances (around 10 km from the city center). However it tends to overestimate population densities going towards the south of the city center and the North. It also clearly underestimates population densities as we move towards the urban fringe of the GBA+ region. As argued above, spatial discrepancies, in particular towards the urban area edge can be explained by the existence of secondary employment centers, social segregation or local amenities that NEDUM-2D does not model, and which attract households. Some major employment centers, indeed exist toward the North, Northwest and West of the urban area, precisely where it appears that NEDUM-2D underestimates population densities.

Finally, the model is also validated against several figures that describe mobility behaviors for households in the Buenos Aires metropolitan area. The mode share for public transportation, which is determined endogenously in NEDUM-2D, is 56%, very close to the 57% average figure reported by the ENMODO mobility survey for the AMBA region (Ministerio del Interior y Transporte, 2010). The average commuting times computed by the model is 54 minutes so slightly higher than, yet in the same magnitude order as the 44 to 49 minutes reported by ENMODO.

While we have shown some local discrepancies between model results and data, the calibration of NEDUM-2D is satisfactory overall for the main features of the internal structure of Buenos Aires urban area: size and shape of the urban footprint, population distribution, land values, average commuting times and mode shares. Improving the NEDUM-2D modelling framework so that it can account for multiple employment centers would improve the fit of the model to data. This endeavor is left for the future, with the belief that although it will add some realism, it will not modify the main conclusions of the current analysis.

[5] If the population density threshold is lower, for example one and five households per hectare, then the agreement between the model goes down to 44% and 45% at the census tract level but remains stable at 50% and 51% at the *zonificaciòn* level. If the population density threshold is increased to 20 households per hectare, the agreement goes up to 49% at the radio level and stays at 51% at the *zonificaciòn* level.

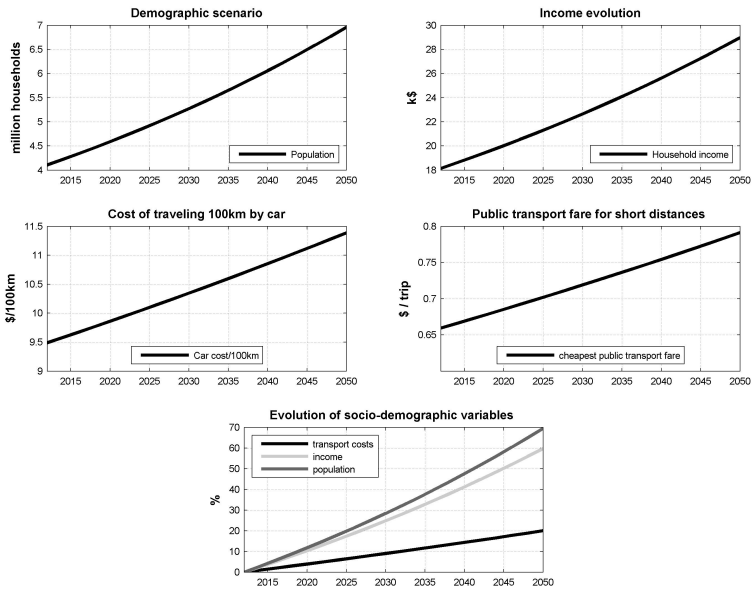

Figure 4.8: Evolution of the population, income and transport costs in the urban area of Buenos Aires over the 2012 – 2050 period in the baseline scenario.

4.6 POLICY ANALYSIS: URBAN SPRAWL, EMISSIONS AND WELFARE

4.6.1 *Evolution of the urban area in the baseline*

In order to investigate the impact over time of the removal of public transport subsidies and alternative scenarios, our study relies on projections of various inputs to the NEDUM-2D model from 2012 to 2050; in particular the future evolution of transport prices, income and population. In the baseline scenario population and income are supposed to pursue their recent trends over the next four decades. In particular, incomes are assumed to grow at the same average annual rate as Argentina's per capita net income over the 1970 – 2015 period (in constant 2010$), i.e. 1.24%, starting at US$ 18,140 in 2012 and reaching close to US$ 29,000 in 2050. The number of households in the urban area will evolve at the same annual pace as it did over the 2001 – 2012 period, reaching a little over 6.96 million in 2050. In the baseline scenario the prices of fuel and public transport fares increase at an identical pace to reach 120% of their 2012 levels in 2050. The evolution of these demographic and economic variables are summarized in Figure 4.8. It is also supposed that the current subsidization rate of public transport remains unchanged over time – around 2/3 of public transport fares. These inputs are a priori identical in the alternative counterfactual scenarios, unless the policies investigated explicitly impact some variables such as transit fares. Robustness to these assumptions on the evolution of main socio-economic variables is explored below with a high growth scenario.

With these main input variables feeding the NEDUM-2D modeling framework we can show the evolution of the urban area over time. It can be seen from Figure 4.9 that, as the population and incomes increase so does the consumption of land in the urban area. The extra urbanization in the simulations occurs mainly in the North along the major transport corridors. The urbanized

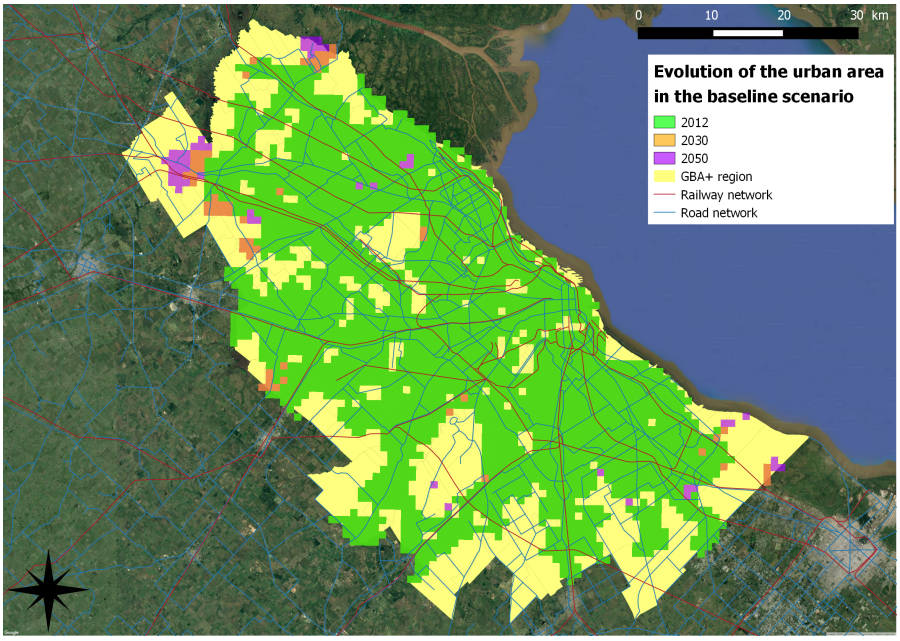

Figure 4.9: Evolution of the Buenos Aires urbanized area over time in the baseline scenario.

area increases from 2568 km^2 in 2012 to 2750 in 2050. This 7.1% increase can seem low. It can be explained by two main reasons. First, whereas population increases always lead to more land consumption in an urban area, income increases have an ambiguous effect. On one hand higher incomes increase the demand for housing space which will translate into more construction and floor space throughout the urban area but also into housing consumption at the fringe which pushes the boundaries of the urban area. On the other hand, higher incomes also mean higher opportunity costs of time thereby increasing the generalized transport costs and promoting density. This effect is far from being negligible as on average in the urban area of Buenos Aires time costs represent 72% of the generalized transport costs in 2012 and increase over time, as time opportunity costs increase more than monetary transport costs, to reach 76% in 2050. So time costs are a strong limit to sprawl.

Second, the model underestimates future urban expansion because it misses urbanization that occurs outside of the GBA+ area, represented as the light yellow background layer in Figure 4.9, due to lack of data on public transport costs and times beyond these boundaries.

We also built a second baseline scenario, to test how sensitive the urban expansion is to our assumptions about the evolution of the main datasets in the model. In this scenario, population in the urban area and the average household income double between 2012 and 2050 reaching respectively 8.2 million households and US$ 36,290. The monetary transport costs for cars and public transport evolve in parallel and decline by 10% over the simulation period. This scenario, by combining a decrease in transport costs and high growth rates of both population and incomes – all factors conducive to sprawl (Brueckner, 2001), naturally leads to an increase in the urbanized area. This increase however, here again remains moderate with 396 extra urbanized km^2 between 2012 and 2050 (compared to 182 km^2 in the previous scenario), a still modest 15% growth over the period. These results are indicative that the amount of new urbanization that is likely to take place over the

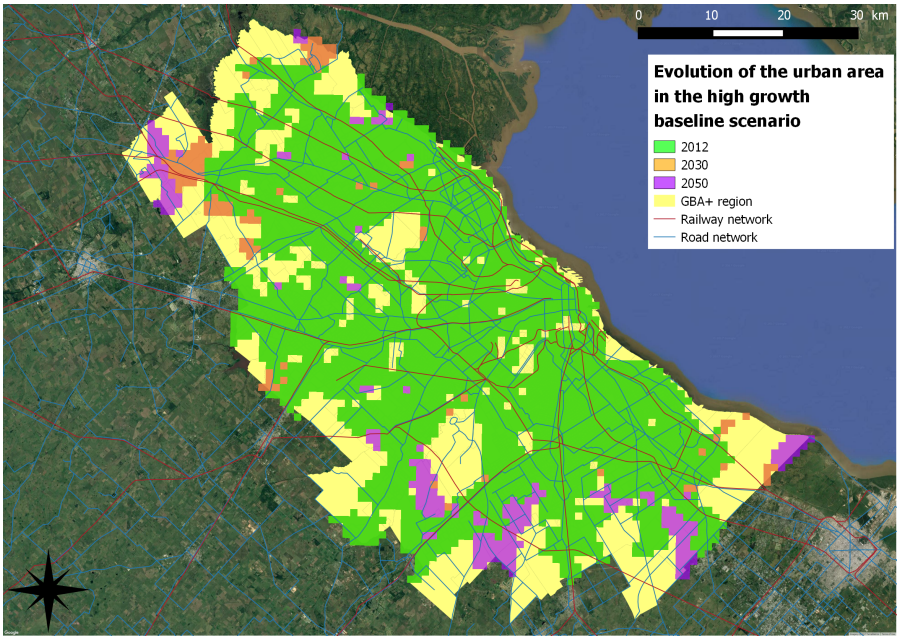

Figure 4.10: Evolution of the Buenos Aires urbanized area over time in the baseline scenario with higher population and income growth as well as a decrease in transport monetary costs.

next four decades in the Buenos Aires urban area is not very sensitive to socio-economic and demographic evolutions to come, that is if the spatial structure of the urban area remains reasonably similar to what it is today.

4.6.2 *Description of alternative policy scenarios*

4.6.2.1 *Public transport subsidy removal*

In this scenario, after 2012, public transport subsidies are removed which translates into a tripling of the public transport fares paid in the baseline scenario. This scenario is an extreme as any policy is likely both to increase fares less drastically and, in any case, more gradually. It is however useful to understand clearly the impacts of removing public transport subsidies and the resulting new urban trajectory. The results from this scenario can thus be interpreted as the maximum impact any public transport subsidy phasing out policy could likely entail. The transit subsidies, which are removed in this scenario, amount to US$ 4.22 billion. This figure is of the same order of magnitude as the reported transit subsidy volume for the urban area of Buenos Aires of US$ 5.4 billion (see section 3). As this figure emerges endogenously from NEDUM-2D, it is one supplementary indication of the realism of the model.

4.6.2.2 *Lump sum transfers of the public transport subsidy to households*

In this scenario where public transport subsidies are removed, the total savings are channeled to households on a lump sum basis. Note that we assume the money does not go to the rest of the country. As a result each household receives US$ 1,030 – 1,230 extra annually or, presented differently, around 4–5% of the average household income depending on the year in the urban area per year. This operation is neutral for local government

budget but will reduce the incentive for public transport ridership. We will document the impact of this lump sum transfer on households' location decisions and well-being.

4.6.2.3 *The introduction of a construction subsidy*

In this scenario, public transit subsidies are entirely re-invested in construction subsidies so that this policy is again neutral for the local government's budget. The aim is to understand if encouraging construction (through lowering its cost) could limit urban sprawl and modify locational decisions of households within the urban area so as to reduce the need to travel long distances which justified in part public transport subsidies in the first place. The subsidized share of construction costs of the new structures reaches 4.7% immediately after the removal of the transit subsidy and decrease to 4.4% in 2050 because the transit subsidies increase less quickly than the construction costs[6].

4.6.2.4 *The introduction of a construction subsidy which targets high accessibility zones*

In this scenario, public transport subsidies are re-invested in construction subsidies targeted for high transit accessibility zones. Can these construction subsidies re-orient urban trajectories towards less land intensive pathways while intensifying land use around public transport corridors and stations? Building on work from Peralta Quirós and Mehndiratta (2015), we identify zones within the urban area of Buenos Aires which benefit from high transit accessibility. The construction subsidies are still equal in volume to the transit subsidies in the baseline scenario; however they can only benefit construction within the high accessibility zones. The choice of the zones and of the criteria to include some and exclude others is therefore crucial. In this exercise, we chose a threshold of 1,000 jobs accessible through transit per capita within one hour. The zones which are eligible to receive the targeted construction subsidy are presented in Figure 4.11 in the left panel. This criterion limits the provision of construction subsidies to zones with high transit accessibility and relatively low population. Other choices are possible (as can be seen in the right panel of Figure 4.11) and will be explored in the future. The construction subsidies when available in this scenario are higher than in the previous and range from 5.5% to 5.4% of the costs of new construction. Indeed, as some zones are excluded from potential subsidization, the structures in the eligible zones benefit from higher construction subsidy rates.

4.6.3 *Policy impacts: Sprawl, distances travelled, emissions and welfare*

In this section we want to investigate the impact that each policy package described above will have on 1/ the size of the urbanized area: can alternative policies limit the growth of the urbanized area over time? and how substantial can the decrease be compared to a scenario with public transit subsidies?, 2/ what are the consequences of these counterfactuals in terms of distances travelled for commuting purposes and CO_2 emissions stemming from these? and 3/ what are the impacts on households' welfare of these policy packages?

[6] Analytically and computationally, the construction subsidies intervene through a modification of the term A in the housing production function described in the appendix in section 4.9.1.3. An increase in the value of A means that less capital is needed to build a given amount of floor space.

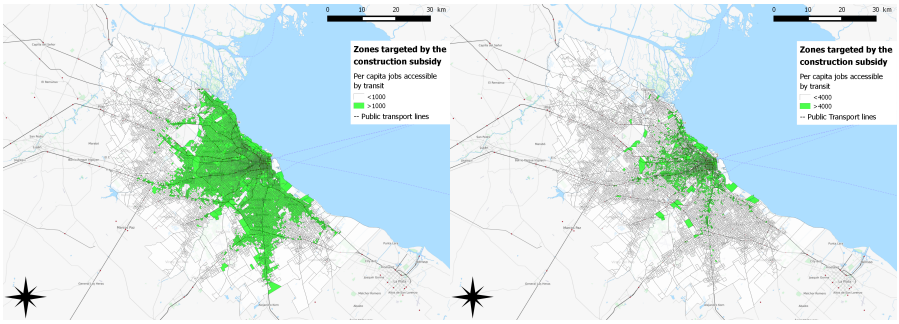

Figure 4.11: Zones targeted by the construction subsidy in this scenario correspond to radios with high per capita transit accessibility (measured in number of jobs accessible per capita in the origin radio for one hour of travel). Left panel presents these zones when a criterion of 1000 jobs accessible by transit and per capita is selected. Right panel presents these zones with a criterion of 4000 jobs.

4.6.3.1 *Consumption-related welfare impacts of alternative policies*

The consumption-related welfare and income-equivalent impacts of alternative policies with respect to the baseline are the described in Table 4.2. Income equivalents are the monetary translation of household utility changes and are reported here because they are more easily understandable.

	Without the public transport subsidy	With a lump sum transfer	With a generalized construction subsidy	With a targeted construction subsidy
Consumption-related utility in 2050 (%)	−3.73%	+1.30%	−2.67%	−2.69%
Equivalent income in 2014 (US$)	−$712	+$325	−$531	−$527
Equivalent income in 2014 (%)	−3.83%	+1.75%	−2.85%	−2.83%
Equivalent income in 2050 (US$)	−$910	+$323	−$644	−$651
Equivalent income in 2050 (%)	−3.14%	+1.11%	−2.22%	−2.25%

Table 4.2: Impacts relative to the baseline on consumption-related welfare and translation into income equivalent (in US$) in each scenario for 2014 and 2050.

We draw two conclusions from these figures. First, while the lump sum dominates the transit subsidy as documented in the simple model presented in section 4.4, the welfare gains (utility) are lower than the schematic model previously presented pointed to (1.3% vs 6.1%). The reason for this difference resides in several realistic features of NEDUM-2D. The use of generalized costs instead of pure monetary costs means that an increase in transport fares does not translate into an equivalent increase of generalized costs because time costs remain the same. As time costs represent more than 70% of the generalized costs in the baseline, the increase in the monetary component only applies to the remaining 30%. So that the subsidy only represents around 20% (0.7×0.3) of total generalized transportation costs. This would place the transit subsidy in a regions which is much closer to its optimal level (see Figure 4.1). In addition, while in the schematic model only one transport mode is available, in the NEDUM-2D model, households have the

choice of commuting by foot, using cars, transit or a combination of these modes. As a result when transit fares increase, a share of people will switch to an alternative and cheaper transport mode, say cars or walking, so that the actual cost of commuting will increase less than the transit fare increase. The existence of other transport modes can therefore mitigate the increase in public transport fares. So lump sum transfers can increase households' welfare but less than the schematic model would have led us to believe.

The second take-away from the comparison of alternative policies is that the construction subsidy schemes perform better than the uncompensated removal of public transport subsidy (-2.7% for both schemes vs -3.7%) but less well than the public transport subsidy. In terms of welfare, construction subsidies, targeted or generalized, are a poor substitute to transit subsidies.

4.6.3.2 *Beyond consumption-related welfare: Sprawl, distance travelled and emissions*

In this sub-section we look into features that are not captured by our welfare function such as the impact of alternative policies on the extent of the urban area, the average distances travelled and the emissions that stem from commuting.

Figure 4.12 provides a visual representation of how different policy packages would modify the size of the urbanized are in 2050 in our simulations. We selected three different scenarios: the baseline in which transit subsidies exist and amount to two-thirds of the full cost of a trip, the counterfactual in which the transit subsidy is removed, resulting in a tripling of the monetary costs of riding public transport and finally a scenario whereby subsidy removal is coupled with the redistribution of the savings in the form of construction subsidies.

It can be visually seen from Figure 4.12 that the removal (compensated or not) of public transit subsidies has an overall limited impact on the size of the urbanized area. In 2050 the urbanized area decreases by only 11 km^2 (2739 km^2 vs 2750 km^2) for the uncompensated removal of the public transport subsidy (orange in the map) and by 14 km^2 (2736 km^2) for the scenario in which public transport subsidy removal is accompanied by a generalized construction subsidy (green in the map). The orange shade is virtually indistinguishable because it is overlayed with the green layer.

The lump sum transfer scenario yields an urbanized area in 2050 which is slightly larger compared to the baseline: 2797 km, i.e. a 1.7% increase. And finally the targeted construction subsidy scenario results in a slight decrease of the urbanized area of -0.8% (2729 km^2 vs 2750 km^2). The conclusion which we draw from these simulations is that the potential to curb urban sprawl through removing the public transport subsidies exists but is limited and therefore so would the savings in terms of infrastructure costs associated to increased urbanization.

The next question is: would the public transport subsidy removal trigger an increase in transport related CO_2 emissions? This question is even more relevant as we have just seen that the benefits to be expected in terms of lower land consumption for residential purposes are limited.

The most notable fact in the first half of Table 4.3 is that whereas the reductions in urbanized area are small (or even increase with the lump sum transfer), the average distance of a household to their job center decreases much more substantially and across all counterfactual scenarios. This is the long term (2050) result of an internal restructuring of the urban area caused

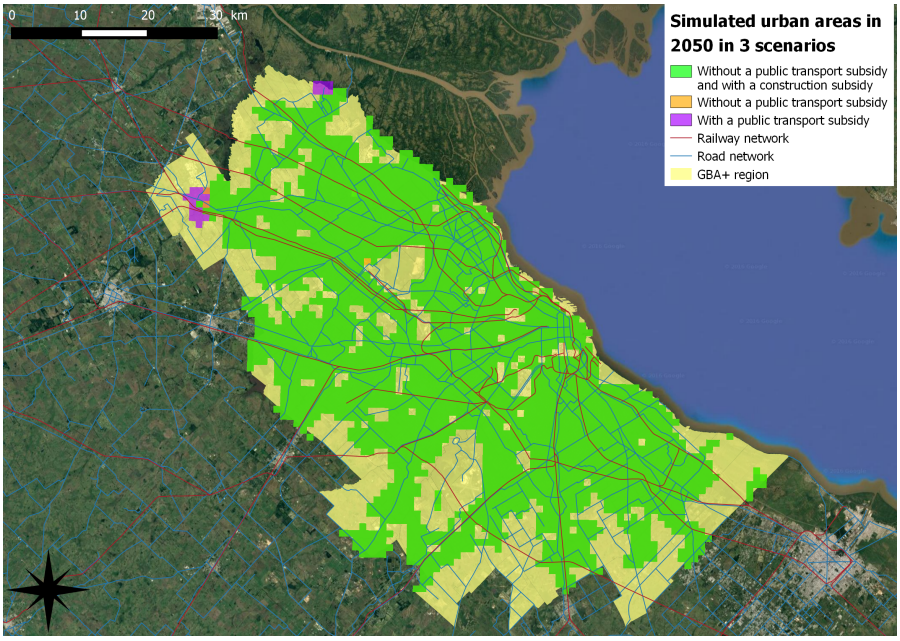

Figure 4.12: Simulated urban areas in the three scenarios which differ by the existence of public transport subsidies and construction subsidies.

by the rise in public transport fares, where, in order to save on transportation costs, households choose to locate closer to the city center. Higher buildings will progressively replace smaller ones in the vicinity to the city center and residents will occupy smaller dwellings, both these mechanisms leading to higher central population densities.

This finding is important because it also means that the traveled distances to jobs will be shortened substantially – not exactly by the same amount as the distance to the city center, as roads are not straight, but not far off. This should lead to lower CO_2 emissions from transport, all else equal. On the other hand public transport ridership will also decrease as the result of the increase in fares triggered by the subsidy removal. And because cars are less energy efficient[7] than public transport, mainly buses or *colectivos* in the urban area of Buenos Aires, this will lead to the opposite effect on CO_2 emissions with an increase, all else equal. The net effect in terms of commuting related CO_2 emissions is a priori ambiguous and this is precisely where numerical simulations can be useful. The last line in Table 4.3 summarizes the impacts on CO_2 emissions in the various counterfactual scenarios. It can be seen that the reduction in the distances travelled for commuting nearly cancel out the increase in emissions/pkm resulting from mode share switch away from public transport. The increase in emissions is indeed limited (around 1%). It can also be seen that the lump sum transfer scenario would result in a much less anecdotal increase in emissions. Part of the lump sum will be used to consume moor floor space per household, thus limiting the internal movement of households closer to the city center[8]. Finally the targeted

[7] See section 4.9.2.4 for details about respective gasoline consumption of buses and cars over time in the Buenos Aires region. In our simulations buses emit 3.5 less than cars per passenger.kilometer. If this number increased, so would emissions in alternative scenarios compared to the baseline. If buses were less than 3.5 more efficient than cars then the opposite situation would arise and a decrease in public transport ridership would be associated with a lower increase in emissions.

[8] We do not account for larger AC/heating costs of larger dwellings.

	Without the public transport subsidy	With a lump sum transfer	With a generalized construction subsidy	With a targeted construction subsidy
Urban sprawl				
Average distance to the city center	−6.97%	−3.65%	−7.10%	−8.73%
Urbanized area	−0.40%	1.71%	−0.51%	−0.76%
Average density in the urban area	0.40%	−1.68%	0.51%	0.77%
Climate change / CO_2 emissions				
Public transport mode share	−19.15%	−18.95%	−19.14%	−19.18%
CO_2 emissions from commuting	1.28%	5.11%	1.12%	−0.69%
Welfare				
Household utility	−3.73%	1.30%	−2.67%	−2.69%

Table 4.3: Evolution of indicators pertaining to urban sprawl, CO_2 emissions from commuting and household welfare in alternative scenarios when compared to the baseline scenario with public transport subsidies.

construction subsidy, is able to achieve an overall reduction in commuting related CO_2 emissions, although such a reduction remains limited.

It appears overall that removing the public transit subsidy would have only limited impacts in reducing sprawl over time and thus the associated costs in terms of infrastructure for example. This is disappointing because it appeared to be a reasonable motivation for removing the public transport subsidies and maybe replacing them by another policy less likely to induce sprawl. On the other hand, it is equally surprising that although the removal of the transit subsidy leads to a decrease in public transport ridership, this mode switch leads to only moderate increases in commuting related CO_2 emissions (except in the scenario where transit subsidy savings are channeled to households through a lump sum transfer). Our simulations even show that alternative policies such as targeted construction subsides could decrease the level of transport related CO_2 emission with respect to the baseline, although the decrease would remain limited.

It should be noted however that the switch away from public transport, triggered by the subsidy removal, could complicate future CO_2 emission reductions as cities display path dependencies which make subsequent mitigation actions more expensive (Avner, Rentschler, and Hallegatte, 2014).

4.7 POLITICAL ECONOMY/HOTSPOT ANALYSIS OF TRANSIT SUBSIDY REMOVAL

An important concern for policy makers when considering the modification of public transport prices is the redistributive impacts of these changes and in particular for the poor. NEDUM-2D, in this present version, cannot be used to perform a full study of the impact of public transport subsidy removal on the poorest. To be able to do so, the model would need to endogenously represent the location decisions of various income groups, which is beyond its current capacity. We however can document how the budget committed to transport and housing costs would be affected by location by the subsidy removal, coupled or not with lump sum transfers and other devices, if this modification did not impact the location of the households. In the short term, this assumption is valid as relocation is characterized by high inertia. Over

Annual household income by socio-economic quintile (US$)				
1	2	3	4	5
5,196	10,268	15,471	22,747	41,756

Table 4.4: Annual average income for a household in Greater Buenos Aires disaggregated by socio-economic quintile in 2012 (data source: INDEC 2013).

a longer time frame however, decisions about where to live and how much living space to consume will adjust to changed transport costs.

The urban area of Buenos Aires is characterized by sizeable inequalities in terms of socio-economic levels. We capture these inequalities in Table 4.4 through the disaggregation of annual household income by quintile. It can be seen that the average annual income of the richest 20% of households in Buenos Aires is about eight times that of the poorest.

4.7.1 *In the short run: Detrimental to transit users*

With the NEDUM-2D model we assess the distributional impact of removing the public transport subsidy and replacing it with a lump sum transfer. The lump sum transfer is distributed to each household and amounts to a little over US$ 1,000 in 2012. While this amount represents around 4% of households' average income it is nearly 20% of the poorest budget. We place ourselves in the very short term, immediately after the policy change, when it can be safely assumed that households have not had time to adjust and move to areas within the Buenos Aires area which benefit from lower transport costs.

Figure 4.13 shows the spatial impact of the replacement of the transit subsidy by a lump sum transfer for transit users. It displays for households that commute by transit the net impact on the evolution of residual budgets after transport expenditures of increasing public transport fares (by a factor of 3 as before) but receiving a compensatory lump sum transfer.

Figure 4.13 shows that all transit users lose from the replacement of the transit subsidy by a lump sum transfer as their budgets after transport expenditures decrease everywhere. Even in the most central locations of the Buenos Aires urban area, the annual cost of commuting daily to jobs outweighs the lump sum. The increase in transport budget for transit users is not spatially uniform: it increases with the distance to the city center (in parallel to transit budgets) and is higher for lower income quintiles. The black dots in Figure 4.13 represent the centroid of the census tracts where the 20% poorest households reside. It can be seen that these census tracts are often hit the hardest, simply because a given monetary increases in fares has a larger impact on their budget. Some exceptions are however found when the census tract of the poorest is close to the city center.

So, whereas a generalized the lump sum transfer is the most efficient use of public funds, as discussed in section 4.4, it also potentially carries negative redistributive impacts in the very short term which will hurt the heaviest users of public transport or those that do not have the option to switch modes (for cars for example).

A solution to benefit from the efficiency virtues of lump sum transfers and yet protect the poorest against the adverse impacts of removing the transit subsidy would be to channel the transfers exclusively to the poorest households. Whereas such a policy is technically feasible it requires up to

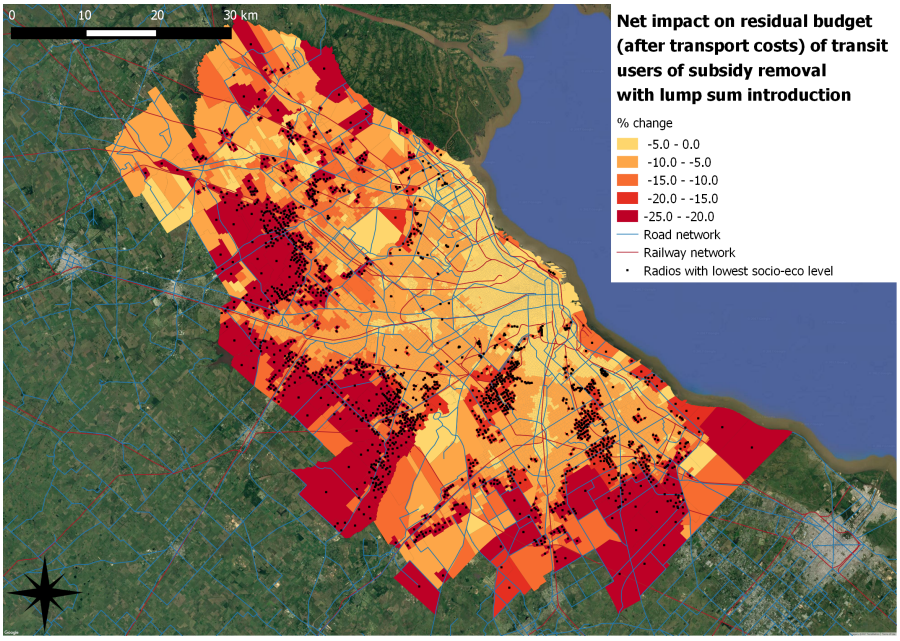

Figure 4.13: Hotspot analysis of the subsidy removal coupled with a lump sum transfer on the residual budget after transport expenditures of transit users by census tract accounting for the socio-economic level of each census tract.

date registries which can capture the earnings of all households in the urban area of Buenos Aires. The allocation of lump sum transfers would then be decided on the basis of these registries following an agreed upon criteria. When registries of household earnings do not already exist, implementing cash transfers is not a trivial task[9] as urban targeting is notoriously difficult (Gentilini, 2015).

The picture painted here hinges on the limits of the model as NEDUM-2D in its current version is unable to link mode shares to income brackets. Whereas we show budgetary impacts of transit fare increases on transport budgets for public transport users we are unable to show explicitly how price increases would affect the poorest vs the others because Figure 4.13 considers only users of public transport. The literature suggests that the middle income class is the heaviest user of transit so that they are likely to be hit harder than both the poorest and the richest.

4.7.2 *In the longer run: Housing market adjusts*

The discussion above focuses on the very short run, immediately after the replacement of transit subsidy by a lump sum transfer. As discussed, the consequences for the users of public transport are harsh, in particular if they are poor. Over a longer time frame, however, the housing market will adjust to the shock on public transport fares. In particular, areas that face strong increases in generalized transport costs will become less desirable for households and so will lead to a decrease in housing rents.

Figure 4.14 visually depicts the change in rents per square meter of housing with a lump sum transfer compared to the situation with a transit subsidy. For tenants, the impacts on rents will mitigate in part the negative

[9] Although, there are successful precedents such as in Chile between 2004 and 2006 (Estupiñán et al., 2007).

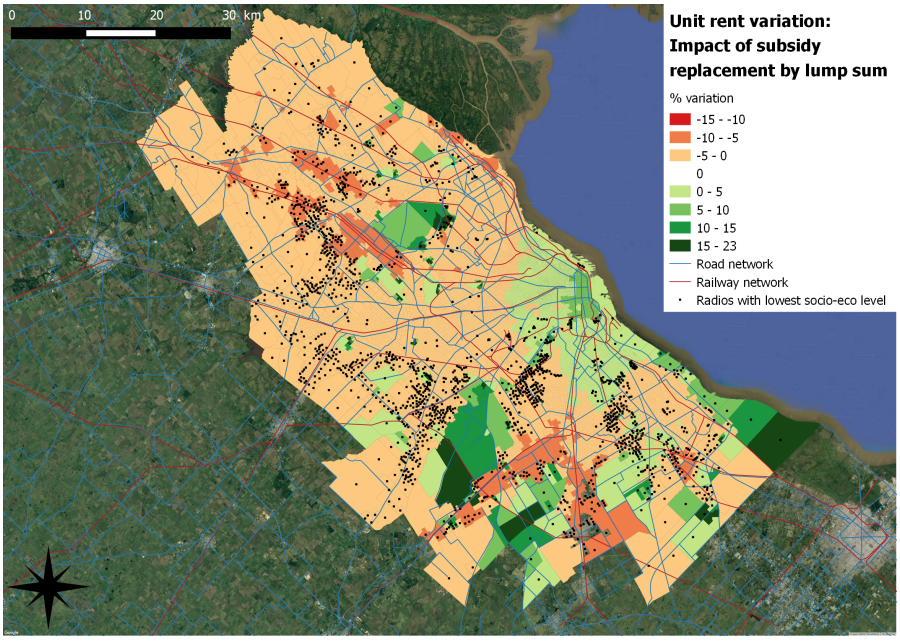

Figure 4.14: Variation in rents per square meter with replacement of the public transport subsidy with a lump sum transfer.

redistributive impacts of removing the transit subsidy and implementing a lump sum. Indeed, the areas that benefit most from a decrease in rents are also the ones which are hardest hit by the increase in transit fares (see Figure 4.13) and in most instances coincide with where the poorest currently reside. Conversely, the areas with green shades will see an increase in rents because generalized transport costs will increase less than in other parts of the urban area and thus become more attractive in relative terms.

Figure 4.15 shows the impact of replacing transit subsidies by lump sum transfers on the combined housing and transport households' budgets. A first important results is that in some areas of the cities the change in rents induced in the medium term by the increase in transit fares will more than compensate the price increase resulting in a net decrease in the budget allocated to transport and housing (accounting for changes in housing space consumption). These areas appear green in Figure 4.15. Conversely in areas which appear in yellow, the decrease in rents or housing space consumption does not compensate for higher transport costs. In many instances the NEDUM-2D model predicts that the census tracts where the poor reside will face a higher combined budget dedicated to housing and transport. However, the increase in transit prices appears to be less harsh when accounting for the housing adjustment than when looking solely at budgets affected to transport.

The decrease in rents and housing expenditures shown in Figure 4.14 has been interpreted as welfare improving in the previous section. This assumption is true for newcomers to the urban area and for renters but does not hold for households which own their dwelling. If households own their dwellings they are actually hit even harder by the increase in transit fares as they will both have to face higher transport costs and accept a loss in the resale price of their dwelling.

Finally an important caveat needs to be mentioned here. As acknowledged, the NEDUM-2D modeling framework does not represent the locational decisions of multiple income classes. We have circled around this

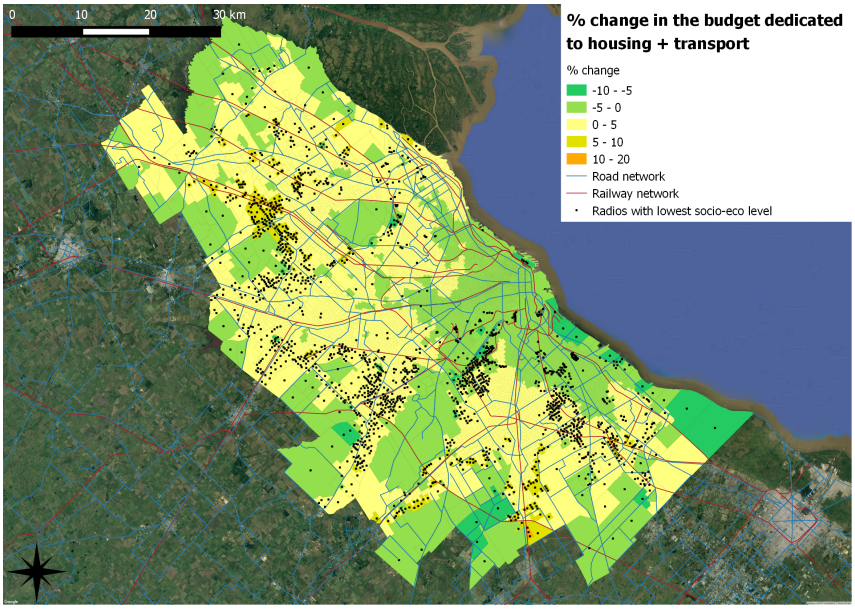

Figure 4.15: Change in household budget shares dedicated to housing and transport with replacement of the public transport subsidy with a lump sum transfer.

difficulty by looking at very short and short term impacts of replacing transit subsidies by lump sum transfers, assuming that in these time frames households would not have time to move. But our research is silent on the longer term redistributive impacts when households will adjust their consumption of housing, transport and other goods to the increase in public transport fares. Our short term result should therefore be interpreted with caution and not as a long term exercise.

4.8 CONCLUSIONS AND PERSPECTIVES

The research presented above could benefit from modeling improvements to become more realistic and shed light on a richer set of issues. The most pressing need is to develop the NEDUM-2D model so that it can represent multiple income classes and their locational decisions within urban areas. This would allow to look at the long term redistributive impacts of various policies. A second possible direction for improvement is to enhance NEDUM-2D so that it can account for multiple job centers, going beyond the monocentric assumption, and include amenities and social segregation mechanisms. This addition to the model would help get rid of some discrepancies between simulation results and data and would therefore increase its capacity to convince. While we strongly believe that our main conclusions would be unaffected by the addition of polycentrism, it remains an empirical question. Lastly, the NEDUM-2D model does not account for congestion as it implicitly assumes that investments can be made so that additional road or public transport frequentation does not lead to higher transport times. Explicitly accounting for congestion would be an important improvement to the modeling framework.

The set of results presented in this paper paints a complex picture of public transport subsidies in the urban area of Buenos Aires. It appears that an ideal solution would be to channel lump sum transfers only to the poorest households. This solution requires detailed registries recording households'

incomes and their evolution over time. A second best alternative would be to have only the poorest households in Buenos Aires benefit from transit subsidies. This solution would protect the poor users of transit without entailing dramatic efficiency or environmental negative impacts. It would also allow for some public finance savings which could be channeled toward other issues such as investments in the public transport infrastructure or could be put towards targeted construction subsidies as discussed in this paper.

4.9 APPENDICES

4.9.1 *Description of the NEDUM-2D modelling framework*

We use a model inspired by Von Thünen (1826), adapted by Alonso (1964), Mills (1967), and Muth (1969) and comprehensively described by Fujita (1989) and Brueckner (1987). Assuming that a city is defined by a number of jobs located in a single location, this model is based on two trades-offs, made by two categories of economic actors:

- Households choose their housing location in the agglomeration by arbitrating between larger and cheaper apartments further from the city center, and increased commuting costs to the city center where all jobs are supposed to be located.
- Landowners choose where and how much to invest (i.e., what buildings to construct), as a function of expected rents at each location.

These two trades-offs characterize a static equilibrium in the urban system.

Symbol	Signification
R	Housing rents (or, equivalently, annualized real estate price per square meter)
R_0	Metropolitan area border rent or transaction costs
L	Available land for construction
K	Invested capital
ρ	Depreciation rate of capital
i	Interest rate : cost of capital
p	Unitary transport cost/km
n	Household density
q	Flat size
N	Population in the agglomeration
r	Distance to the city center
r_f	Limit of the city, maximum radius to the center

Table 4.5: Nomenclature.

4.9.1.1 *Household behavior*

Each household is composed of one representative worker living at a distance r from the city business district (CBD) where all jobs are located. Each

worker has to commute once a day to the CBD, and this commuting entails transportation costs $T(r)$. All households are supposed to earn the same income Y and – at the equilibrium – they have the same level of satisfaction described by a utility function U that depends on both the level of consumption of a composite good z and of the size of their apartment q. The level of rents per square meter (or, equivalently, the annualized real estate price per square meter) is $R(r)$, at each location in the city. Each household maximizes his utility function under a budget constraint:

$$\text{Max}_{r,z,q} U(z,q) \quad \text{s.t.} \quad z(r) + R(r)\, q(r) + T(r) \leq Y + \overline{L} \tag{4.3}$$

The term $\overline{L}$ found in (4.3) represents the annual amount accruing from land rents per household which is recycled in the urban economy in the form of increased incomes. It can schematically take on one of two values depending on the type of model used: Closed City model with Absentee landowners (CCA) or Closed City model with Public ownership of land (CCP). In the closed city model with absentee landowners (CCA), landowners are supposed to live outside the urban area which means that land rents are not recycled in the local economy in the form of increased incomes. In this case $\overline{L} = 0$. At the opposite end of the spectra, if all land plots are supposed to be owned by a local government (or by all households in equal shares) then $\overline{L} = \int_0^{r_f} \frac{\pi(r)}{N} \text{dr}$, where N is the number of households in the urban area.

4.9.1.2 *Landowner behavior*

Landowners choose what amount of capital $K(r)$ to invest at each distance from to produce a housing surface $H(r) = F(L(r), K(r))$; in this framework, they are thus also the owners of the buildings. The construction function F is assumed to have constant returns to scale. The profit function of a landowner or equivalently the land value assuming $R(r)$ as exogenous and known is then given by:

$$\pi = [(R - R_0)\, F(K, L) - (i + \rho)K] \tag{4.4}$$

ρ represents the joined effect of real-estate depreciation and annual taxes payed by land owners on real-estate capital. i is the interest rate so that iK represents the annual cost of borrowing capital or its opportunity cost. Finally the border of the metropolitan area is defined by a rent R_0, below which it is no longer profitable to build housing. This value corresponds to transaction costs in the building and renting process, such as the costs of finding tenants, ensuring that the communal areas of collective housing remain clean. . . , and can be considered to be proportional to the quantity of housing built. NEDUM-2D differs from traditional urban economics models in this respect, as they usually assume that the edge of the metropolitan area is given when land value for housing falls below the revenue that could be generated from using this land for agricultural purposes. Although this method is appealing, it is not supported by data which shows a clear disconnection between land values for agricultural and housing purposes even at the edge of urban areas. The much lower values for agricultural land are indicative that another mechanism is at play. We chose to capture this through transaction costs R_0.

Landowners maximize their profit function to determine how much housing to build and how much capital to invest:

$$K^*(r) = \text{Arg}\max[(R(r) - R_0)\, F(L(r), K(r)) - (\rho + i)\, K(r)] \tag{4.5}$$

The absentee landowner in fact chooses the capital/land ratio $k = K/L$ that maximizes his land's value. If we assume that the housing production function has constant returns to scale[10], then this ratio does not change as a function of the amount of land that is used but varies only as a function of the distance to the CBD. We can then use $f(k) = \frac{F(K,L)}{L} = h$ as a proxy for housing density or building's height and define:

$$k^* = \arg\max_k [(R - R_0) f(k) - (\rho + i) k] \tag{4.6}$$

At the city limits we have:

$$R\left(r_f\right) = R_0$$

4.9.1.3 *Functional forms and assumptions*

We use Cobb-Douglas functional forms with constant returns to define households' utility and the housing service construction function. This choice is widely shared in urban economics (Brueckner, 1980; Fujita, 1989; Mills, 1972). It is possible to show analytically that there is both existence and uniqueness of an urban equilibrium (Gusdorf and Hallegatte, 2007).

$$U(z,q) = z^{\alpha} q^{\beta} \text{ where } \alpha, \beta > 0 \text{ and } \alpha + \beta = 1$$
$$F(L,K) = AL^a K^b \text{ where } a, b > 0 \text{ and } a + b = 1$$

4.9.1.4 *Dynamics of NEDUM-2D*

NEDUM-2D is a dynamic model which explicitly represents inertia and path dependence. This feature allows the model to account for the fact that housing infrastructure cannot adapt instantaneously to changing conditions (income, transport prices etc...). NEDUM-2D can therefore account for temporary imbalances between housing supply and demand.

There are two steps in defining the dynamic behavior of the NEDUM-2D model. First, developers' decisions on how much to build and where in the urban area are determined (or equivalently how much capital to invest for residential purposes in each location). This allows the model to determine the new housing stock which accounts for inertia in building decisions. Second rents, dwelling sizes and population densities (and all other model outputs) adjust in such a manner that an equilibrium utility can emerge consistently with the static version of the model. This two-tier approach to the dynamics of NEDUM-2D differs from the one used in Avner, Viguié, and Hallegatte (2013), Viguié and Hallegatte (2012), and Viguié, Hallegatte, and Rozenberg (2014). We will discuss these differences and their consequences a bit further in this section.

Step 1: In practice for each time step a "pseudo-equilibrium" value is computed for the housing stock. This "pseudo-equilibrium" value is the value toward which the housing stock state variable will evolve. It depends on the model input, but also on the value of the other state variables (rents, population densities, dwelling sizes...). Between this time-step and the following, the housing stock state variable will evolve towards its "pseudo-equilibrium" value with some inertia. At the following time step, a new "pseudo-equilibrium" value for the housing stock is computed. It can be

[10] This is logical as a doubling of both capital and land factors should lead to two similar housing structures being built (Brueckner, 2011).

identical to the last one, or can be different because the values of the other state variables have changed, or because model inputs are different (e.g. construction costs have changed). The housing stock state variable will now again evolve towards this new "pseudo-equilibrium" value etc. The pseudo-equilibrium value for the housing stock is computed in such a manner that, if exogenous model inputs (population, transport costs, construction costs, income...) do not evolve any more, the housing stock state variable converges towards the actual equilibrium value.

For each time step, developers when choosing whether or not and how much to build assess their expected profits using equation (4.4). In this version of the model the developers are considered to be myopic, meaning that they do not anticipate that housing rents from the previous time step will change as a function of different socio-economic conditions. They choose the new amount of capital that they would wish to instantaneously invest in each location ("pseudo-equilibrium"), or equivalently the capital to land ratio k' leading to the housing to land ratio h' through:

$$k'(r) = \underset{k'(r)}{\arg\max}[(R(r) - R_0)\, h'(r) - (\rho + i)\, k'(r)] \tag{4.7}$$

Construction and building depreciation however, take time so that the capital invested does not translate immediately into new buildings or the destruction of old ones. We here follow Viguié, Hallegatte, and Rozenberg (2014) in supposing that financial investments are transformed into buildings with a time lag τ_H, which corresponds to the time required to achieve the construction. We also suppose that a decrease in current built floor space ratio to land ($h(r)$) can happen through depreciation only, with the timescale τ_{dH}. It follows that in a dynamic perspective housing evolution at each time step is given by:

$$\frac{dh(r)}{\mathrm{dt}} = \begin{cases} \frac{h'(r) - h(r)}{\tau_H} & \text{if } h'(r) \geq h(r) \\ -\frac{h(r)}{\tau_{dh}} & \text{if } h'(r) < h(r) \end{cases} \tag{4.8}$$

Step 2: At each time step the other model variables (rents, population densities, dwelling sizes...) adjust perfectly to the new socio-economic conditions and to the new housing stock. Indeed households adjust their locational and consumption choices in a way that ensures that utility levels are equal for all households throughout the urban area, consistently with the static version of the model. This second step of the dynamics of NEDUM-2D is equivalent to the maximization of households' utility in a static framework with an exogenous housing stock.

4.9.1.5 *Discussion of the mono-centric assumption*

In the present study, we use this model with the assumption that all households commute every day to the center of the *Ciudad Autónoma de Buenos Aires* (CABA), where jobs are assumed to be located. This mono-centric hypothesis is important, and can seem a strong assumption as secondary employment centers exist within the urban area of Buenos Aires. However, the Buenos Aires region displays a very strong mono-centric structure. For instance, in 2012 more than 40%[11] of all jobs in the Buenos Aires region are localized in CABA even though CABA only represents 5.3% of *Region Metropolitana*'s

[11] Projections based on Censo Nacional Economic 04/05 (CNE 04/05) and Encuesta Permanente de Hogares, 2011 (EPH, 2011).

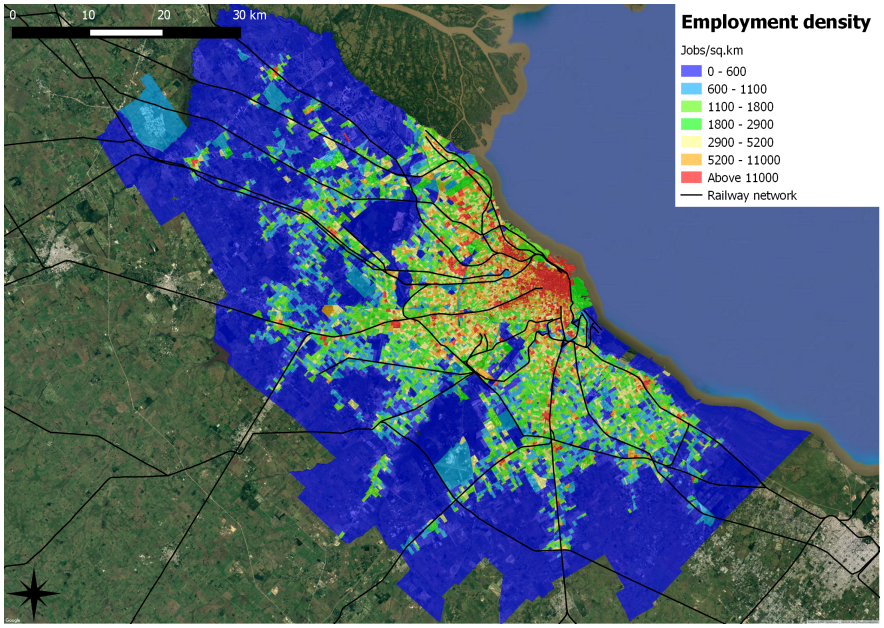

Figure 4.16: Employment densities for each census tract (Radio censal) unit within the Buenos Aires region in 2012 (data source: projections based on Censo Nacional Economic 04/05 (CNE 04/05) and Encuesta Permanente de Hogares, 2011 (EPH, 2011)).

area. Figure 4.16 represents the employment densities for each census tract or "radio" in the Buenos Aires region. The use of employment densities instead of absolute employment numbers can correct a statistical "radio size" bias. Indeed, as radios have different sizes, larger radios would appear as very "employment-rich" while smaller radios will display only small employment numbers.

Figure 4.16 shows that job dispersal exists along the major public transport lines, the railway network (represented as black lines), but is nearly non-existent elsewhere. This suggests that the radial public transportation network plays a strong role in the location of employment centers which is characteristic of dominantly mono-centric urban forms.

Figure 4.17 shows in another manner the very clear concentration of employment around the city center. The most important features of the curve (red dashed line) is 1/ that it is virtually flat and close to zero beyond km 12 and 2/ that the slope of the curve is very steep within eight kilometers of the city center. There is a real Central Business District which has slightly extended beyond CABA. This tendency should not mask that there is also clearly some dispersion around the average of the data, indicating the existence of employment centers beyond the CABA region. Some of the decentralized employment centers can even be very "job intensive".

There are also indications that the radial public and, to some extent, private transportation networks plays a strong role in the mono-centric structure of the Buenos Aires region. Indeed, even when people work outside CABA, they mostly still have to commute through the city center. Therefore, in deciding where to live, the location of housing relatively to the city center is still fundamental.

Considering that cities are perfectly monocentric is a widespread assumption in urban economics and land use – transport models. In the case of Buenos Aires, it is clearly an approximation, but, as we have demonstrated

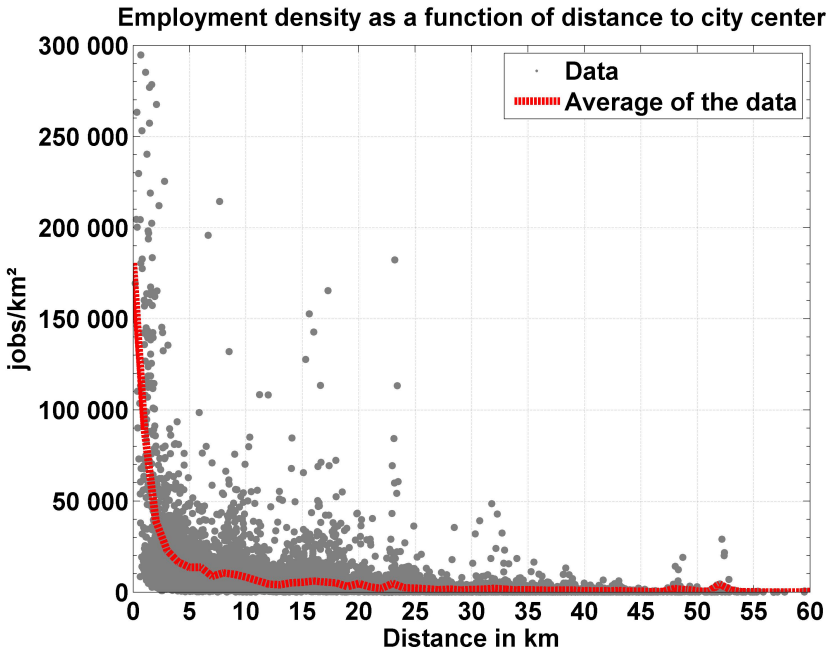

Figure 4.17: Employment density as a function of the distance to the city center in 2012 within the Buenos Aires region.

above, an approximation which finds strong support in the data. Hence, the mono-centric version of NEDUM-2D is a priori a useful and well suited framework to represent the internal structure of the Greater Buenos Aires.

A more fundamental line of argument against the mono-centric approach is that the importance of distances travelled for commuting trips is declining relatively to trips for other motives such as leisure. Adversaries of the mono-centric approach therefore argue that there is little reason to consider commuting costs as decisive when choosing where to live. Although it is true that commuting travel shares are declining, we argue that trips made and costs incurred on a daily basis play a much larger role in determining housing patterns than lengthy trips which are undertaken only a few times a year.

In its current version, NEDUM-2D also relies on the hypothesis that all households within the urban area earn the same average income. It does not currently possess the sophistication to account for multiple household types and thus ignores income inequalities[12]. This simplification is acceptable for some indicators such as the extent of urbanization. However it can have some impacts for NEDUM-2D's ability to capture the dispersion in rents and real estate prices around an average. Indeed, real estate prices are strongly affected by neighborhood characteristics among which social segregation can play a role. We will overcome this limitation to a certain degree by interacting our results with a map of current income dispersion.

4.9.2 *Data and choice of parameters*

We will detail in this section the data used and the choice of parameters for 1/ socio-economic and demographic inputs, 2/ household utility function

[12] A version of NEDUM-2D that is able to represent multiple household types differing by annual average income is currently being developed in CIRED.

3/ developers' behavior, the housing production function and construction costs, 4/ transport data and modelling choices and 5/ land use and building regulation data.

4.9.2.1 *Socio-economic and demographic inputs*

- Population in the Greater Buenos Aires urban area: Population for the GBA+ region in 2012 is estimated to be 13,744,044 in 2012 according to projections of the Censo Nacional de Poblacion, Hogares y Vivienda 2001 (CNPHyV 01) for 2012. With an average household size of 3.3, this corresponds to 4,106,479 households. The demographic scenario used in this exercise considers that the population will increase smoothly at the same pace that it evolved over the 2001 – 2012 period, reaching a little over 6.96 million in 2050. This corresponds to nearly a 70% increase compared to 2012 with an annual demographic growth rate of 1.40%. We equally use a second demographic scenario whereby the number of households doubles in 2050 compared to 2012. This second demographic scenario corresponds to an annual growth rate of 1.84%.

- Income evolution of the average household: With the current version of the model in which we only consider one income class, we need an average income per household. Data from INDEC gives us this information separately for Buenos Aires and the other 'partidos' of the Gran Buenos Aires at trimestral intervals. We thus calculate a weighted average based on their respective household populations for all semesters of year 2012. This yields an average yearly income of AR$ 85,540 or around US$ 18,140.

  In the baseline scenario, average incomes will grow at the same average annual rate as Argentina's per capita net income over the 1970 – 2015 period (in constant 2010$), i.e. 1.24%, starting at US$ 18,140 in 2012 and reaching close to US$ 29,000 in 2050. In the sprawl scenario, average income doubles over the 2012 – 2050 period, increasing at an annual rate of 1.84% and reaching close to US$ 36,300.

4.9.2.2 *Household utility*

The household utility function reads as follows:

$$U\left(z(r), q(r)\right) = z(r)^{\alpha} q(r)^{\beta} \text{ where } \alpha, \beta > 0 \text{ and } \alpha + \beta = 1 \tag{4.9}$$

The widespread choice of this Cobb-Douglas functional form in urban economics is consistent with findings that households devote a near constant budget to rental housing expenditures through time and space (Davis and Ortalo-Magné, 2011). In this case, households spend a share β of their income net of transportation costs on housing. Indeed, maximizing (4.9) with respect to q and replacing z with the budget constraint by $Y + \overline{L} - q(r)R(r) - T(r)$, we find: $q^*(r)R(r) = \beta(Y + \overline{L} - T(r))$. For the purpose of the simulations in this study we must characterize β. We chose a value of 0.4 for β and thus 0.6 for α. This means that in the city center, where transportation costs are assumed to be zero in the monocentric theory, households will spend 40% of their income on housing expenditures. This figure is consistent with official statistics from INDEC which place average expenditure shares at 15.2% and 17.7% respectively for transport and housing and expenditures at 164% of income (INDEC, 2013).

4.9.2.3 *Housing production function*

The housing production function is defined by:

$$F\left(L(r), K(r)\right) = H(r) = AL(r)^a K(r)^b \text{ where } a,\ b > 0 \text{ and } a + b = 1 \quad (4.10)$$

The choice of a Cobb-Douglas function to represent the housing production function is widespread in the literature (Fujita, 1989; Muth, 1969) and finds some empirical support (Ahlfeldt and McMillen, 2014; Thorsnes, 1997). It can be rewritten as the absentee landowner in fact chooses the capital/land ratio $k = K/L$ that maximizes his land's value. Since F has constant returns to scale equation (4.10) can be simplified as the ratio of capital to land will only change as a function of rents and not the amount of land each landowner possesses.

$$f\left(k(r)\right) = \frac{F\left(K(r), L(r)\right)}{L(r)} = A\left(\frac{K(r)}{L(r)}\right)^b = Ak(r)^b \quad (4.11)$$

In the absence of detailed datasets about construction costs, we relied on partial data gathered from the INDEC that provided some information about average construction costs for various building heights for July 2012. We interpolated the various data points and achieved a curve which seems to increase quasi linearly with building height. Model parameters A and b were calibrated so as to minimize discrepancy between the INDEC interpolated data and the simulated construction costs in the model. The calibration procedure led to values of $A = 0.25$ and $b = 0.70$ (with $a = 1 - b = 0.30$). As a result the construction cost curve of NEDUM-2D seems in general agreement with the partial data we have although it presents a more convex shape leading to an underestimation of costs for low building heights and an overestimation for larger number of floors (Figure 4.18). Parameter A of the construction function evolves over time with income as follows $A_t = A_0 \cdot (Y_t/Y_0)^{-b}$ to account for the upward trend observed in building construction costs over the 2001 – 2012 period (INDEC, CLARIN).

4.9.2.4 *Transport data and competition between modes*

Transport costs are essential to all land use – transport models. NEDUM-2D uses complete or generalized transport costs which encompass both the monetary and time components of travels.

TRANSPORT TIMES

- Walking times: they are calculated on the basis of the Euclidian distance to the CBD. We assign an average speed of 5km/hour to pedestrians.
- Public transport times: Public transport times were retrieved from the Open Trip Planner Analyst (OPTA) accessibility tool, developed by the World Bank in conjunction with Conveyal. This tool is fed by GTFS data that represents the public transport network and provides Origin-destination travel times at peak and off-peak times. Public transport vehicles in the GBA+ region can be either Colectivo, Ferrocarril, Subte / Premetro, Charter / combi and Bus empresa. These transport times are considered to remain constant throughout the 2012 – 2050 period. This assumption is tantamount to assuming that there will be investments made in currently existing public transport lines in such a manner that the system can absorb population growth without additional

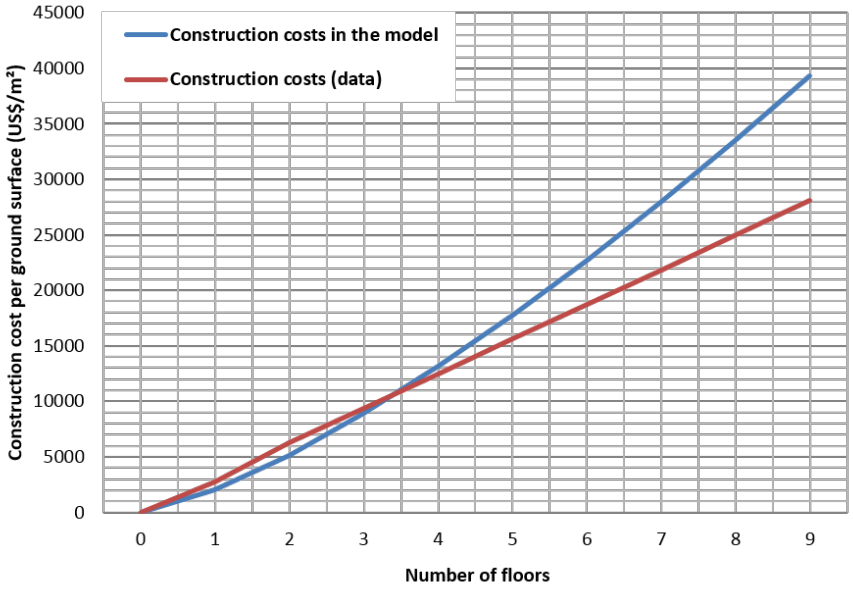

Figure 4.18: Comparison of data and simulated construction costs per square meter of ground floor as a function of number of floors of the building.

congestion. The number of lines and their routes are assumed to remain unchanged throughout the time period.

- Private transport times: Travel times for cars were gathered by collecting Googlemap estimated times systematically throughout the urban area of Buenos Aires. We were able to collect transport times for trips originating in 9674 different locations (always apart by at least 1km) going far beyond the GBA+ region. As for the public transport infrastructure, it is assumed that there will be investment in roads so that they can absorb a demographic increase without leading to additional congestion. We here again assume that the number of roads will remain constant.

MONETARY TRANSPORT COSTS

- Private car costs: These were estimated to be 0.44 AR$/km or 0.095 US$/km in 2012. They concern both cars and SUVs. It is assumed that the cost of traveling one kilometer by car increases by 20% over the 2012 – 2050 period to reach 0.114 US$/km in 2050 in the baseline scenario. In the sprawl scenario, fuel costs are assumed to decrease by 10% over the simulation period reaching US$ 0.085 in 2050.

- Public transport fares: The public transport fares were retrieved from the internet for the buses or *Colectivos*. They depend on the distance travelled and we proxied this distance by a bee line distance from origin to destination. The fares do not present a large spatial variation. The ticket costs between US$ 0.65 and US$ 1. As a simplification, and because buses are the overwhelmingly used public transport means in the Buenos Aires urban area (87%), it is assumed that the fares for the metro system (*subte*) and trains (*ferrocarril*) are identical to those of the buses. As for the costs of traveling by car it is assumed that they evolve to reach 120% of their 2012 level by 2050 in the baseline scenario. In the

sprawl scenario, public transport fares are equally assumed to follow the evolution of the price of fuel and decrease by 10% in 2050.

COST OF TIME

NEDUM-2D uses generalized transport costs which encompass both monetary and time costs. How to value transport times is however a difficult issue which has triggered a vast number of scientific papers and reports (Boiteux and Baumstarck, 2001; Litman, 2008; Mackie et al., 2003; Oort, 1969; Small, Winston, and Yan, 2005) focusing mainly on the topic of how to quantify the benefits of transport investments which accrue in the form of travel time savings. No definite consensus has emerged from the literature; in fact estimates range from 25% (Litman, 2008) to close to 180% of an hourly wage with large heterogeneities depending on the traveler (Small, Winston, and Yan, 2005). Most estimates however seem to fall within the 50%-100% range of an hourly wage with Small and Verhoef (2007) arguing for the former and Glaeser, Kahn and Rappaport inclined to the latter (2008). Given the uncertainty surrounding the value that should be chosen, we retained one that fell within the 50%-100% range of hourly wage and that led to a good agreement between simulations and data for population densities and land values. We use the value of 65% of the average hourly wage in our simulations.

MODE COMPETITION AND GENERALIZED TRANSPORT COSTS

Mode competition: The transportation module of the NEDUM-2D model represents modal choice. For each location in the urban area, citizens choose between walking, public transport and private vehicles, or a combination thereof as a means for commuting. The competition between these modes is organized on the basis of their *generalized costs* (i.e. the total cost including both the cost of time and the monetary costs incurred during the trip to the city center). It is assumed in this study that modal switch does not affect congestion levels and therefore leaves commuting times unchanged.

In order to reflect the heterogeneity of citizens' preferences in terms of transport modes we employ a discrete choice model (De Palma and Thisse, 1987). We follow a common approach in transportation economics by using a multinomial logit model which assigns usage probabilities to each transport mode (see Salon, 2009; Washbrook, Haider, and Jaccard, 2006). This method ensures that even when one mode is much cheaper than the others, it will not be used by all residents in a location for all trips. This approach assumes that, for each transport mode i, the inhabitants do not take into consideration the generalized cost p_i, but this cost plus an idiosyncratic random term following a Gumbel distribution. The result is that the probability of choosing mode i in a given location depends on the generalized cost of this mode relative to other modes. The cheaper it is, the higher the probability that it is chosen: the probability to choose the mode i is:

$$P_{m_i} = \frac{e^{-\lambda \frac{p_i}{p_{\min}}}}{\sum_k e^{-\lambda \frac{p_k}{p_{\min}}}} \tag{4.12}$$

where $P_{\min} = (P_k)$ and λ is a coefficient. At a given location, the average transport cost, taking into account all transport modes, is given by the log-sum of generalized transport costs of all modes.

The value of λ is calibrated so as to minimize average mode share discrepancies with the data and is estimated to be equal to 1 in this study. The mode

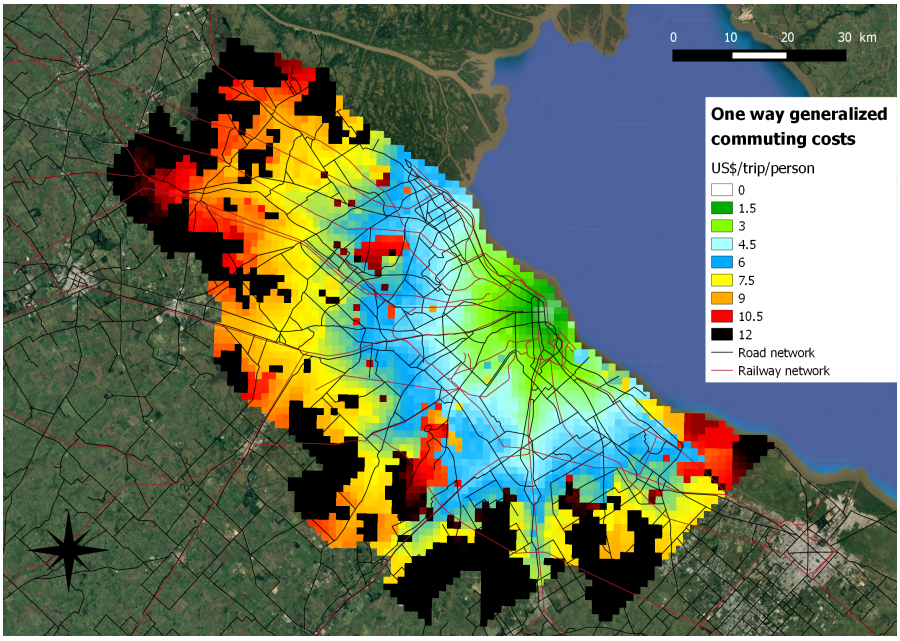

Figure 4.19: One-way generalized costs of commuting for the GBA+ urban area based on the simplifying hypothesis that all jobs are situated in the center of Buenos Aires. The transport costs thus tend to increase as we move away from downtown Buenos Aires. For a given distance to the center they are lower when one is close to a public transport line.

share of public transport in the model in 2012 for the Buenos Aires urban area (measured as the share of people using public transport) is around 56%, so very close to the 57% reported in 2009 by the ENMODO travel survey (Ministerio del Interior y Transporte, 2010). Figure 4.19 shows the resulting map of one-way generalized commuting costs used in this study.

VEHICLE CONSUMPTION, LOAD FACTORS AND EMISSIONS

In order to compute the CO_2 emissions from commuting in our simulations we need some information about vehicle gasoline consumption and load factors both for cars and for buses. We use the data and projections of the IEA and WBCSD Sustainable Mobility Project (SMP) focusing on inputs for the Latin America region (IEA and WBCSD, 2004).

Fuel consumption of cars: For the Latin America region, the SMP spreadsheet indicates that cars will consume 8.3 liters/100km in 2010. We interpolate their data so that cars consume 8.2 liters/100km in 2012 and reach 6.5 liters/100km in 2050. This corresponds to a 20% decrease over the 2012 – 2050 period.

Fuel consumption of buses: We here again draw our data from the SMP model, so that buses in the model consume 26 liters/100km in 2012. We make the supplementary assumption that technological progress will allow the consumption of buses to decrease at the same pace as for cars so that consumption of buses reaches 21 liters/100km in 2050.

Load factors: cars are supposed to carry 1.72 passengers/trip on average in 2012 and buses approximately 19. These average load factors decrease at the same pace reaching 1.51 for cars and 16.68 for buses in 2050. This corresponds to a little more than a 12% decrease over the 2012 – 2050 period.

Vehicle unitary emissions: With a CO_2 content of 2416 gCO_2/liter of gasoline, vehicles emit on average 114 and 33 grams of CO_2/passenger.km for cars and buses respectively in 2012, i.e. a ratio of 3.5. These figures go down to 104 gCO_2/pkm for cars and 30 gCO_2/pkm for buses in 2050. The ratio between unitary emissions remains constant throughout time as gasoline consumptions and load factors evolve in parallel for cars and buses. These figures are in line with those reported by Carbontrust[13].

4.9.2.5 *Land use and building restrictions*

Land uses incompatible with urbanization: In order to be able to reproduce the location and extent of urban areas in the Buenos Aires region correctly, NEDUM-2D accounts for regulations or land uses that are incompatible with the development of residential areas. NEDUM-2D therefore requires a map of land use constraints which is used as a filter to exclude some zones from potential urbanization. For example, it excludes zones occupied by water or protected natural areas such as forests. Water bodies (sea, rivers and lakes) are excluded from potential urbanization as a first step. In a second step a detailed land use map (see Figure 4.20) is used to identify supplementary zones that need to be excluded from potential urbanization. The exclusion map encompasses any area occupied by protected natural areas, equipment such as the military zones in Campo de Mayo and infrastructure (port, railway station, Ezeiza international airport for example). While the total area of exclusion is non-negligible, it remains, by far, lower than the area that could be potentially urbanized. This is indicative that although the exclusion map can avoid major discrepancies between the simulation and the data, it is not a main driver behind the overall accuracy of our results regarding the match between simulated and observed urbanized areas.

Land area available for buildings: We assume that in each pixel of our grid, after excluding for restricted land uses as shown in Figure 4.20, a maximum of 55% of the land area can be used for buildings. The remaining 45% is expected to be used for roads and infrastructure which are essential for any urban area to function correctly.

Building height regulations: We also add a map that provides information about the maximum Floor Area Ratios in *CABA* together with the type of use allowed in each zone. We thus limit the maximum height of buildings within *CABA*. We also exclude zones that are uniquely destined to commercial or industrial uses from being urbanized for residential purposes. To do so we intersected our grid with data from the 2011 Código de Planeamiento Urbano (CPU accessible at: http://data.buenosaires.gob.ar/). The CPU map provides for each zone the classification of buildings that can be built. From this information we can retrieve the type of buildings (residential commercial etc...) and the maximum allowed height. For each grid cell we averaged the data to obtain the average building height for residential purposes in *CABA*. Beyond *CABA* however we do not introduce maximum building heights for residential purposes.

4.9.2.6 *Other parameters*

A few other parameters are required by NEDUM-2D:

- Building's depreciation rate ρ: The depreciation rate of buildings ρ intervenes in landowner's profit function and plays a role in the determi-

[13] https://www.carbontrust.com/conversionfactors.

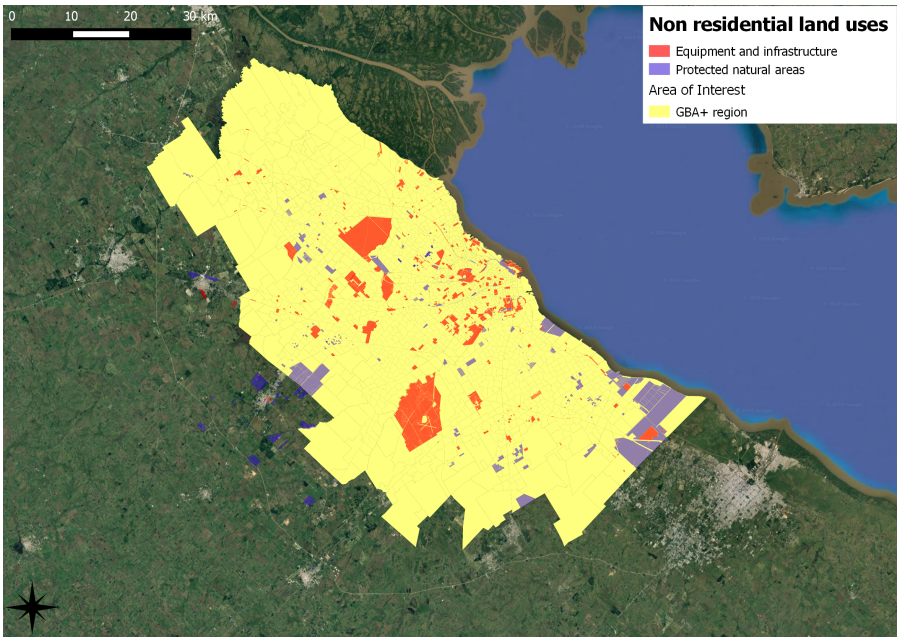

Figure 4.20: Land use exclusion map showing areas that are excluded from potential urbanization in the model for 2012 (Goytia and Pasquini, 2013). Land used for "equipment and infrastructure" or which is labelled as "protected natural areas" cannot be used for residential purposes and is therefore excluded from potential NEDUM-2D simulated urbanization.

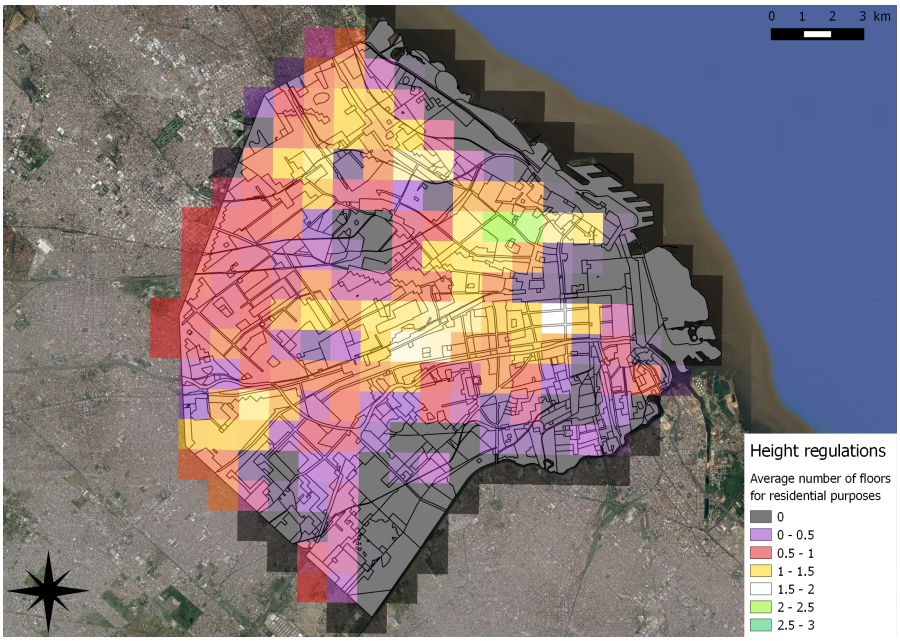

Figure 4.21: Maximum number of floors for residential purposes in CABA (data source: Código de Planeamiento Urbano - 2011, SSPLAN). Outside CABA, we assume that there are no building regulations.

nation of the amount of capital invested in structures throughout the urban area (equation (4.5)). It represents the natural depreciation of structures and is therefore used to express the average yearly annual costs of refurbishing them. Given that structures in urban areas tend to have widely varying lifetimes ranging from 30 to 150 years (Hallegatte, 2009) we chose a simple figure of 0.01 to express that on average annual maintenance costs are 1% of buildings' construction costs.

- Interest rate i: The interest rate also intervenes in the model by affecting construction costs as it represents the opportunity cost of capital or the financial cost of borrowing money to finance the construction of buildings. It is difficult to ascertain an interest rate that would adequately represent the annual financial burden of construction in an urban area like Buenos Aires which has developed over centuries. We therefore chose the value of 2% which appears to be reasonable.

- Border rent/transaction costs R_0: As discussed in section 4.9.1.2, NEDUM-2D differs from classic urban economic models because it chooses to model the edge of a city through a transaction cost below which it is no longer profitable to build structures instead of using an agricultural land value. The transaction cost that was retained in NEDUM-2D for the Buenos Aires urban area is 1US\$/m^2 in 2012. The border rent/transaction cost is assumed to evolve over time at the same rate as household income.

- Time lags for the dynamics of the housing stock: The inertia that characterizes investments in building structures, τ_H, is set to a value of 10 years. This time lag encompasses necessary time for the actual construction to take place and other transaction costs such as possibly negotiating a bank loan, finding the appropriate location and land plot, finding a suitable construction firm and negotiating building permits. This value of 10 years means that each year only a tenth of the optimal construction can take place. In terms of the inertia that characterizes the destruction of buildings, τ_{dH}, it is set at the same value as the depreciation rate, ρ, meaning that without any investments, buildings would be destroyed over the course of 100 years.

REFERENCES

Ahlfeldt, Gabriel and Daniel P. McMillen (2014). "New Estimates of the Elasticity of Substitution of Land for Capital." In: *ERSA conference papers" European Regional Science Association*.

Alonso, W. (1964). *Location and land use: toward a general theory of land rent*. Harvard University Press.

Anas, Alex and Hyok-Joo Rhee (2006). "Curbing excess sprawl with congestion tolls and urban boundaries." In: *Regional Science and Urban Economics* 36.4, pp. 510–541. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2006.03.003.

Anas, Alex and Rong Xu (1999). "Congestion, land use, and job dispersion: a general equilibrium model." In: *Journal of Urban Economics* 45.3, pp. 451–473.

Avner, Paolo, Jun E. Rentschler, and Stéphane Hallegatte (2014). "Carbon Price Efficiency: Lock-In and Path Dependence in Urban Forms and Transport Infrastructure." In: *World Bank Policy Research Working Paper* 6941.

Avner, Paolo, Vincent Viguié, and Stéphane Hallegatte (2013). "Modélisation de l'effet d'une taxe sur la construction: le Versement pour Sous-Densité." In: *Ville et Logement*. Ed. by Sabine Le Bayon, Sandrine Levasseur, and Christine Rifflart. Revue de l'OFCE - Débats et Politiques 128. Puteaux: Editions du Net.

Basso, Leonardo J. and Hugo E. Silva (2014). "Efficiency and Substitutability of Transit Subsidies and Other Urban Transport Policies." In: *American Economic Journal: Economic Policy* 6.4, pp. 1–33. ISSN: 1945-7731, 1945-774X. DOI: 10.1257/pol.6.4.1.

Bertaud, Alain and Jan K. Brueckner (2005). "Analyzing building-height restrictions: predicted impacts and welfare costs." In: *Regional Science and Urban Economics* 35.2, pp. 109–125. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2004.02.004.

Boiteux, Marcel and Luc Baumstarck (2001). *Transports: choix des investissements et coût des nuisances*. Tech. rep. Paris, La Documentation française: Commissariat général du plan.

Bondorevsky (2007). "Un Análisis Distributivo sobre el Efecto de los Subsidios al Transporte Público de Pasajeros entre 2002 y 2006 en la Región Metropolitana de Buenos Aires [A distributive analysis of public urban transport services in the Metropolitan Area of Buenos Aires between 2002 and 2006]." Paper prepared for the World Bank.

Borck, Rainald (2016). "Will skyscrapers save the planet? Building height limits and urban greenhouse gas emissions." In: *Regional Science and Urban Economics* 58, pp. 13–25. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2016.01.004.

Borck, Rainald and Matthias Wrede (2005). "Political economy of commuting subsidies." In: *Journal of Urban Economics* 57.3, pp. 478–499. ISSN: 0094-1190. DOI: 10.1016/j.jue.2004.12.003.

— (2008). "Commuting subsidies with two transport modes." In: *Journal of Urban Economics* 63.3, pp. 841–848. ISSN: 0094-1190. DOI: 10.1016/j.jue.2007.06.002.

Brueckner, Jan K. (1980). "A vintage model of urban growth." In: *Journal of Urban Economics* 8.3, pp. 389–402. ISSN: 0094-1190. DOI: doi:DOI:10.1016/0094-1190(80)90039-X.

— (1987). "Chapter 20 The structure of urban equilibria: A unified treatment of the muth-mills model." In: *Handbook of Regional and Urban Economics*. Ed. by Edwin S. Mills. Vol. Volume 2. Urban Economics. Elsevier, pp. 821–845. ISBN: 1574-0080.

— (2001). "Urban Sprawl: Lessons from Urban Economics [with Comments]." In: *Brookings-Wharton Papers on Urban Affairs*, pp. 65–97. ISSN: 15287084.

— (2005). "Transport subsidies, system choice, and urban sprawl." In: *Regional Science and Urban Economics* 35.6, pp. 715–733. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2005.01.001.

— (2011). *Lectures on urban economics*. Cambridge, Mass: MIT Press. ISBN: 978-0-262-01636-0.

Castel, J. C (2007). "Coûts immobiliers et arbitrages des opérateurs: un facteur explicatif de la ville diffuse." In: *Annales de la recherche urbaine* 102.

Davis, Morris A. and François Ortalo-Magné (2011). "Household expenditures, wages, rents." In: *Review of Economic Dynamics* 14.2, pp. 248–261. ISSN: 10942025. DOI: 10.1016/j.red.2009.12.003.

De Palma, André and Jacques-François Thisse (1987). "Les modèles de choix discrets." In: *Annales d'économie et de statistique* n°9.

Duranton, Gilles and Diego Puga (2015). "Urban Land use." In: *Handbook of Regional and Urban Economics*. Ed. by Gilles Duranton, J. Vernon Henderson, and William C. Strange. Vol. 5. Elsevier, pp. 467–560. ISBN: 978-0-444-59533-1.

Estupiñán, Nicolás, Andrés Gómez-Lobo, Ramón Muñoz-Raskin, and Tomás Serebrisky (2007). "Affordability and subsidies in public urban transport: what do we mean, what can be done?" In: *World Bank Policy Research Working Paper Series* 4440.

Fay, Marianne. (2005). *The urban poor in Latin America*. Washington, D.C.: World Bank. ISBN: 0-8213-6070-1 978-0-8213-6070-5 978-0-8213-6069-9 0-8213-6069-8.

Fujita, Masahisa (1989). *Urban economic theory: land use and city size*. Cambridge, New York: Cambridge University Press. ISBN: 978-0-521-39645-5.

Gentilini, Ugo (2015). "Safety Nets in Urban Areas: Emerging Issues, Evidence and Practices." In: *The State of Social Safety Nets*, pp. 62–72.

Glaeser, Edward L. (2009). "Green cities, brown suburbs." In: *City Journal* 19.1, pp. 50–5.

Glaeser, Edward L., Matthew E. Kahn, and Jordan Rappaport (2008). "Why do the poor live in cities? The role of public transportation." In: *Journal of urban Economics* 63.1, pp. 1–24.

Gonzalez-Navarro, Marco and Matthew Turner (2018). *Subways and Urban Growth: Evidence from Earth*. Tech. rep. w24996. Cambridge, MA: National Bureau of Economic Research. DOI: 10.3386/w24996.

Goytia, Cynthia and Ricardo A. Pasquini (2013). "Zoning and Land Cover Metrics for Municipalities in Argentina (1990 - 2001)." In: *Lincoln Institute of Land Policy Working Paper* WP13CG1.

Gusdorf, François and Stéphane Hallegatte (2007). "Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks." In: *Energy Policy* 35.10, pp. 4826–4838. ISSN: 03014215. DOI: 10.1016/j.enpol.2007.04.017.

Gwilliam, Kenneth M. (2017). "Moving to Access. Transport Pricing and Accessibility." In:

Hallegatte, Stéphane (2009). "Strategies to adapt to an uncertain climate change." In: *Global Environmental Change* 19.2, pp. 240–247. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2008.12.003.

Helsley, Robert W. and William C. Strange (2007). "Urban interactions and spatial structure." In: *Journal of Economic Geography* 7.2, pp. 119–138. ISSN: 1468-2702, 1468-2710. DOI: 10.1093/jeg/lbl027.

IEA and WBCSD (2004). *Sustainable Mobility Project*.

INDEC (2013). *Encuesta Permanente de Hogares (EPH)*.

Institut Montaigne (2012). *Transport de voyageurs: Comment réformer un modèle à bout de souffle?* Tech. rep. Institut Montaigne.

Kenworthy, Jeffrey R., Felix B. Laube, and Jean Vivier (2001). *Millennium cities database for sustainable transport*. IUTP.

Krupp, Jason and Khyaati Acharya (2014). "UP OR OUT? Examining the Trade-offs of Urban Form." In: *NYU Marron Institute of Urban Management* Working paper #13.

LeRoy, Stephen F. and Jon Sonstelie (1983). "Paradise lost and regained: Transportation innovation, income, and residential location." In: *Journal of Urban Economics* 13.1, pp. 67–89.

Litman, Todd (2008). "Valuing Transit Service Quality Improvements." In: *Journal of Public Transportation* 11.2, pp. 43–63. ISSN: 1077-291X, 2375-0901. DOI: 10.5038/2375-0901.11.2.3.

Mackie, P. J., M. Wardman, A. S. Fowkes, G. Whelan, J. Nellthorp, and J. Bates (2003). *Values of travel time savings UK*. Tech. rep. University of Leeds, Leeds, UK: Institute of Transport Studies.

Masson, Valéry et al. (2014). "Adapting cities to climate change: A systemic modelling approach." In: *Urban Climate*. ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment 10, pp. 407–429. ISSN: 2212-0955. DOI: 10.1016/j.uclim.2014.03.004.

Mills, Edwin S. (1967). "An Aggregative Model of Resource Allocation in a Metropolitan Area." In: *The American Economic Review* 57.2, pp. 197–210. ISSN: 00028282.

— (1972). *Studies in the structure of the urban economy*. Baltimore: Published for Resources for the Future by Johns Hopkins Press. ISBN: 0-8018-1367-0 978-0-8018-1367-2.

Ministerio del Interior y Transporte (2010). *Enmodo: Encuesta de Movilidad Domiciliaria. Movilidad en el Àrea Metropolitana de Buenos Aires 2009 - 2010.* Tech. rep.

Mohring, Herbert (1972). "Optimization and Scale Economies in Urban Bus Transportation." In: *The American Economic Review* 62.4, pp. 591–604. ISSN: 00028282.

Muth, Richard F. (1969). *Cities and housing; the spatial pattern of urban residential land use*. Chicago: University of Chicago Press.

OECD (2012). *Compact city policies a comparative assessment.* Paris: OECD. ISBN: 978-92-64-16784-1 92-64-16784-6 978-92-64-16786-5 92-64-16786-2.

Oort, C. J. (1969). "The Evaluation of Travelling Time." In: *Journal of Transport Economics and Policy* 3.3, pp. 279–286. ISSN: 00225258. DOI: 10.2307/20052155.

Parry, Ian W. H. and Kenneth A. Small (2009). "Should Urban Transit Subsidies Be Reduced?" In: *The American Economic Review* 99.3, pp. 700–724.

Parry, Ian W. H. and Govinda R. Timilsina (2010). "How should passenger travel in Mexico City be priced?" In: *Journal of Urban Economics* 68.2, pp. 167–182. ISSN: 00941190. DOI: 10.1016/j.jue.2010.03.009.

Peralta Quirós, Tatiana and Shomik Raj Mehndiratta (2015). "Accessibility Analysis of Growth Patterns in Buenos Aires, Argentina: Density, Employment, and Spatial Form." In: *Transportation Research Record: Journal of the Transportation Research Board* 2512, pp. 101–109. ISSN: 0361-1981. DOI: 10.3141/2512-12.

Rosenthal, Stuart S. and William C. Strange (2004). "Chapter 49 Evidence on the nature and sources of agglomeration economies." In: *Handbook of Regional and Urban Economics*. Vol. 4. Elsevier, pp. 2119–2171. ISBN: 978-0-444-50967-3.

Salon, Deborah (2009). "Neighborhoods, cars, and commuting in New York City: A discrete choice approach." In: *Transportation Research Part A: Policy and Practice* 43.2, pp. 180–196.

Small, Kenneth A. and Erik T. Verhoef (2007). *The economics of urban transportation*. New York: Routledge. ISBN: 1-134-49571-4.

Small, Kenneth A., Clifford Winston, and Jia Yan (2005). "Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability." In: *Econometrica* 73.4, pp. 1367–1382. ISSN: 0012-9682, 1468-0262. DOI: 10.1111/j.1468-0262.2005.00619.x.

Su, Qing and Joseph S. DeSalvo (2008). "The Effect of Transportation Subsidies On Urban Sprawl." In: *Journal of Regional Science* 48.3, pp. 567–594.

Thorsnes, Paul (1997). "Consistent Estimates of the Elasticity of Substitution between Land and Non-Land Inputs in the Production of Housing." In: *Journal of Urban Economics* 42.1, pp. 98–108. ISSN: 0094-1190. DOI: 10.1006/juec.1996.2015.

Tscharaktschiew, Stefan and Georg Hirte (2012). "Should subsidies to urban passenger transport be increased? A spatial CGE analysis for a German metropolitan area." In: *Transportation Research Part A: Policy and Practice* 46.2, pp. 285–309. ISSN: 0965-8564. DOI: 10.1016/j.tra.2011.09.006.

Viguié, Vincent (2012). "Urban Dynamics Modelling, application to economics assessment of climate change." PhD thesis. Université Paris-Est.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

Von Thünen, J. H. (1826). *Isolated State*. Pergamon, Oxford.

Washbrook, Kevin, Wolfgang Haider, and Mark Jaccard (2006). "Estimating commuter mode choice: A discrete choice analysis of the impact of road pricing and parking charges." In: *Transportation* 33.6, pp. 621–639.

CONCLUSION

> « *Je pratique le métronome dans un claquement de doigts.*
> *J'habite une métropole près d'un arbre en bois.* »
>
> Ahmad, Sameer. "Sitting Bull." *Apaches*, Bad Cop Bad Cop, 2019.

The internal structure of urban areas – the way people and jobs are distributed through space in cities – determines distances between homes and jobs and thus average commuting patterns, distances travelled and strongly impacts transport-related CO_2 emissions through the travel ***A***ctivity channel. Urban form also is a strong determinant of mode ***S***hares which also impacts the carbon content of travel, as more carbon sober collective/public transport investments only make economic and political sense when transport demand densities are high enough to ensure that buses or commuter trains do not run three-quarters empty, and soft modes (pedestrians, cyclists) are only accessible to people travelling limited distances.

Technological solutions consisting in more fuel efficient or less carbon ***I***ntensive vehicles and tail pipe carbon sober ***F***uels such as electricity or hydrogen have a key role to play in decarbonizing transport in general and urban transport in particular. But they currently come with large uncertainties as to how much they can contribute to limiting transport emissions and climate change in the future and by when. Producing energy is always costly, including from renewable sources. Stocking energy is a challenge, requiring technological break-throughs in batteries and fuel cells, while also relying on scarce materials such as Lithium (in the case of batteries). Carrying and distributing energy and ensuring "continuity of service", even when produced from intermittent sources such as wind will require massive infrastructure investments and the creation of "copper plates".

At a time when urbanization rates are unprecedented with people flocking to cities in developing countries at a vertiginous speed, this suggests that there is a role for urban and transport policies to curb greenhouse gas emissions from urban transport by acting on travel demand through the shape of cities. Failure to do so now means coping with irreversible urban forms and quasi-incompressible travel patterns in the future as structures such as the housing stock are characterized by high sunk costs and the impossibility of being relocated. Even if technological transport and energy solutions outperformed expectations in the future, this concern about acting on urban forms early to avoid lock-ins would be a robust strategy. It will always be possible to expand cities spatially in the future whereas the opposite is untrue. In Claude Henry's words (Henry, 1974), which resonate acutely with recent developments, the choice of replacing the cathedral Notre Dame with a parking lot (irrespective of whether it makes sense in the first place) at a given time is an irreversible decision. Delaying that decision preserves the possibility of the replacement in the future while acting now does not – it won't be possible (or easy, or cheap) to rebuild Notre Dame cathedral if it is razed and replaced by a parking lot. Notre Dame carries a value option attached to the fact that it is irreplaceable. Similarly, compact urban forms carry a value option, in the sense that failure to preserve this character is irreversible.

But if the idea of acting on travel activity demand through more compact urban forms makes sense, what are the tools that could enable such an outcome? This is in fact a two—pronged question as the technical soundness of a policy does not guarantee that it will or can be applied in practice. This is the core of the dissertation. To be applicable policies must be both (1) sound technically, i.e. they can deliver expected outcomes in an idealized world and (2) they are politically acceptable – meaning that they do not deteriorate the welfare of agents in such a way that they would be widely opposed. This dissertation indeed starts from the premise that climate change mitigation in urban areas (and elsewhere) does not happen in a vacuum and that other outcomes and policy goals need to be considered. In particular, it is essential that policies aiming to limit urban sprawl and/or reduce CO_2 emissions from commuting do not come at the expense of higher housing costs.

To be able to capture both the effectiveness and political economy of interventions aiming at mitigating urban sprawl and transport-related CO_2 emissions, we relied on a simple urban economy model calibrated on real world cities. A validation exercise performed for the urban areas of Paris and Buenos Aires showed that, despite simplifying assumptions and local discrepancies, the modelling approach was able to reproduce the main features of these agglomerations: population, housing rent and land value distributions, average mode shares and overall shape and size of the built-up footprint. Starting from these baseline calibration of urban areas, this dissertation goes on to examine the impacts of various interventions through the use of counterfactual scenarios by "shocking" the system and comparing the outcomes with what would happen under the baseline.

In three different essays, this dissertation looked at:

1. The potential for **investments in public transport** infrastructure to reduce CO_2 emissions and increase the acceptability of carbon taxes. It is shown that the price elasticity of CO_2 emissions is twice as high in the short run if public transport options exist. Reducing commuting-related emissions thus requires lower – and therefore more acceptable – tax levels in the presence of dense public transportation.

2. The potential for density-tied **land taxes** to curb urban sprawl without increasing the housing effort rate of households. It is found that a specific scheme, the Payment for Insufficient Density, can achieve both these goals if implemented correctly. However, if implemented incorrectly, it could lead to counter-productive effects on both counts.

3. How reforming **public transport subsidies** in Buenos Aires would impact transport-related CO_2 emissions, urban sprawl and what welfare consequences are to be expected disentangling between homeowners and renters. The analysis concludes to complex impacts of replacing the transit subsidy but argues that under nearly all scenarios it would lead to larger CO_2 emissions and that only a lump sum transfer scheme could do better in terms of average welfare – nevertheless hurting homeowners living in distant areas most.

This set of results shows that it is possible to act on urban transport-related CO_2 emissions and urban sprawl through urban and transport interventions that influence the shape of cities. It also shows these policies need not be politically contentious and that it is possible to build synergies between climate and other welfare objectives. At the center of these possible synergies lies

the need to carefully account for housing as a major expense for households and one that is fundamental to their welfare.

The definition of these policies is however not straightforward and the possibility of "getting them wrong" should not be assessed as minimal or disregarded. This is where modelling proves to be useful; sometimes allowing to avoid large mistakes by showing the conditions for success of interventions but most of the time, more modestly, by simply pointing out the possibility of overlooking them.

In concluding this dissertation, it is useful to point to areas for future work. Chapter 1 started with a discussion around optimal model complexity for representing cities. A challenge ahead would thus be to add more realism to NEDUM-2D without losing the benefits of its current simplicity. Three different routes appear as natural candidates. The first one is to lift the monocentric assumption and allow the model to represent multiple job centers. The second option is to lift the assumption of the average household and account for multiple income classes in the model. As we aim to increasingly investigate challenges in developing country cities, where most of the urban growth is taking place, this appears to be a core priority. The third option is to build a more complex/realistic transport module able to account for congestion levels in a dynamic way. While this dissertation stops short of these improvements, the good news is that current efforts in CIRED are close to fruition on the first two aspects, opening up new applied research possibilities.

REFERENCES

Henry, Claude (1974). "Investment Decisions Under Uncertainty: The "Irreversibility Effect"." In: *The American Economic Review* 64.6, pp. 1006–1012. ISSN: 00028282.

BIBLIOGRAPHY

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012). "The Environment and Directed Technical Change." In: *American Economic Review* 102.1, pp. 131–166. ISSN: 0002-8282. DOI: 10.1257/aer.102.1.131.

Acheampong, Ransford Antwi and Elisabete Silva (2015). "Land use–transport interaction modeling: A review of the literature and future research directions." In: *Journal of Transport and Land Use*. ISSN: 1938-7849. DOI: 10.5198/jtlu.2015.806.

Aguejdad, Rahim, J. Hidalgo, O. Doukari, Valéry Masson, and Thomas Houet (2012). "Assessing the influence of long-term urban growth and climate change scenarios on urban climate." In: Leipzig, Germany.

Ahlfeldt, Gabriel M. and Daniel P. McMillen (2015). "The vertical city: the price of land and the height of buildings in Chicago 1870-2010." In: *SERC Discussion Papers*, SERCDP0180.

Ahlfeldt, Gabriel and Daniel P. McMillen (2014). "New Estimates of the Elasticity of Substitution of Land for Capital." In: *ERSA conference papers" European Regional Science Association*.

Alonso, W. (1964). *Location and land use: toward a general theory of land rent*. Harvard University Press.

Anas, Alex and Tomoru Hiramatsu (2012). "The effect of the price of gasoline on the urban economy: From route choice to general equilibrium." In: *Transportation Research Part A: Policy and Practice* 46.6, pp. 855–873. ISSN: 09658564. DOI: 10.1016/j.tra.2012.02.010.

Anas, Alex and Yu Liu (2007). "A Regional Economy, Land Use, and Transportation Model (RELU-TRAN©): Formulation, Algorithm Design, and Testing." In: *Journal of Regional Science* 47.3, pp. 415–455.

Anas, Alex and Hyok-Joo Rhee (2006). "Curbing excess sprawl with congestion tolls and urban boundaries." In: *Regional Science and Urban Economics* 36.4, pp. 510–541. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2006.03.003.

Anas, Alex and Rong Xu (1999). "Congestion, land use, and job dispersion: a general equilibrium model." In: *Journal of Urban Economics* 45.3, pp. 451–473.

Anderson, Soren T., Ian W. H. Parry, James M. Sallee, and Carolyn Fischer (2011). "Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives." In: *Review of Environmental Economics and Policy* 5.1, pp. 89–108. ISSN: 1750-6816, 1750-6824. DOI: 10.1093/reep/req021.

Angel, Shlomo and Alejandro M. Blei (2015a). "Commuting and the productivity of American cities." In: *NYU Marron Institute of Urban Management* Working paper #19, pp. 1–44.

— (2015b). "Commuting and the spatial structure of American cities." In: *NYU Marron Institute of Urban Management* Working paper #20, pp. 1–55.

Arnott, Richard (2005). "Neutral Property Taxation." In: *Journal of Public Economic Theory* 7.1, pp. 27–50. ISSN: 1467-9779. DOI: 10.1111/j.1467-9779.2005.00192.x.

Audoly, Richard, Adrien Vogt-Schilb, and Celine Guivarch (2014). *Pathways toward zero-carbon electricity required for climate stabilization*. Tech. rep. WPS7075. The World Bank, pp. 1–20.

Avner, Paolo, Shomik Raj Mehndiratta, Vincent Viguie, and Stéphane Hallegatte (2017). "Buses, houses or cash ? socio-economic, spatial and environmental consequences of reforming public transport subsidies in Buenos Aires." In: *World Bank Policy Research Working Paper* 8166, pp. 1–54.

Avner, Paolo, Jun E. Rentschler, and Stéphane Hallegatte (2014). "Carbon Price Efficiency: Lock-In and Path Dependence in Urban Forms and Transport Infrastructure." In: *World Bank Policy Research Working Paper* 6941.

Avner, Paolo, Vincent Viguié, and Stéphane Hallegatte (2013). "Modélisation de l'effet d'une taxe sur la construction: le Versement pour Sous-Densité." In: *Ville et Logement*. Ed. by Sabine Le Bayon, Sandrine Levasseur, and Christine Rifflart. Revue de l'OFCE - Débats et Politiques 128. Puteaux: Editions du Net.

Baer, Paul, John Harte, Barbara Haya, Antonia V. Herzog, John Holdren, Nathan E. Hultman, Daniel M. Kammen, Richard B. Norgaard, and Leigh Raymond (2000). "Equity and Greenhouse Gas Responsibility." In: *Science* 289.5488, p. 2287. DOI: 10.1126/science.289.5488.2287.

Balaras, Constantinos A., Gershon Grossman, Hans-Martin Henning, Carlos A. Infante Ferreira, Erich Podesser, Lei Wang, and Edo Wiemken (2007). "Solar air conditioning in Europe—an overview." In: *Renewable and Sustainable Energy Reviews* 11.2, pp. 299–314. ISSN: 13640321. DOI: 10.1016/j.rser.2005.02.003.

Basso, Leonardo J. and Hugo E. Silva (2014). "Efficiency and Substitutability of Transit Subsidies and Other Urban Transport Policies." In: *American Economic Journal: Economic Policy* 6.4, pp. 1–33. ISSN: 1945-7731, 1945-774X. DOI: 10.1257/pol.6.4.1.

Baum-Snow, Nathaniel (2007b). "Suburbanization and transportation in the monocentric model." In: *Journal of Urban Economics* 62.3, pp. 405–423. ISSN: 00941190. DOI: 10.1016/j.jue.2006.11.006.

Bell, Michelle L., Richard Goldberg, Christian Hogrefe, Patrick L. Kinney, Kim Knowlton, Barry Lynn, Joyce Rosenthal, Cynthia Rosenzweig, and Jonathan A. Patz (2007). "Climate change, ambient ozone, and health in 50 US cities." In: *Climatic Change* 82.1-2, pp. 61–76. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-006-9166-7.

Bentick, Brian L. (1979). "The Impact of Taxation and Valuation Practices on the Timing and Efficiency of Land Use." In: *Journal of Political Economy* 87.4, pp. 859–868. ISSN: 0022-3808.

Bento, Antonio M., M. L. Cropper, A. M. Mobarak, and K. Vinha (2005). "The effects of urban spatial structure on travel demand in the United States." In: *Review of Economics and Statistics* 87.3, pp. 466–478. ISSN: 0034-6535, 1530-9142. DOI: 10.1162/0034653054638292.

Bento, Antonio M., Sofia F. Franco, and Daniel Kaffine (2006). "The efficiency and distributional impacts of alternative anti-sprawl policies." In: *Journal of Urban Economics* 59.1, pp. 121–141. ISSN: 0094-1190. DOI: 10.1016/j.jue.2005.09.004.

Bento, Antonio M., Daniel Kaffine, Kevin Roth, and M. Zaragoza (2014). "The Effects of Regulation in the Presence of Multiple Unpriced Externalities: Evidence from the Transportation Sector." In: *American Economic Journal: Economic Policy* 6.3, pp. 1–29. DOI: 10.1257/pol.6.3.1.

Bertaud, Alain (2002). "The spatial organization of cities: Deliberate outcome or unforeseen consequence?" In: *World Development Report 2003, background paper*.

Bertaud, Alain and Jan K. Brueckner (2005). "Analyzing building-height restrictions: predicted impacts and welfare costs." In: *Regional Science and Urban Economics* 35.2, pp. 109–125. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2004.02.004.

Billen, G., S. Barles, P. Chatzimpiros, and J. Garnier (2012). "Grain, meat and vegetables to feed Paris: where did and do they come from? Localising Paris food supply areas from the eighteenth to the twenty-first century." In: *Regional Environmental Change* 12.2, pp. 325–335. ISSN: 1436-3798, 1436-378X. DOI: 10.1007/s10113-011-0244-7.

Bjerke, Tore, Torbjørn Østdahl, Christer Thrane, and Einar Strumse (2006). "Vegetation density of urban parks and perceived appropriateness for recreation." In: *Urban Forestry & Urban Greening* 5.1, pp. 35–44. ISSN: 16188667. DOI: 10.1016/j.ufug.2006.01.006.

Boiteux, Marcel and Luc Baumstarck (2001). *Transports: choix des investissements et coût des nuisances*. Tech. rep. Paris, La Documentation française: Commissariat général du plan.

Bondorevsky (2007). "Un Análisis Distributivo sobre el Efecto de los Subsidios al Transporte Público de Pasajeros entre 2002 y 2006 en la Región Metropolitana de Buenos Aires [A distributive analysis of public urban transport services in the Metropolitan Area of Buenos Aires between 2002 and 2006]." Paper prepared for the World Bank.

Borck, Rainald (2016). "Will skyscrapers save the planet? Building height limits and urban greenhouse gas emissions." In: *Regional Science and Urban Economics* 58, pp. 13–25. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2016.01.004.

Borck, Rainald and Matthias Wrede (2005). "Political economy of commuting subsidies." In: *Journal of Urban Economics* 57.3, pp. 478–499. ISSN: 0094-1190. DOI: 10.1016/j.jue.2004.12.003.

— (2008). "Commuting subsidies with two transport modes." In: *Journal of Urban Economics* 63.3, pp. 841–848. ISSN: 0094-1190. DOI: 10.1016/j.jue.2007.06.002.

Box, George EP and Norman R. Draper (1987). *Empirical model-building and response surfaces*. John Wiley & Sons. ISBN: 0-471-81033-9.

Brasington, David M. and Diane Hite (2005). "Demand for environmental quality: a spatial hedonic analysis." In: *Regional Science and Urban Economics* 35.1, pp. 57–82. ISSN: 01660462. DOI: 10.1016/j.regsciurbeco.2003.09.001.

Brooks, Leah and Byron F. Lutz (2014). "Vestiges of Transit: Urban Persistence at a Micro Sale." In: *SSRN Electronic Journal*. ISSN: 1556-5068. DOI: 10.2139/ssrn.2752034.

Brownstone, David and Thomas F. Golob (2009). "The impact of residential density on vehicle usage and energy consumption." In: *Journal of Urban Economics* 65.1, pp. 91–98. ISSN: 0094-1190. DOI: 10.1016/j.jue.2008.09.002.

Brueckner, Jan K. (1980). "A vintage model of urban growth." In: *Journal of Urban Economics* 8.3, pp. 389–402. ISSN: 0094-1190. DOI: doi:DOI:10.1016/0094-1190(80)90039-X.

— (1987). "Chapter 20 The structure of urban equilibria: A unified treatment of the muth-mills model." In: *Handbook of Regional and Urban Economics*. Ed. by Edwin S. Mills. Vol. Volume 2. Urban Economics. Elsevier, pp. 821–845. ISBN: 1574-0080.

— (2000). "Urban sprawl: Diagnosis and remedies." In: *International regional science review* 23.2, pp. 160–171.

Brueckner, Jan K. (2001). "Urban Sprawl: Lessons from Urban Economics [with Comments]." In: *Brookings-Wharton Papers on Urban Affairs*, pp. 65–97. ISSN: 15287084.

— (2005). "Transport subsidies, system choice, and urban sprawl." In: *Regional Science and Urban Economics* 35.6, pp. 715–733. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2005.01.001.

— (2011). *Lectures on urban economics*. Cambridge, Mass: MIT Press. ISBN: 978-0-262-01636-0.

Brueckner, Jan K. and Hyun-A. Kim (2003). "Urban sprawl and the property tax." In: *International Tax and Public Finance* 10.1, pp. 5–23.

Bueno, Bruno, Julia Hidalgo, Grégoire Pigeon, Leslie Norford, and Valéry Masson (2013). "Calculation of Air Temperatures above the Urban Canopy Layer from Measurements at a Rural Operational Weather Station." In: *Journal of Applied Meteorology and Climatology* 52.2, pp. 472–483. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/JAMC-D-12-083.1.

Bueno, Bruno, Leslie Norford, Grégoire Pigeon, and Rex Britter (2012). "A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate." In: *Building and Environment* 54, pp. 116–125. ISSN: 03601323. DOI: 10.1016/j.buildenv.2012.01.023.

Bueno, Bruno, Grégoire Pigeon, Leslie Norford, Karim Zibouche, and Colette Marchadier (2012). "Development and evaluation of a building energy model integrated in the TEB scheme." In: *Geoscientific Model Development* 5.2, pp. 433–448. ISSN: 1991-9603. DOI: 10.5194/gmd-5-433-2012.

Burchfield, Marcy, Henry G. Overman, Diego Puga, and Matthew A. Turner (2006). "Causes of Sprawl: A Portrait from Space." In: *The Quarterly Journal of Economics* 121.2, pp. 587–633. ISSN: 0033-5533, 1531-4650. DOI: 10.1162/qjec.2006.121.2.587.

Buzy-Cazaux, Henry (2012). *Augmentation des droits à construire : une mesure d'optique - Blogs Immobilier*.

Carbone, Jared C., Richard D. Morgenstern, and Roberton C. Williams III (2012). "Carbon taxes and deficit reduction." In: *unpublished paper*.

Castel, J. C (2007). "Coûts immobiliers et arbitrages des opérateurs: un facteur explicatif de la ville diffuse." In: *Annales de la recherche urbaine* 102.

Charmes, Eric (2007). "Le malthusianisme foncier." In: *Etudes foncières* 125, pp. 12–16.

Chateau, Bertrand, Domenico Rossetti, European Union, European Commission, and Directorate-General for Research and Innovation (2011). *World and European energy and environment transition outlook: WETO-T*. Luxembourg: Publications Office of the European Union. ISBN: 978-92-79-20044-1.

Chrysoulakis, Nektarios et al. (2013). "Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project." In: *Landscape and Urban Planning* 112, pp. 100–117. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2012.12.005.

Clarke, Keith C. (2008). "A decade of cellular urban modeling with SLEUTH: Unresolved issues and problems Chapter 3." In: *Planning Support Systems for Cities and Regions*. Ed. by RK Brail. Cambridge, MA: Lincoln Institute of Land Policy, pp. 47–60.

Clarke, Keith C. and Leonard J. Gaydos (1998). "Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore." In: *International Journal of Geographical Information Science* 12.7, pp. 699–714. ISSN: 1365-8816, 1362-3087. DOI: 10.1080/136588198241617.

Clarke, Keith C., S. Hoppen, and Leonard J. Gaydos (1997). "A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area." In: *Environment and Planning B: Planning and Design* 24.2, pp. 247–261. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b240247.

Coulombel, Nicolas (2017). "Prudential measures in housing access: Should one include transport costs in the front-end ratio?" In: *Journal of Transport and Land Use* 10.1, pp. 627–654. ISSN: 19387849.

Crane, R. (2000). "The Influence of Urban Form on Travel: An Interpretive Review." In: *Journal of Planning Literature* 15.1, pp. 3–23. ISSN: 0885-4122. DOI: 10.1177/08854120022092890.

Cremer, Helmuth, Firouz Gahvari, and Norbert Ladoux (1998). "Externalities and optimal taxation." In: *Journal of Public Economics* 70.3, pp. 343–364.

Creutzig, Felix, Peter Agoston, Jan C. Minx, Josep G. Canadell, Robbie M. Andrew, Corinne Le Quéré, Glen P. Peters, Ayyoob Sharifi, Yoshiki Yamagata, and Shobhakar Dhakal (2016). "Urban infrastructure choices structure climate solutions." In: *Nature Climate Change* 6.12, pp. 1054–1056. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate3169.

Creutzig, Felix, Rainer Mühlhoff, and Julia Römer (2012). "Decarbonizing urban transport in European cities: four cases show possibly high co-benefits." In: *Environmental Research Letters* 7.4, p. 044042. ISSN: 1748-9326. DOI: 10.1088/1748-9326/7/4/044042.

Crifo, Patricia, Matthieu Glachant, Stéphane Hallegatte, Eloi Laurent, and Raphaël Gibert (2012). *L'économie verte contre la crise.* Hors Collection. PUF. ISBN: 978-2-13-060798-4.

Czepkiewicz, Michał, Jukka Heinonen, and Juudit Ottelin (2018). "Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel." In: *Environmental Research Letters* 13.7, p. 073001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aac9d2.

Dahl, Carol (1995). "Demand for transportation fuels: a survey of demand elasticities and their components." In: *Journal of Energy Literature* 1.2, pp. 3–27.

Dargay, Joyce, Dermot Gately, and Martin Sommer (2007). "Vehicle Ownership and Income Growth, Worldwide: 1960-2030." In: *The Energy Journal* 28.4, pp. 143–170. ISSN: 01956574, 19449089.

Davis, Morris A. and François Ortalo-Magné (2011). "Household expenditures, wages, rents." In: *Review of Economic Dynamics* 14.2, pp. 248–261. ISSN: 10942025. DOI: 10.1016/j.red.2009.12.003.

De Jong, Gerard and Hugh Gunn (2001). "Recent evidence on car cost and time elasticities of travel demand in Europe." In: *Journal of Transport Economics and Policy*, pp. 137–160.

De La Barra, Tomas (2001). "Integrated land use and transport modeling: the TRANUS experience." In: *Planning Support Systems: Integrating Geographic Information Systems, Models and Visualization Tools*. Ed. by RK Brail and RE Klosterman. Redlands, CA: ESRI Press, pp. 129–156.

De la Barra, Tomas (2005). *Integrated land use and transport modelling. Decision chains and hierarchies*. Cambridge University Press. ISBN: 0-521-24318-1.

De Munck, Cécile, Grégoire Pigeon, Valéry Masson, Francis Meunier, Pierre Bousquet, Brice Tréméac, Michèle Merchat, Pierre Poeuf, and Colette Marchadier (2013). "How much can air conditioning increase air temperatures for a city like Paris, France?" In: *International Journal of Climatology* 33.1, pp. 210–227. ISSN: 08998418. DOI: 10.1002/joc.3415.

De Palma, André and Jacques-François Thisse (1987). "Les modèles de choix discrets." In: *Annales d'économie et de statistique* n°9.

De Roo, Ad, Jose Barredo, Carlo Lavalle, Katalin Bodis, and Rado Bonk (2007). "Potential Flood Hazard and Risk Mapping at Pan-European Scale." In: *Digital Terrain Modelling*. Ed. by William Cartwright, Georg Gartner, Liqiu Meng, Michael P. Peterson, Robert Joseph Peckham, and Gyozo Jordan. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 183–202. ISBN: 978-3-540-36730-7 978-3-540-36731-4. DOI: 10.1007/978-3-540-36731-4_8.

Dearing, John, Ademola Braimoh, Anette Reenberg, Billie Turner, and Sander Van der Leeuw (2010). "Complex land systems: the need for long time perspectives to assess their future." In: *Ecology and Society* 15.4.

Deloitte (2016). *Deloitte Africa Automotive Insights*. Tech. rep. Deloitte.

Dessai, Suraje (2003). "Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change." In: *International Journal of Biometeorology* 48.1, pp. 37–44. ISSN: 0020-7128, 1432-1254. DOI: 10.1007/s00484-003-0180-4.

DGFiP (2010). *L'annuaire statistique des impôts 2010*. Tech. rep. Direction Générale des Finances Publiques.

Dijkstra, Lewis and Hugo Poelman (2014). *A harmonised definition of cities and rural areas: the new degree of urbanisation*. Tech. rep. WP 01/2014. European Commission.

Doukari, O., Rahim Aguejdad, and Thomas Houet (2013). "SLEUTH*: a scenario-based version of SLEUTH for simulating breaking trends urban sprawl futures." In: *Comput. Environ. Urban Syst.(submitted)*.

DRIEA (2005). *Les déplacements des Franciliens en 2001 - 2002. Enquête Globale de Transports*. Tech. rep. Direction Régionale de l'Equipement Ile-de-France.

Duranton, Gilles and Diego Puga (2015). "Urban Land use." In: *Handbook of Regional and Urban Economics*. Ed. by Gilles Duranton, J. Vernon Henderson, and William C. Strange. Vol. 5. Elsevier, pp. 467–560. ISBN: 978-0-444-59533-1.

Ebi, Kristie L. et al. (2013). "A new scenario framework for climate change research: background, process, and future directions." In: *Climatic Change*, pp. 1–10. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0912-3.

Edenhofer, Ottmar, Linus Mattauch, and Jan Siegmeier (2013). "Hypergeorgism: when is rent taxation as a remedy for insufficient capital accumulation socially optimal?" In: *CESifo Working Papers Series* 4144.

Edenhofer, Ottmar et al., eds. (2015). *Climate Change 2014: Mitigation of Climate Change ; Summary for Policymakers Technical Summary ; Part of the Working Group III Contribution to the Fifth Asessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel on Climate Change. ISBN: 978-92-9169-142-5.

EEA (2006). *Urban sprawl in Europe–the ignored challenge*. No. 10. EEA, Copenhagen, Denmark.

Ellaway, Anne, Sally Macintyre, Rosemary Hiscock, and Ade Kearns (2003). "In the driving seat: psychosocial benefits from private motor vehicle transport compared to public transport." In: *Transportation Research Part F: Traffic Psychology and Behaviour* 6.3, pp. 217–231.

Epple, Dennis, Brett Gordon, and Holger Sieg (2010). "A New Approach to Estimating the Production Function for Housing." In: *The American Economic Review* 100.3, pp. 905–924. ISSN: 0002-8282.

Estupiñán, Nicolás, Andrés Gómez-Lobo, Ramón Muñoz-Raskin, and Tomás Serebrisky (2007). "Affordability and subsidies in public urban transport: what do we mean, what can be done?" In: *World Bank Policy Research Working Paper Series* 4440.

European Union and SOes (2006). *Corine Land Cover, 2006*.

Ewing, Reid and Robert Cervero (2010). "Travel and the Built Environment: A Meta-Analysis." In: *Journal of the American Planning Association* 76.3, pp. 265–294. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944361003766766.

Fay, Marianne. (2005). *The urban poor in Latin America*. Washington, D.C.: World Bank. ISBN: 0-8213-6070-1 978-0-8213-6070-5 978-0-8213-6069-9 0-8213-6069-8.

Fay, Marianne, Stéphane Hallegatte, Adrien Vogt-Schilb, Julie Rozenberg, Ulf Narloch, and Tom Kerr (2015). *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. The World Bank. ISBN: 978-1-4648-0479-3 978-1-4648-0606-3. DOI: 10.1596/978-1-4648-0479-3.

Fouquet, Roger (2012). "Trends in income and price elasticities of transport demand (1850–2010)." In: *Special Section: Past and Prospective Energy Transitions - Insights from History* 50.0, pp. 62–71. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2012.03.001.

Friggit, J. (2010). "Le prix des logements sur le long terme." In: *Structure* 3, p. 1.

Fujii, Hidemichi, Kazuyuki Iwata, and Shunsuke Managi (2017). "How do urban characteristics affect climate change mitigation policies?" In: *Journal of Cleaner Production* 168, pp. 271–278. ISSN: 09596526. DOI: 10.1016/j.jclepro.2017.08.221.

Fujita, Masahisa (1989). *Urban economic theory: land use and city size*. Cambridge, New York: Cambridge University Press. ISBN: 978-0-521-39645-5.

Gabriel, Katharina M.A. and Wilfried R. Endlicher (2011). "Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany." In: *Environmental Pollution* 159.8-9, pp. 2044–2050. ISSN: 02697491. DOI: 10.1016/j.envpol.2011.01.016.

GEA (2012). *Global Energy Assessment - Toward A Sustainable Future*. Ed. by Thomas B. Johansson, Anand Patwardhan, Nebojša Nakićenović, Luis Gomez-Echeverri, and International Institute for Applied Systems Analysis. Cambridge : Laxenburg, Austria: Cambridge University Press ; International Institute for Applied Systems Analysis. ISBN: 978-1-107-00519-8 978-0-521-18293-5.

Gentilini, Ugo (2015). "Safety Nets in Urban Areas: Emerging Issues, Evidence and Practices." In: *The State of Social Safety Nets*, pp. 62–72.

Gillingham, Kenneth, Alan Jenn, and Inês M.L. Azevedo (2015). "Heterogeneity in the response to gasoline prices: Evidence from Pennsylvania and implications for the rebound effect." In: *Energy Economics* 52, S41–S52. ISSN: 01409883. DOI: 10.1016/j.eneco.2015.08.011.

Glaeser, Edward L. (2009). "Green cities, brown suburbs." In: *City Journal* 19.1, pp. 50–5.

Glaeser, Edward L. and Matthew E. Kahn (2004). "Sprawl and urban growth." In: *Handbook of Regional and Urban Economics*. Ed. by J. Vernon Henderson and Jacques-François Thisse. Vol. Volume 4. Cities and Geography. Elsevier, pp. 2481–2527. ISBN: 1574-0080.

— (2010). "The greenness of cities: Carbon dioxide emissions and urban development." In: *Journal of Urban Economics* 67.3, pp. 404–418. ISSN: 00941190. DOI: 10.1016/j.jue.2009.11.006.

Glaeser, Edward L., Matthew E. Kahn, and Jordan Rappaport (2008). "Why do the poor live in cities? The role of public transportation." In: *Journal of urban Economics* 63.1, pp. 1–24.

Godet, Michel (1986). "Introduction to la prospective." In: *Futures* 18.2, pp. 134–157. ISSN: 00163287. DOI: 10.1016/0016-3287(86)90094-7.

Gonzalez-Navarro, Marco and Matthew Turner (2018). *Subways and Urban Growth: Evidence from Earth*. Tech. rep. w24996. Cambridge, MA: National Bureau of Economic Research. DOI: 10.3386/w24996.

Goodwin, Phil B. (1992). "A review of new demand elasticities with special reference to short and long run effects of price changes." In: *Journal of transport economics and policy*, pp. 155–169.

Goodwin, Phil B., Joyce Dargay, and Mark Hanly (2004). "Elasticities of road traffic and fuel consumption with respect to price and income: a review." In: *Transport Reviews* 24.3, pp. 275–292.

Gordon, Ian (1997). "Densities, urban form and travel behaviour." In: *Town and Country Planning* 66.9, pp. 239–241.

— (2008). "Density and the built environment." In: *Energy Policy* 36.12, pp. 4652–4656. ISSN: 03014215. DOI: 10.1016/j.enpol.2008.09.002.

Gordon, Peter, Ajay Kumar, and Harry W. Richardson (1989). "The influence of metropolitan spatial structure on commuting time." In: *Journal of Urban Economics* 26.2, pp. 138–151. ISSN: 00941190. DOI: 10.1016/0094-1190(89)90013-2.

Gordon, Peter and Harry W. Richardson (1989). "Gasoline Consumption and Cities: A Reply." In: *Journal of the American Planning Association* 55.3, pp. 342–346. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944368908975421.

Gordon, Peter, Harry W. Richardson, and Myung-Jin Jun (1991). "The Commuting Paradox Evidence from the Top Twenty." In: *Journal of the American Planning Association* 57.4, pp. 416–420. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944369108975516.

Goulder, Lawrence H. (1995). "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis." In: *Journal of Environmental Economics and Management* 29.3, pp. 271–297. ISSN: 00950696. DOI: 10.1006/jeem.1995.1047.

Goytia, Cynthia and Ricardo A. Pasquini (2013). "Zoning and Land Cover Metrics for Municipalities in Argentina (1990 - 2001)." In: *Lincoln Institute of Land Policy Working Paper* WP13CG1.

Gracia, Clémence, Fabio Grazi, Nicole Madariaga, and Ophélie Risler (2015). *Cities in Climate Change Mitigation Policy*. A Question of Development 21. AFD.

Graham, Daniel J. and Stephen Glaister (2002). "The demand for automobile fuel: a survey of elasticities." In: *Journal of Transport Economics and policy*, pp. 1–25.

— (2004). "Road traffic demand elasticity estimates: a review." In: *Transport reviews* 24.3, pp. 261–274.

Grazi, Fabio and Jeroen C.J.M. van den Bergh (2008). "Spatial organization, transport, and climate change: Comparing instruments of spatial planning and policy." In: *Ecological Economics* 67.4, pp. 630–639. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2008.01.014.

Grazi, Fabio, Jeroen C.J.M. van den Bergh, and Jos N. van Ommeren (2008). "An Empirical Analysis of Urban Form, Transport, and Global Warming." In: *The Energy Journal* 29.4.

Gudipudi, Ramana, Till Fluschnik, Anselmo García Cantú Ros, Carsten Walther, and Jürgen P. Kropp (2016). "City density and CO2 efficiency." In: *Energy Policy* 91, pp. 352–361. ISSN: 03014215. DOI: 10.1016/j.enpol.2016.01.015.

Guivarch, Céline and Stéphane Hallegatte (2011). "Existing infrastructure and the 2°C target." In: *Climatic Change* 109.3-4, pp. 801–805. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-011-0268-5.

Gusdorf, François and Stéphane Hallegatte (2007a). "Behaviors and housing inertia are key factors in determining the consequences of a shock in transportation costs." In: *Energy Policy* 35.6, pp. 3483–3495. ISSN: 03014215. DOI: 10.1016/j.enpol.2006.12.022.

— (2007b). "Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks." In: *Energy Policy* 35.10, pp. 4826–4838. ISSN: 03014215. DOI: 10.1016/j.enpol.2007.04.017.

Gusdorf, François, Stéphane Hallegatte, and Alain Lahellec (2008). "Time and space matter: How urban transitions create inequality." In: *Global Environmental Change* 18.4, pp. 708–719. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2008.06.005.

Gwilliam, Kenneth M. (2017). "Moving to Access. Transport Pricing and Accessibility." In:

Haase, Dagmar and Nina Schwarz (2009). "Simulation Models on Human-Nature Interactions in Urban Landscapes: A review including spatial economics, system dynamics, cellular automata and agent-based approaches." In: *Living Reviews in Landscape Research* 3.2.

Hallegatte, Stéphane (2009). "Strategies to adapt to an uncertain climate change." In: *Global Environmental Change* 19.2, pp. 240–247. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2008.12.003.

Hallegatte, Stéphane, Marianne Fay, and Adrien Vogt-Schilb (2013). *Green Industrial Policies*. Tech. rep. The World Bank.

Hallegatte, Stéphane, G. Heal, M. Fay, and D. Treguer (2012). *From Growth to Green Growth-a Framework*. Policy Research Working Paper 5872. Washington DC.: World Bank.

Hamilton, Stuart E. and Ash Morgan (2010). "Integrating lidar, GIS and hedonic price modeling to measure amenity values in urban beach residential property markets." In: *Computers, Environment and Urban Systems* 34.2, pp. 133–141. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2009.10.007.

Hammar, Henrik, Åsa Löfgren, and Thomas Sterner (2004). "Political Economy Obstacles to Fuel Taxation." In: *Energy Journal* 25.3, pp. 1–17. ISSN: 01956574.

Hardy, M. H. (2012). "Simplified Integrated Transportation and Land Use Modeling to Support Metropolitan Planning Decisions: An Application and Assessment." PhD thesis. George Mason University.

Helsley, Robert W. and William C. Strange (2007). "Urban interactions and spatial structure." In: *Journal of Economic Geography* 7.2, pp. 119–138. ISSN: 1468-2702, 1468-2710. DOI: 10.1093/jeg/lbl027.

— (2008). "A game-theoretic analysis of skyscrapers." In: *Journal of Urban Economics* 64.1, pp. 49–64. ISSN: 00941190. DOI: 10.1016/j.jue.2007.08.004.

Henderson, J. Vernon, A. J. Venables, T. Regan, and I. Samsonov (2016). "Building functional cities." In: *Science* 352.6288, pp. 946–947. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.aaf7150.

Henry, Claude (1974). "Investment Decisions Under Uncertainty: The "Irreversibility Effect"." In: *The American Economic Review* 64.6, pp. 1006–1012. ISSN: 00028282.

Hidalgo, Julia, Valéry Masson, and Christophe Baehr (2014). "From daily climatic scenarios to hourly atmospheric forcing fields to force Soil-

Vegetation-Atmosphere transfer models." In: *Frontiers in Environmental Science* 2. ISSN: 2296-665X. DOI: 10.3389/fenvs.2014.00040.

Holden, Erling and Ingrid Norland (2005). "Three challenges for the compact city as a sustainable urban form: Household consumption of energy and transport in eight residential areas in the greater Oslo Region." In: *Urban Studies* 42.12, pp. 2145–2166. ISSN: 0042-0980, 1360-063X. DOI: 10.1080/00420980500332064.

Hoornweg, Daniel, Mila Freire, Marcus J. Lee, Perinaz Bhada-Tata, and Belinda Yuen (2011). *Cities and Climate Change: Responding to an Urgent Agenda*. The World Bank. ISBN: 978-0-8213-8493-0 978-0-8213-8667-5. DOI: 10.1596/978-0-8213-8493-0.

Hornbeck, Richard and Daniel Keniston (2017). "Creative Destruction: Barriers to Urban Growth and the Great Boston Fire of 1872." In: *American Economic Review* 107.6, pp. 1365–1398. ISSN: 0002-8282. DOI: 10.1257/aer.20141707.

Houet, Thomas, Thomas R. Loveland, Laurence Hubert-Moy, Cédric Gaucherel, Darrell Napton, Christopher A. Barnes, and Kristi Sayler (2010). "Exploring subtle land use and land cover changes: a framework for future landscape studies." In: *Landscape Ecology* 25.2, pp. 249–266. ISSN: 0921-2973, 1572-9761. DOI: 10.1007/s10980-009-9362-8.

Hughes, J. E., C. R. Knittel, and D. Sperling (2008). "Evidence of a shift in the short-run price elasticity of gasoline demand." In: *Energy Journal* 29.1, pp. 113–134.

Hunt, J. D., D. S. Kriger, and E. J. Miller (2005). "Current operational urban land-use–transport modelling frameworks: A review." In: *Transport Reviews* 25.3, pp. 329–376. ISSN: 0144-1647, 1464-5327. DOI: 10.1080/0144164052000336470.

Huriot, Jean-Marie and Lise Bourdeau-Lepage (2009). *Économie des villes contemporaines*. Paris: Économica. ISBN: 978-2-7178-5694-1.

Iacono, M., D. Levinson, and A. El-Geneidy (2008). "Models of Transportation and Land Use Change: A Guide to the Territory." In: *Journal of Planning Literature* 22.4, pp. 323–340. ISSN: 0885-4122. DOI: 10.1177/0885412207314010.

IAU îdF and Région Île de France (2011). *L'environnement en Île de France - Mémento 2011*. Tech. rep. Institut d'Aménagement Urbain de la Région Ile de France.

IEA (2009). *Transport, energy and CO2: moving toward sustainability*. Paris: International Energy Agency. ISBN: 978-92-64-07316-6.

— (2011). *World Energy Outlook 2011*. Paris: International Energy Agency. ISBN: 978-92-64-12413-4.

— (2016a). *CO2 Emissions from Fuel Combustion - 2016 edition - Key CO2 Emissions Trends*. Tech. rep. Paris: International Energy Agency.

— (2016b). *Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems*. Paris: International Energy Agency.

IEA and WBCSD (2004). *Sustainable Mobility Project*.

IMF (2013). *Energy Subsidy Reform: Lessons and Implications*. Tech. rep. Washington, D.C.: International Monetary Fund.

INDEC (2013). *Encuesta Permanente de Hogares (EPH)*.

Institut Montaigne (2012). *Transport de voyageurs: Comment réformer un modèle à bout de souffle?* Tech. rep. Institut Montaigne.

Interagency Working Group on Social Cost of Carbon, US Government (2010). *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, 2*. Tech. rep.

IPCC (2007). *Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

— (2013). *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

— (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]* Geneva, Switzerland: IPCC.

Jacquet, Pierre, R. K. Pachauri, Laurence Tubiana, Tata Energy Research Institute, Institut du développement durable et des relations internationales, and Agence française de développement, eds. (2010). *Cities: steering towards sustainability*. New Delhi: Teri Press. ISBN: 978-81-7993-131-8.

Jenkins, Jesse D. (2014). "Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?" In: *Energy Policy* 69, pp. 467–477. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2014.02.003.

Johnson, Daniel P. and Jeffrey S. Wilson (2009). "The socio-spatial dynamics of extreme urban heat events: The case of heat-related deaths in Philadelphia." In: *Applied Geography* 29.3, pp. 419–434. ISSN: 01436228. DOI: 10.1016/j.apgeog.2008.11.004.

Karathodorou, Niovi, Daniel J. Graham, and Robert B. Noland (2010). "Estimating the effect of urban density on fuel demand." In: *Energy Economics* 32.1, pp. 86–92. ISSN: 01409883. DOI: 10.1016/j.eneco.2009.05.005.

Kaya, Yoichi and Keiichi Yokobori (1997). *Environment, Energy and Economy; Strategies for Sustainability*. United Nations University Press. ISBN: 92-808-0911-3.

Kenworthy, J. R. and F. B. Laube (1999). "Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy." In: *Transportation Research Part A: Policy and Practice* 33.7, pp. 691–723.

Kenworthy, Jeffrey R., Felix B. Laube, and Jean Vivier (2001). *Millennium cities database for sustainable transport*. IUTP.

Klosterman, Richard E (2012). "Simple and complex models." In: *Environment and Planning B: Planning and Design* 39.1, pp. 1–6. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b38155.

Knowlton, Kim, Barry Lynn, Richard A. Goldberg, Cynthia Rosenzweig, Christian Hogrefe, Joyce Klein Rosenthal, and Patrick L. Kinney (2007). "Projecting Heat-Related Mortality Impacts Under a Changing Climate in the New York City Region." In: *American Journal of Public Health* 97.11, pp. 2028–2034. ISSN: 0090-0036, 1541-0048. DOI: 10.2105/AJPH.2006.102947.

Kok, Kasper, Peter H. Verburg, and Tom (A.) Veldkamp (2007). "Integrated Assessment of the land system: The future of land use." In: *Land Use Policy* 24.3, pp. 517–520. ISSN: 02648377. DOI: 10.1016/j.landusepol.2006.04.007.

Kopp, Andreas, Rachel I. Block, and Atsushi Iimi (2013). *Turning the right corner: ensuring development through a low-carbon transport sector*. Directions in development, environment and sustainable development. Washington, D.C: World Bank. ISBN: 978-0-8213-9835-7.

Krayenhoff, E. Scott and James A. Voogt (2010). "Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time Scales: Model Results and Synthesis of Previous Work." In: *Journal of Applied Meteorology and Climatology* 49.8, pp. 1634–1648. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/2010JAMC2356.1.

Krupp, Jason and Khyaati Acharya (2014). "UP OR OUT? Examining the Trade-offs of Urban Form." In: *NYU Marron Institute of Urban Management* Working paper #13.

Kusaka, Hiroyuki, Masayuki Hara, and Yuya Takane (2012). "Urban Climate Projection by the WRF Model at 3-Km Horizontal Grid Increment: Dynamical Downscaling and Predicting Heat Stress in the 2070's August for Tokyo, Osaka, and Nagoya Metropolises." In: *Journal of the Meteorological Society of Japan. Ser. II* 90B.0, pp. 47–63. ISSN: 2186-9057, 0026-1165. DOI: 10.2151/jmsj.2012-B04.

Lac, C., R. P. Donnelly, Valéry Masson, S. Pal, S. Riette, S. Donier, S. Queguiner, G. Tanguy, L. Ammoura, and I. Xueref-Remy (2013). "CO2 dispersion modelling over Paris region within the CO2-MEGAPARIS project." In: *Atmospheric Chemistry & Physics* 13.9. ISSN: 1680-7324. DOI: 10.5194/acp-13-4941-2013.

Lall, Somik V., ed. (2013). *Planning, connecting, and financing cities–now: priorities for city leaders*. Washington, DC: World Bank. ISBN: 978-0-8213-9839-5.

Lall, Somik V., J. Vernon Henderson, and Anthony J. Venables (2017). *Africa's Cities: Opening Doors to the World*. Washington D.C.: The World Bank. ISBN: 978-1-4648-1044-2. DOI: 10.1596/978-1-4648-1044-2.

Lecocq, Franck and Zmarak Shalizi (2014). "The economics of targeted mitigation in infrastructure." In: *Climate Policy* 14.2, pp. 187–208. ISSN: 1469-3062. DOI: 10.1080/14693062.2014.861657.

Lee, Douglass B. (1994). "Retrospective on Large-Scale Urban Models." In: *Journal of the American Planning Association* 60.1, pp. 35–40. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944369408975549.

Lefevre, Benoît (2007). "La soutenabilité environnementale des transports urbains dans les villes du sud. Le couple "transport - usages des sols" au coeur des dynamiques urbaines." PhD thesis. Ecole des Mines de Paris - ENSMP.

Lemonsu, Aude, Raphaëlle Kounkou-Arnaud, Julien Desplat, Jean-Luc Salagnac, and Valéry Masson (2013). "Evolution of the Parisian urban climate under a global changing climate." In: *Climatic Change* 116.3-4, pp. 679–692. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-012-0521-6.

Lemonsu, Aude, Valéry Masson, L. Shashua-Bar, E. Erell, and D. Pearlmutter (2012). "Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas." In: *Geoscientific Model Development* 5.6, pp. 1377–1393. ISSN: 1991-9603. DOI: 10.5194/gmd-5-1377-2012.

LeRoy, Stephen F. and Jon Sonstelie (1983). "Paradise lost and regained: Transportation innovation, income, and residential location." In: *Journal of Urban Economics* 13.1, pp. 67–89.

Li, Shanjun, Christopher Timmins, and Roger H. von Haefen (2009). "How Do Gasoline Prices Affect Fleet Fuel Economy?" In: *American Economic Journal: Economic Policy* 1.2, pp. 113–137. ISSN: 19457731. DOI: 10.2307/25760042.

Litman, Todd (2008). "Valuing Transit Service Quality Improvements." In: *Journal of Public Transportation* 11.2, pp. 43–63. ISSN: 1077-291X, 2375-0901. DOI: 10.5038/2375-0901.11.2.3.

Louchart, Philippe (2010). *Près d'un million de ménages Franciliens en plus à l'horizon 2030*. Tech. rep. 495. IAU.

Mackie, P. J., M. Wardman, A. S. Fowkes, G. Whelan, J. Nellthorp, and J. Bates (2003). *Values of travel time savings UK*. Tech. rep. University of Leeds, Leeds, UK: Institute of Transport Studies.

Marchadier, C., Thomas Houet, and G. Bretagne (2012). "How to define and assess city adaptation strategies." In: *8th International Conference on Urban Climate, Dublin*. Vol. 2012.

Masson, Valéry (2000). "A Physically-Based Scheme For The Urban Energy Budget In Atmospheric Models." In: *Boundary-Layer Meteorology* 94.3, pp. 357–397. ISSN: 0006-8314, 1573-1472. DOI: 10.1023/A:1002463829265.

Masson, Valéry, Y. Lion, A. Peter, G. Pigeon, J. Buyck, and E. Brun (2013). ""Grand Paris": regional landscape change to adapt city to climate warming." In: *Climatic Change* 117.4, pp. 769–782. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-012-0579-1.

Masson, Valéry et al. (2014). "Adapting cities to climate change: A systemic modelling approach." In: *Urban Climate*. ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment 10, pp. 407–429. ISSN: 2212-0955. DOI: 10.1016/j.uclim.2014.03.004.

Mills, David E. (1981). "The Non-Neutrality of Land Value Taxation." In: *National Tax Journal* 34.1, pp. 125–129. ISSN: 00280283.

Mills, Edwin S. (1967). "An Aggregative Model of Resource Allocation in a Metropolitan Area." In: *The American Economic Review* 57.2, pp. 197–210. ISSN: 00028282.

— (1972). *Studies in the structure of the urban economy*. Baltimore: Published for Resources for the Future by Johns Hopkins Press. ISBN: 0-8018-1367-0 978-0-8018-1367-2.

Ministerio del Interior y Transporte (2010). *Enmodo: Encuesta de Movilidad Domiciliaria. Movilidad en el Àrea Metropolitana de Buenos Aires 2009 - 2010.* Tech. rep.

Mohring, Herbert (1972). "Optimization and Scale Economies in Urban Bus Transportation." In: *The American Economic Review* 62.4, pp. 591–604. ISSN: 00028282.

Moulinié, Claire and Muriel Naudin-Adam (2005). *Appréhender la densité 3. "Formes urbaines et densités"*. Note Rapide sur l'Occupation des sols 384. Paris: Institut d'Aménagement Urbain de la Région Ile de France.

Munafò, Sébastien (2017). "Forme urbaine et mobilités de loisirs : l'« effet barbecue » sur le grill." In: *Cybergeo*. ISSN: 1278-3366. DOI: 10.4000/cybergeo.28634.

Muth, Richard F. (1969). *Cities and housing; the spatial pattern of urban residential land use*. Chicago: University of Chicago Press.

Næss, Petter (2006). "Are short daily trips compensated by higher leisure mobility?" In: *Environment and Planning B: Planning and Design* 33.2, pp. 197–220. ISSN: 0265-8135, 1472-3417. DOI: 10.1068/b31151.

— (2012). "Urban form and travel behavior: experience from a Nordic context." In: *Journal of Transport and Land Use* 5.2. ISSN: 1938-7849. DOI: 10.5198/jtlu.v5i2.314.

— (2016). "Urban Planning: Residential Location and Compensatory Behaviour in Three Scandinavian Cities." In: *Rethinking Climate and Energy Policies*. Ed. by Tilman Santarius, Hans Jakob Walnum, and Carlo Aall. Cham: Springer International Publishing, pp. 181–207. ISBN: 978-3-319-38805-2 978-3-319-38807-6. DOI: 10.1007/978-3-319-38807-6_11.

Nechyba, Thomas J. and Randall P. Walsh (2004). "Urban Sprawl." In: *The Journal of Economic Perspectives* 18.4, pp. 177–200. ISSN: 0895-3309.

Neuman, M. (2005). "The Compact City Fallacy." In: *Journal of Planning Education and Research* 25.1, pp. 11–26. ISSN: 0739-456X. DOI: 10.1177/0739456X04270466.

Newman, Peter W. G. and Jeffrey R. Kenworthy (1989a). *Cities and automobile dependence: a sourcebook*. Aldershot, Hants., England ; Brookfield, Vt., USA: Gower Technical. ISBN: 0-566-07040-5.

— (1989b). "Gasoline Consumption and Cities." In: *Journal of the American Planning Association* 55.1, pp. 24–37. ISSN: 0194-4363, 1939-0130. DOI: 10.1080/01944368908975398.

Noilhan, J. and S. Planton (1989). "A simple parameterization of land surface processes for meteorological models." In: *Monthly weather review* 117.3, pp. 536–549.

Nordhaus, William D. (2008). *A question of balance: Weighing the options on global warming policies*. Yale University Press. ISBN: 0-300-16598-6.

Nowak, William P. and Ian Savage (2013). "The cross elasticity between gasoline prices and transit use: Evidence from Chicago." In: *Transport Policy* 29, pp. 38–45.

O'Neill, Brian C., Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stéphane Hallegatte, Timothy R. Carter, Ritu Mathur, and Detlef P. Vuuren (2013). "A new scenario framework for climate change research: the concept of shared socioeconomic pathways." In: *Climatic Change*, pp. 1–14. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0905-2.

Oates, Wallace E. and Robert M. Schwab (1997). "The impact of urban land taxation: The Pittsburgh experience." In: *National Tax Journal* 50.1, pp. 1–21.

OECD (2012). *Compact city policies a comparative assessment*. Paris: OECD. ISBN: 978-92-64-16784-1 92-64-16784-6 978-92-64-16786-5 92-64-16786-2.

Oke, T. R. (2008). "Urban observations. Guide to meteorological instruments and methods of observation, Part II of Observing Systems, WMO-No. 8." In: *World Meteorological Organization, II-11-1–II-11-25*.

Oort, C. J. (1969). "The Evaluation of Travelling Time." In: *Journal of Transport Economics and Policy* 3.3, pp. 279–286. ISSN: 00225258. DOI: 10.2307/20052155.

Orfeuil, J and D Soleyret (2002). "Quelles interactions entre les marchés de la mobilité à courte et à longue distance ?What are the interactions between the short and long-distance travel markets?" In: *Recherche - Transports - Sécurité* 76, pp. 208–221. ISSN: 07618980. DOI: 10.1016/S0761-8980(02)00013-4.

Parry, Ian W. H. and Kenneth A. Small (2005). "Does Britain or the United States Have the Right Gasoline Tax?" In: *The American Economic Review* 95.4, pp. 1276–1289. ISSN: 00028282.

— (2009). "Should Urban Transit Subsidies Be Reduced?" In: *The American Economic Review* 99.3, pp. 700–724.

Parry, Ian W. H. and Govinda R. Timilsina (2010). "How should passenger travel in Mexico City be priced?" In: *Journal of Urban Economics* 68.2, pp. 167–182. ISSN: 00941190. DOI: 10.1016/j.jue.2010.03.009.

Peralta Quirós, Tatiana and Shomik Raj Mehndiratta (2015). "Accessibility Analysis of Growth Patterns in Buenos Aires, Argentina: Density, Employment, and Spatial Form." In: *Transportation Research Record: Journal of the Transportation Research Board* 2512, pp. 101–109. ISSN: 0361-1981. DOI: 10.3141/2512-12.

Perrissin Fabert, Baptiste, Patrice Dumas, and Jean-Charles Hourcade (2012). *What social cost of carbon? a mapping of the climate debate*. Tech. rep. Nota di lavoro, Fondazione Eni Enrico Mattei: Climate Change and Sustainable Development.

Pigeon, Grégoire, Karim Zibouche, Bruno Bueno, J Le Bras, and Valéry Masson (2014). "Evaluation of building energy simulations with the TEB model against EnergyPlus for a set of representative buildings in Paris." In: *Build. Environ* 76, pp. 1–14.

Pigou, A. C. (1920). *The economics of welfare*. London: Macmillan and Co.

Pindyck, Robert S. (2013). "Climate Change Policy: What Do the Models Tell Us?" In: *Journal of Economic Literature* 51.3, pp. 860–872. DOI: 10.1257/jel.51.3.860.

Przylusky, Valentin and Stéphane Hallegatte (2012). *Gestion des risques naturels : leçons de la tempête Xynthia*. Matière à débattre et décider. Versailles Cedex: Quae. ISBN: 978-2-7592-1820-2 2-7592-1820-1.

Ramsey, F. P. (1927). "A Contribution to the Theory of Taxation." In: *The Economic Journal* 37.145, p. 47. ISSN: 00130133. DOI: 10.2307/2222721.

Rausch, Sebastian and John Reilly (2012). *Carbon tax revenue and the budget deficit: A win-win-win solution?* Tech. rep. MIT Joint Program on the Science and Policy of Global Change.

Robert-Bobée, Isabelle (2006). *Projections de Population pour la France Métropolitaine a l'horizon 2050*. Tech. rep. 1089. INSEE.

Roberts, Mark, Brian Blankespoor, Benjamin P. Stewart, and Chandan Deuskar (2017). *Urbanization and development : is Latin America and the Caribbean different from the rest of the world?* Tech. rep. WPS8019. The World Bank, pp. 1–37.

Rosenthal, Stuart S. and William C. Strange (2004). "Chapter 49 Evidence on the nature and sources of agglomeration economies." In: *Handbook of Regional and Urban Economics*. Vol. 4. Elsevier, pp. 2119–2171. ISBN: 978-0-444-50967-3.

Rosenzweig, Cynthia, David C. Major, Kate Demong, Christina Stanton, Radley Horton, and Melissa Stults (2007). "Managing climate change risks in New York City's water system: assessment and adaptation planning." In: *Mitigation and Adaptation Strategies for Global Change* 12.8, pp. 1391–1409. ISSN: 1381-2386, 1573-1596. DOI: 10.1007/s11027-006-9070-5.

Rosenzweig, Cynthia et al. (2011). "Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies." In: *Climatic Change* 106.1, pp. 93–127. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-010-0002-8.

Rouchaud, D. and A. Sauvant (2004). "Prix des logements et coûts de transports: un modèle global d'équilibre en Ile-de-France." In: *Notes de synthèses du SES, DAEI, Ministère de l'équipement*.

Rozenberg, Julie, Stéphane Hallegatte, Adrien Vogt-Schilb, Olivier Sassi, Céline Guivarch, Henri Waisman, and Jean-Charles Hourcade (2010). "Climate policies as a hedge against the uncertainty on future oil supply." In: *Climatic Change* 101.3, pp. 663–668. ISSN: 0165-0009. DOI: 10.1007/s10584-010-9868-8.

Rozenberg, Julie, Adrien Vogt-Schilb, and Stéphane Hallegatte (2013). "How Capital-Based Instruments Facilitate the Transition Toward a Low-Carbon Economy." In: *World Bank Policy Research Working Paper* n°6609.

— (2014). *Transition to Clean Capital, Irreversible Investment and Stranded Assets*. Policy Research Working Papers. The World Bank. DOI: 10.1596/1813-9450-6859.

Salon, Deborah (2009). "Neighborhoods, cars, and commuting in New York City: A discrete choice approach." In: *Transportation Research Part A: Policy and Practice* 43.2, pp. 180–196.

Sandmo, Agnar (1975). "Optimal taxation in the presence of externalities." In: *The Swedish Journal of Economics*, pp. 86–98.

Saujot, Mathieu (2013). "Analyse économique et simulation prospective dans la planification de la ville sobre en carbone. Application à Grenoble du modèle TRANUS+." PhD thesis. École Nationale Supérieure des Mines de Paris.

Saujot, Mathieu, Matthieu de Lapparent, Elise Arnaud, and Emmanuel Prados (2016). "Making land use – Transport models operational tools for planning: From a top-down to an end-user approach." In: *Transport Policy* 49, pp. 20–29. ISSN: 0967070X. DOI: 10.1016/j.tranpol.2016.03.005.

Schipper, Lee, Celine Marie-Lilliu, and Roger Gorham (2000). "Flexing the link between transport and greenhouse gas emissions." In: *IEA*.

Seow, K. L., M. Doya, Xavier Briottet, R. Ceolato, N. Riviere, and S. K. Pang (2012). "Spectral BRDF of common urban materials." In: *2012 4th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)*. IEEE, pp. 1–4. ISBN: 1-4799-3406-2.

Seto, Karen C. et al. (2014). "Human settlements, infrastructure and spatial planning." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Ottmar Edenhofer et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Sims, R. et al. (2014). "Transport." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Siodla, James (2015). "Razing San Francisco: The 1906 disaster as a natural experiment in urban redevelopment." In: *Journal of Urban Economics* 89, pp. 48–61. ISSN: 00941190. DOI: 10.1016/j.jue.2015.07.001.

Small, Kenneth A. and Erik T. Verhoef (2007). *The economics of urban transportation*. New York: Routledge. ISBN: 1-134-49571-4.

Small, Kenneth A., Clifford Winston, and Jia Yan (2005). "Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability." In: *Econometrica* 73.4, pp. 1367–1382. ISSN: 0012-9682, 1468-0262. DOI: 10.1111/j.1468-0262.2005.00619.x.

Solomon, Susan (2007). "The physical science basis: Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change." In: *Intergovernmental Panel on Climate Change (IPCC), Climate change 2007* 996.

Song, Yan and Yves Zenou (2006). "Property tax and urban sprawl: Theory and implications for US cities." In: *Journal of Urban Economics* 60.3, pp. 519–534. ISSN: 0094-1190. DOI: doi:DOI:10.1016/j.jue.2006.05.001.

— (2009). "How do differences in property taxes within cities affect urban sprawl?" In: *Journal of Regional Science* 49.5, pp. 801–831. ISSN: 00224146, 14679787. DOI: 10.1111/j.1467-9787.2009.00616.x.

Spiller, Elisheba, Heather Stephens, Christopher Timmins, and Allison Smith (2014). "The Effect of Gasoline Taxes and Public Transit Investments on Driving Patterns." In: *Environmental and Resource Economics* 59.4, pp. 633–657. ISSN: 0924-6460, 1573-1502. DOI: 10.1007/s10640-013-9753-9.

Sterner, Thomas (2007). "Fuel taxes: An important instrument for climate policy." In: *Energy Policy* 35.6, pp. 3194–3202. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2006.10.025.

Stewart, I. D. and T. R. Oke (2012). "Local Climate Zones for Urban Temperature Studies." In: *Bulletin of the American Meteorological Society* 93.12, pp. 1879–1900. ISSN: 0003-0007, 1520-0477. DOI: 10.1175/BAMS-D-11-00019.1.

Stiglitz, Joseph E. et al. (2017). "Report of the High-Level Commission on Carbon Prices." In:

Su, Qing and Joseph S. DeSalvo (2008). "The Effect of Transportation Subsidies On Urban Sprawl." In: *Journal of Regional Science* 48.3, pp. 567–594.

Thorsnes, Paul (1997). "Consistent Estimates of the Elasticity of Substitution between Land and Non-Land Inputs in the Production of Housing." In: *Journal of Urban Economics* 42.1, pp. 98–108. ISSN: 0094-1190. DOI: 10.1006/juec.1996.2015.

Tideman, T. Nicolaus (1982). "A Tax on Land Value Is Neutral." In: *National Tax Journal* 35.1, pp. 109–111. ISSN: 00280283.

Timbeau, Xavier (2013). "Les bulles «robustes»." In: *Revue de l'OFCE* 2, pp. 277–313.

Tol, Richard SJ (2005). "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." In: *Energy policy* 33.16, pp. 2064–2074.

Transportation Research Board - NRC (2002). *Costs of sprawl – 2002*. TCRP Report 74. Washington, D.C.: National Academy Press. ISBN: 1073-4872.

Tremeac, Brice, Pierre Bousquet, Cecile de Munck, Grégoire Pigeon, Valéry Masson, Colette Marchadier, Michele Merchat, Pierre Poeuf, and Francis Meunier (2012). "Influence of air conditioning management on heat island in Paris air street temperatures." In: *Applied Energy* 95, pp. 102–110. ISSN: 03062619. DOI: 10.1016/j.apenergy.2012.02.015.

Trusilova, Kristina, Barbara Früh, Susanne Brienen, Andreas Walter, Valéry Masson, Grégoire Pigeon, and Paul Becker (2013). "Implementation of an Urban Parameterization Scheme into the Regional Climate Model COSMO-CLM." In: *Journal of Applied Meteorology and Climatology* 52.10, pp. 2296–2311. ISSN: 1558-8424, 1558-8432. DOI: 10.1175/JAMC-D-12-0209.1.

Tscharaktschiew, Stefan and Georg Hirte (2012). "Should subsidies to urban passenger transport be increased? A spatial CGE analysis for a German metropolitan area." In: *Transportation Research Part A: Policy and Practice* 46.2, pp. 285–309. ISSN: 0965-8564. DOI: 10.1016/j.tra.2011.09.006.

Turner, B. L., E. F. Lambin, and A. Reenberg (2007). "The emergence of land change science for global environmental change and sustainability." In: *Proceedings of the National Academy of Sciences* 104.52, pp. 20666–20671. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.0704119104.

Turton, Hal and Filipe Moura (2008). "Vehicle-to-grid systems for sustainable development: An integrated energy analysis." In: *Technological Forecasting and Social Change* 75.8, pp. 1091–1108.

UN DESA (2015a). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. Tech. rep. New York, NY: UN Department of Economic and Social Affairs.

— (2015b). *World Urbanization Prospects. The 2014 Revision*. Tech. rep. New York: UN Department of Economic and Social Affairs.

Van Der Leeuw, Sander et al. (2011). "Toward an Integrated History to Guide the Future." In: *Ecology and Society* 16.4, art2. ISSN: 1708-3087. DOI: 10.5751/ES-04341-160402.

Viguié, Vincent (2012). "Urban Dynamics Modelling, application to economics assessment of climate change." PhD thesis. Université Paris-Est.

Viguié, Vincent and Stéphane Hallegatte (2012). "Trade-offs and synergies in urban climate policies." In: *Nature Climate Change* 2.5, pp. 334–337. ISSN: 1758-678X, 1758-6798. DOI: 10.1038/nclimate1434.

Viguié, Vincent, Stéphane Hallegatte, and Julie Rozenberg (2014). "Downscaling long term socio-economic scenarios at city scale: A case study on Paris." In: *Technological Forecasting and Social Change* 87, pp. 305–324. ISSN: 00401625. DOI: 10.1016/j.techfore.2013.12.028.

Vogt-Schilb, Adrien and Stéphane Hallegatte (2014). "Marginal abatement cost curves and the optimal timing of mitigation measures." In: *Energy Policy* 66, pp. 645–653. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2013.11.045.

Vogt-Schilb, Adrien, Stéphane Hallegatte, and Christophe De Gouvello (2014). "Long-term mitigation strategies and marginal abatement cost curves: a case study on Brazil." In: *World Bank Policy Research Working Papers* 6808.

Vogt-Schilb, Adrien, Guy Meunier, and Stéphane Hallegatte (2012). "How inertia and limited potentials affect the timing of sectoral abatements in optimal climate policy." In: *World Bank Policy Research Working Paper* 6154.

— (2013). "Optimal timing, cost and sectoral distribution of emission reductions: abatement cost curves vs. abatement investment." In: ASSA.

— (2018). "When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment." In: *Journal of Environmental Economics and Management* 88, pp. 210–233. ISSN: 00950696. DOI: 10.1016/j.jeem.2017.12.001.

Von Thünen, J. H. (1826). *Isolated State*. Pergamon, Oxford.

Waddell, P. (2002). "UrbanSim: Modeling urban development for land use, transportation, and environmental planning." In: *Journal of the American Planning Association* 68.3, pp. 297–314.

Waisman, Henri-David, Celine Guivarch, and Franck Lecocq (2013). "The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility." In: *Climate Policy* 13.sup01, pp. 106–129. ISSN: 1469-3062, 1752-7457. DOI: 10.1080/14693062.2012.735916.

Waisman, Henri, Céline Guivarch, Fabio Grazi, and Jean-Charles Hourcade (2012). "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." In: *Climatic Change* 114.1, pp. 101–120. ISSN: 0165-0009. DOI: 10.1007/s10584-011-0387-z.

Wang, H., P. Zhou, and D.Q. Zhou (2012). "An empirical study of direct rebound effect for passenger transport in urban China." In: *Energy Economics* 34.2, pp. 452–460. ISSN: 01409883. DOI: 10.1016/j.eneco.2011.09.010.

Washbrook, Kevin, Wolfgang Haider, and Mark Jaccard (2006). "Estimating commuter mode choice: A discrete choice analysis of the impact of road pricing and parking charges." In: *Transportation* 33.6, pp. 621–639.

Wegener, Michael (2004). "Overview of land-use transport models." In: *Handbook of transport geography and spatial systems* 5, pp. 127–146.

— (2014). "Land-Use Transport Interaction Models." In: *Handbook of Regional Science*. Ed. by Manfred M. Fischer and Peter Nijkamp. Springer Berlin Heidelberg, pp. 741–758. ISBN: 978-3-642-23429-3 978-3-642-23430-9.

Wegener, Michael and Franz Fürst (2004). *Land-use transport interaction: state of the art*.

Wheaton, William C. (1974). "A comparative static analysis of urban spatial structure." In: *Journal of Economic Theory* 9.2, pp. 223–237. ISSN: 0022-0531. DOI: doi:DOI:10.1016/0022-0531(74)90068-4.

Wildasin, David E. (1982). "More on the Neutrality of Land Taxation." In: *National Tax Journal* 35.1, pp. 105–108. ISSN: 00280283.

World Bank (2012). *Inclusive Green Growth: The Pathway to Sustainable Development*. The World Bank. ISBN: 978-0-8213-9551-6 978-0-8213-9552-3. DOI: 10.1596/978-0-8213-9551-6.

Zahavi, Yacov and Antti Talvitie (1980). "Regularities in travel time and money expenditures." In: *Transport Research Record* 750, pp. 13–19.

Zhang, Ming (2004). "The role of land use in travel mode choice: evidence from Boston and Hong Kong." In: *Journal of the American Planning Association* 70.3, pp. 344–360.