Urban simulation with alternative road pricing scenarios

Marko Kryvobokov, Aurélie Mercier, Alain Bonnafous, Dominique Bouf

Transports Economic Laboratory, 14 avenue Berthelot, 69363 Lyon cedex 07, France

Email for correspondence: aurelie.mercier@let.ish-lyon.cnrs.fr

Abstract

The application of the urban simulation framework UrbanSim is interacted with the transportation model MOSART to simulate road pricing scenarios in the Lyon Urban Area in France. The reference scenario of transportation and land use simulation in 2000-2030 is compared with four alternatives of mobility cost increase: the implementations of urban tolls and distance based charging. The dynamics of spatial distribution of population, jobs, residential development and housing prices is analyzed. The methodologies used in the applied land use models are multinomial logit and OLS regression. We conclude that the UrbanSim application in Lyon is capable to capture changes in transport policy on urban development simulating these effects at geographical dimension.

Keywords: transportation-land use modeling, UrbanSim, transportation model, road pricing scenario, mobility cost increase

1. Introduction

There is widespread acceptance that sustainability requires integrating decisions in land use, transport and environment policy (Geerlings and Stead, 2003). Transportation-land use models are powerful tools capable to simulate urban development in a holistic sense. Their modeling potential is more and more widely exploited not only in academic research, but also by decision-makers in practical policy evaluations. The last-decade literature on transportation-land use modeling includes the comprehensive reviews of Wegener (2004), Hunt et al. (2005), Chang (2006) and Iacono et al. (2008).

Excessive reliance on static equilibrium assumptions with lack of path dependence in many of existing modeling frameworks is criticized in Hunt et al. (2005). Simmonds et al. (2011) classify urban change processes and show how the equilibrium approach fails to deal with them; they consider quasi- or recursive dynamics as a rational trade-off between theory and operationality. In France, where regulation in land use planning has crucial impact, it is particularly important to apply dynamic modeling for simulation of long-term economic and environmental consequences of major planning decisions made by public administration.

Transportation and land use patterns are assumed to mutually influence each other over time. In modeling, this can be established with different relationships ranging from “linked” to “loosely coupled” and “integrated” (see Kelly, 1994 and Iacono et al., 2008). According to Hunt et al. (2005), the term “integrated” means that “feedback exists between the transport and urban activity systems, so that the short- and long-run interactions between transport network performance and land development/location choice behavior are captured appropriately within the model”.

We apply the Open Platform for Urban Simulation (OPUS) and the land use modeling framework UrbanSim designed in the late 1990s at the University of Washington (Waddell, 2002; Waddell et al., 2003). There are many operational applications of UrbanSim in the U.S., European and other urban areas (e.g. Waddell et al., 2007; Borning et al., 2008; de Palma et al., 2005; Felsenstein and Ashbel, 2010). Among the notable features of UrbanSim is dynamic disequilibrium modeling approach with annual time increments (Hunt et al., 2005). A highly disaggregate UrbanSim structure in comparison with other frameworks is recognized in the literature (Hunt et al., 2005; Iacono et al., 2008).

Transportation model is external in UrbanSim. There are the following recent examples of integration of UrbanSim with transportation models: with the aggregated zone activity-based travel model (Waddell et al., 2010) and with the disaggregated “agent-based” MATSim (Nicolai et al., 2011).

In Lyon, the prototype UrbanSim application was gridcell-based with one gridcell per zone (Patterson et al., 2010). After geographically-specific calibration, the municipal level of a zone-based application has been chosen (Bonnafous et al., 2010) . At this geographical level, the UrbanSim’s multinomial logit model of residential location choice provides the best prediction comparable with an evenly split population growth, though neither the former nor the latter method demonstrates convincing superiority. The former model however is potentially capable to capture the effects of transportation system on land use attributes and vice versa. In the current study, we analyze policy scenarios with UrbanSim models at the selected geographical level of municipalities.

Our land use simulation at the 2030 time horizon is focused on the dynamics of spatial distribution of households, jobs, residential development and housing prices. The four-step transportation model, external to UrbanSim, is provided by the MOSART platform, see Section 3. While in the reference scenario simulation, the transportation-land use interaction takes place without major changes in transportation system, the alternative scenarios capture the effects of the implementations of three versions of urban tolls and a dramatic petrol price increase. The aim of our paper is to evaluate the interaction between the UrbanSim application and MOSART and its capability to simulate different scenarios of mobility cost increase. A possibility to select one or another policy scenario knowing the simulated long-term consequences contributes to sustainability in urban planning and development. The spatial dynamics of urban development is analyzed applying the already calibrated modeling tool. As the study is about simulation of future development, historical validation is impossible, and sensitivity analysis is focused instead, as in Waddell et al. (2007), who incorporate UrbanSim in the U.S. metropolitan transportation planning.

The next two sections are about MOSART and the Lyon UrbanSim application. Section 4 is devoted to the details of the reference scenario. The alternative scenarios are described in Section 5. The final section concludes.

2. Accessibility: the key attribute

The MOSART platform is exploited to compute accessibility index. MOSART, a French acronym for Modeling and Simulating Accessibility to Networks and Territories, is a decision-making tool in terms of mobility. This accessibility-based project aims to model and simulate transport policies considering various networks (road, urban or interurban public transport networks and bicycle rental network). This paper is focused on the accessibility by car, and only the road network is presented (see Crozet *et al*., 2008 and Bonnafous *et al.*, 2011 for a detailed description).

Accessibility corresponds to accessibility from each of the 304 municipalities of the Lyon Metropolitan Area to all jobs located on this metropolitan area. One of the interests of such a modeling platform is to be designed using high-resolution land use data. A detailed land-use job data set is associated to detailed transport road networks.

The road network, obtained from the NAVTEQ database, is composed by more than 90,000 nodes and 220,000 links. A detailed road section typology has been implemented to characterize each link according to about 50 road types with length, capacity, maximum speed and driving direction.

The four-stage transportation model is entirely developed in the VISUM software. In the field of transport modeling, many operational and comprehensive transport modeling software are developed. The use the VISUM model both by practitioners and researchers improves its efficiency and usability. The 4-steps models developed in MOSART, with VISUM software. It uses the sequential procedure (trip generation, trip distribution, modal choice and traffic assignment) to forecast transportation demand. In MOSART, the forecast estimates road traffic for each section using household demographics and socio-economic factors combined with the road transport network. The MOSART “products” refer to road transport demand (including road congestion level), travel time and accessibility (see Mercier and Stoiber, 2010 for details).

The peculiarity of this urban model is that traffic predications and assignment vary in different periods of the day. Two periods are addressed: a peak period presents traffic between 7 and 10 a.m. according to the 2006 household trip survey, while an off-peak period corresponds to an average daily traffic level, but only the former is used in the current study. The accessibility index is calculated at zonal level as a gravity-based measure:

$$A_i = \sum_{j=1}^{n} E_j e^{-\beta C_{ij}} \quad (1)$$

where E_j – number of jobs in zone *j*;

C_{ij} – generalized travel cost between zone *i* and zone *j*;

β – cost sensitivity parameter;

n – number of zones.

The travel cost is estimated as follows:

$$C_{ij} = P_{ij} + \nu T_{ij} \quad (2)$$

where P_{ij} – monetary cost;

ν –value of time;

T_{ij} – travel time.

This potential accessibility measure with negative exponential function is the most often used and also the most closely tied to travel behavior theory, though this measure has difficulty in interpretation, and competition effects and temporal constraints are excluded (Handy and Niemeier, 1997; Geurs and van Wee, 2004).

In this study, the accessibility measure (1) provides a link between transportation and land use models and, as in Geurs and van Wee (2004), can be seen as an indicator for the impact of both types of development on the functioning of the society in general.

Travel time is composed by in-vehicle time and two added "penalties": an access-time from origin to road network (time spent by individual to reach his car) and a final time from road network to destination. Parking searching time is not yet integrated in our computations. In-vehicle travel time is estimated between points on road network using a shortest path algorithm. It includes congestion charges determined by a four-step model: trip generation integrates population variation between different time periods. The access-time and final time refer to a distance "as the crow flies" between each centroid and the closest road network node on the basis of a 4 km/hour walking speed.

Travel time in (2) is weighted by a value of time. This value refers to the amount that a traveler would be willing to pay in order to save time. In economic assessment it is used to give a monetary value on time spent in transport system. In France, the value of time for home-based work trips usually is calculated as ν = 11.4 euro/hour independently from transport mode.

Monetary cost P_{ij} in (2) is calculated as the sum of fixed (buy and parking costs) and variable costs (fuel and maintenance costs), depending on distance. The cost of 0.49 euro/km is applied in the reference scenario. A number of jobs by zone (i.e. municipality) is an UrbanSim output. All jobs are considered without qualification level or sector distinction.

Accessibility measurement depends both on individual location and socio-economic characteristics. Literature illustrates travel cost perception variations according to trip purposes (Bonnafous and Masson, 2003) and/or socio-economic features (Johansson *et al.*, 2002). In MOSART, travel cost sensitivity is determined by gravity-based model calibration for each trip purpose. The estimation based on the household trip survey 2006 gives a cost sensitivity parameter β = 0.18 for home-to-work trips.

3. The UrbanSim application

The zone-based UrbanSim version 4.3.2 is used. The Lyon Urban Area with the 1999 population of 1.6 million inhabitants consists of 304 municipalities. The cities of Lyon and Villeurbanne and the urbanized belt around them are named the Greater Lyon. Lyon and Villeurbanne compose the central part of the urban area. Lyon consists of nine districts (*arrondissements*), which are regarded in our study as municipalities. The available data include a number of residential units and area covered by different land use types (water, industry, etc.) in municipalities.

Data on population are available due to the last general census conducted in France in 1999. This is the base year in our dataset. In the available synthetic population 1999 based also on the household trip survey conducted in Lyon in 2006, there are 662,249 households. In the applied version of UrbanSim, each household lives in a building. However, because of the lack of available data about buildings, in our application we created one fictional building in each municipality. The average vacancy rate in municipalities in the Lyon Urban Area is 10.4%.

For each household, there are data on the number of persons (1 to 11), number of working persons, number of cars, age and income group. There are three income groups of population. The low- and high-income groups are composed of the 20% households with the lowest income and the 20% households with the highest income respectively. The middle-income group includes households in the middle 60% of the income range.

The employment data 1999 in municipalities contain a number of jobs in the three economic sectors: the mainly agricultural primary sector; the secondary sector (with division between construction and other industries); and the tertiary sector (with division between commercial and non-commercial jobs). Similarly to population density, employment density is the highest in Lyon and Villeurbanne and, as a consequence of centrifugal urban sprawl, is relatively high in the Greater Lyon.

Average housing prices per square meter in municipalities have been calculated using prices of more than 10,000 apartments and houses sold in the Lyon Urban Area in 1997-2008. Prices of individual properties have been recalculated partly to 1999 and partly to 1998 with price indices in order to have a hedonic model with a one-year price lag (for details, see Kryvobokov *et al*., 2011). Individual prices represented as points are interpolated to raster for estimating average values in municipalities.

The UrbanSim's Household Location Choice Model (HLCM) and residential Real Estate Price Model (REPM) are exploited. The HLCM specification included nineteen variables. With the estimation year 1999, this model has been calibrated using the back-casting period 2000-2005. In 2005, 93.3% of population distribution has been predicted with 10% deviation (Bonnafous *et al*., 2010)[1]. The HLCM is a multinomial logit estimated with 10% randomly selected households and with location alternatives (municipalities) weighted by residential vacancy rate. With this weighted sampling strategy generating consistent, but not fully efficient estimates (Ben-Akiva and Lerman, 1985), we obtained the adjusted pseudo-R^2 of 36.9%, which seems to be reasonable for logit models of residential location choice[2].

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[1] This is the validation result with nineteen variables under the assumption of no household relocation.
[2] De Palma *et al*. (2005) and Lee *et al*. (2010) obtain the pseudo-R^2 of 22% and 30%-36% respectively with multinomial logit; Cho *et al*. (2008) report the range of 2% to 38% in their conditional logit models.

In case of multiple variables relating to detailed characteristics of households and land use attributes, high multicollinearity between them creates noise, which overshadows the effects of interaction with the transportation model. As a result, the consequences of the influence of transport projects on land use are not significant.

Similarly to Nguyen-Luong (2011), who discusses the necessity to avoid the problems with multicollinearity and spatial autocorrelation in UrbanSim models, in this study we focus on model predictive capacity and no more on its explicability. The HLCM applied for simulating transport policy scenarios includes only five variables (Table 1) that take into account the core issues of the Alonso-Mills-Muth model (see e.g. Anas *et al*., 1998): housing price and accessibility (which includes travel costs), as well as income groups and car-ownership status. All the variables represent interactions between municipal land use attributes and individual household characteristics. This model provides the goodness-of-fit of 31.4%; thus, the decrease in the number of explanatory variables from nineteen to five has diminished the performance by only 5.5%. The first three variables in Table 1 are the interactions between the income group of household and average housing price in municipality. Price negatively influences the utility of location for all income groups, the absolute value of coefficient decreases when income increases. The most significant estimate is that of the most numerous middle income group. Employment accessibility index (described in Section 3) has 1.6 times higher utility for households without a car. For motorized households, which compose 78.4%, the estimate of employment accessibility is more significant.

Table 1. HLCM estimation

Variable	Coefficient (*t*-value)
Log housing price if high income household	-0.524 (-9.13)
Log housing price if middle income household	-0.779 (-27.25)
Log housing price if low income household	-1.101 (-25.17)
Log index of employment access if household has a car	1.309 (271.72)
Log index of employment access if household has no car	2.116 (165.89)

The REPM estimation is presented in Table 2. The adjusted R^2 of this ordinary least square (OLS) regression is 93.5%. A one-year price lag is the most significant variable. The main reason of its inclusion is an attempt to keep the simulated price dynamics more similar to actual one. Employment accessibility, population and percentage of area covered by water positively affect price. Vacant residential units and industrial area have negative influence. Predictive capacity and sensitivity of the REPM to changes in housing stock during simulation is analyzed in Kryvobokov *et al*. (2011).

Table 2. REPM estimation

Variable	Coefficient (*t*-value)
Constant	5.038 (48.40)
Log price lag	0.859 (54.07)
Log employment accessibility	0.031 (6.24)
Log vacant residential units	-0.023 (-4.40)
Log population	0.018 (2.51)
Log industrial area, m^2	-0.002 (-3.66)
Log percent water	0.010 (3.03)

Due to the lack of data, residential units and jobs are yearly updated during simulation with simple regression models. A number of residential units in 1999 is a linear OLS regression function of number of households; its adjusted R^2 is 99.9%, see Table 3. In simulation, a number of residential units in each municipality is updated with this regression under the condition that this number is higher than in a previous year. We should admit that in this case the path of real estate development does not correspond to reality: it would be more logical to assume that developers respond to short-term changes by initiating long-term projects, which can phase multiple years (Waddell, 2011). In the Development Project Location Choice Model, represented by a regression function of population growth, a several-year lag could be implemented provided the available data. In the historical 1st and 4th Lyon districts (Lyon 1 and Lyon 4) located between the two rivers, there is no free space for new residential development, and new construction in fact does not take place; therefore a number of residential units is not updated there.

Table 3. Regression functions updating residential units and jobs

Description of regression	Residential units	Construction jobs	Commercial jobs	Non-commercial tertiary jobs
Constant	-66.646	15.911	14.745	-
Coefficient for households (*t*-value)	1.147 (481.27)	-	-	-
Coefficient for population (*t*-value)	-	0.023 (40.07)	0.059 (32.33)	0.351 (40.80)
Adjusted R^2	0.999	0.841	0.775	0.843

The five groups of jobs are addressed individually during simulation. Taking into account the actual data from INSEE[3] for 1999, 2006 and 2008, we assume that the number of jobs in the primary sector and industry is not changed. For example, the illustration of industrial jobs and population dynamics in the districts of Lyon and Villeurbanne (Figure 1, where the arrows begin in 1999 and end in 2006) in general does not demonstrate an increase in the number of jobs when population increases. Construction jobs 2006 are described with a linear regression of population with the adjusted R^2 of 0.84; in comparison with 1999, the positive coefficient, the positive constant and the regression performance are all increasing. Both the commercial and non-commercial job groups of the tertiary sector are marginally better described by log-log regressions of population, but have a negative constant, which could lead to negative estimations during simulation. Therefore we apply linear functions, and in the latter case a model with zero constant is used. Table 3 contains the regression equations for residential units and jobs in sectors.

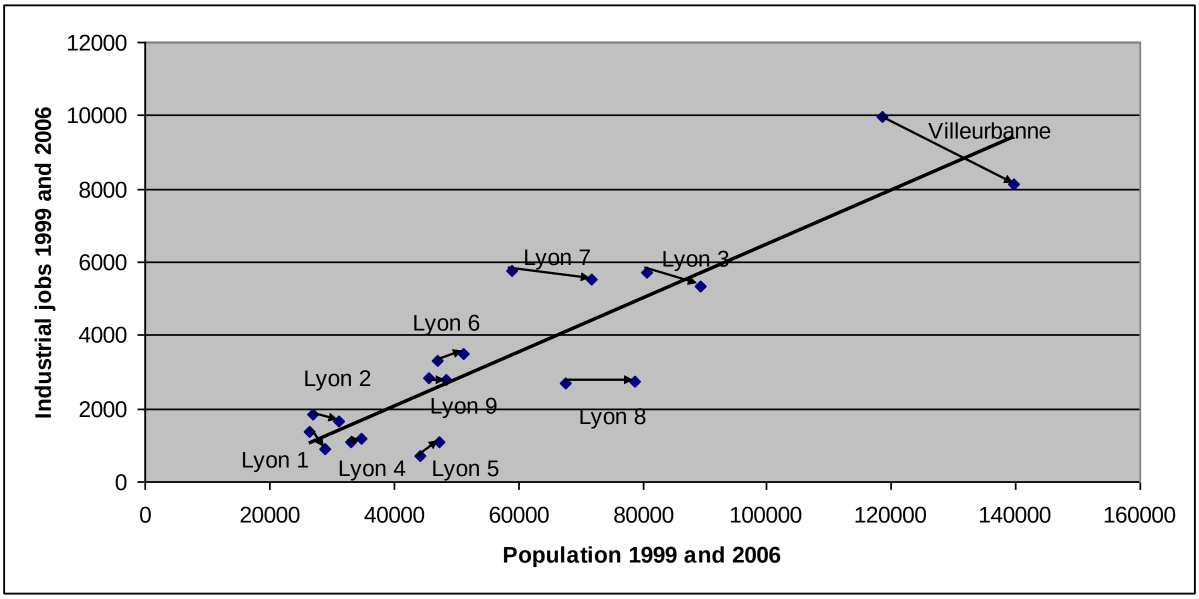


Figure 1. Industrial jobs and population dynamics in Lyon and Villeurbanne

[3] *Institut national de la statistique et des études économiques* (National Institute for Statistics and Economic Studies).

4. Reference scenario

As exogenous data, UrbanSim needs control totals for population for simulation period and household relocation rate. We use the INSEE prediction of a number of households in the Lyon Urban Area in 2000-2030. According to it, in 2030 there will be 2.1 million inhabitants composing 865 thousand households.

Estimating our annual household relocation rate, we start with the annual percentage of households changing accommodation in 2000-2005, which is 7.6%. We subtract from it the annual growth of the number of households (1.1%). According to the INSEE data, annually the share of households, who change accommodation without changing *departement* or municipality, in average composes 5% of total number of households. We assume that half of them do not change municipality and thus subtract 2.5% from the previously calculated rate. Thus, the annual household relocation rate in this study is 4.0%.

In the reference scenario, while population and jobs are updated, the same road network and other parameters are used; the petrol price of 1.5 euro/liter is not changed either. During simulation, employment accessibility indices are recalculated with MOSART three times: in 2006, 2015 and 2025. In comparison with the scenario without updating accessibility indices, the most visible difference is observed with real estate price, which is growing almost everywhere with the 11% average increase by the end of the simulation period.

We analyze the evolution of the following key attributes: employment access, population density and housing price, see Table 4 for the base year and the final simulated year. Employment densities in sectors are not included in the group, because in our model they are functions of populations. The values of skew and kurtosis higher than the normality thresholds of 2 and 7 respectively (West *et al*., 1995) are set in italic type. In 1999, population density is an attribute, whose skew and kurtosis are higher than the normality thresholds. With the reference scenario, in 2030 the attributes under question are changed as follows. The mean of accessibility index is increased by 59%. Population density in the fall of the simulation period is again non-normal, but its skew and kurtosis are a bit lower than in the base year. Average housing price is increased by 89%, while its maximum value in 2030 is more than five times higher than in 1999; moreover, skew and kurtosis are dramatically increased indicating strong non-normality first and foremost at the expense of rocketing prices in the central districts without residential development, whose vacancy rates is only 1%.

Table 4. Descriptive statistics 1999 and 2030

Attribute	Mean	Minimum	Maximum	Std. dev.	Skew	Kurtosis
Employment access, index	48,647.87	2,576.83	251,584.72	51,702.78	1.93	3.50
	77,125.22	4,390.00	352,714.99	76,063.97	1.72	2.58
Population density per square	720.05	9.30	14,451.85	1,873.81	*4.95*	*26.81*
	1089.69	10.31	20,972.78	2,881.62	*4.84*	*25.89*

kilometer						
Housing price, euro per square meter	1,109.46 2,091.71	575.00 680.80	1,873.00 11,892.68	202.46 1,305.40	0.17 *4.06*	0.54 *23.40*

More details on the dynamics of housing price per square meter are provided in Table 5, where the actual price index in Lyon and its closest suburbs, known till 2008, is used for the back-casting analysis. In Table 5, average price in the Lyon Urban Area is reported as well as prices in the two central districts of Lyon (Lyon 1 and Lyon 2). In the reference scenario, during the first simulation decade, the average price is growing rather slowly. This happens at the expense of a big number of smaller municipalities, mainly rural ones located on the fringe. Moreover, the actual price index dynamics belongs to the apartments located in the central part of the agglomeration and mainly concentrated in Lyon and Villeurbanne. In comparison with the actual dynamics, the simulated prices growth much faster in Lyon 1, where there is no new residential development, and slower in Lyon 2, where there is no such constraint.

Table 5. Housing price dynamics

Year	Actual price index	Reference scenario		
		Average	Lyon 1	Lyon 2
1999	1.00	1.00	1.00	1.00
2000	1.04	1.03	1.01	1.01
2001	1.13	1.11	1.22	1.19
2002	1.23	1.19	1.48	1.35
2003	1.37	1.26	2.02	1.51
2004	1.67	1.33	2.63	1.66
2005	1.95	1.39	3.31	1.80
2006	2.21	1.44	4.03	1.92
2007	2.34	1.51	4.81	2.05
2008	2.42	1.57	5.08	2.16
2009	-	1.63	5.22	2.26
2010	-	1.67	5.31	2.35
2015	-	1.80	5.38	2.65
2020	-	1.86	5.46	2.81
2025	-	1.88	5.56	2.89
2030	-	1.89	5.54	2.95

5. Alternative scenarios

Increasing congestion in transportation network and the rise of energy prices are among the main reasons contributing to a close attention to the linkage between transportation and land use in research and practical applications in France (Delons *et al*., 2009). The mentioned source contains a case study of an urban toll around Paris. The first urban motorway toll in the Greater Lyon was opened outside Lyon in 1997. For a theoretical analysis of its acceptability see Raux and Souche (2004).

Following the examples of London, Stockholm and Milan, a possibility to implement urban toll became legal in France in summer 2010. The economic and social consequences of its potential implementation in Paris and other big cities are a hot topic under discussion by decision-makers and experts as well as broad public. Political aspects of urban toll plans depend on the prospective changes in urban development and should take into account not only overall benefits, but potential losers. Nowadays, it is hardly possible to simulate such scenarios without a comprehensive transportation and land use modeling tool. Lack of coordination on urban travel and land use policy can lead to serious organizational problems and inefficiencies in provision of public services (Geerlings and Stead, 2003).

Our alternative scenarios include the three versions of urban tolls: the area wide Lyon-Villeurbanne, the cordon area Lyon-Villeurbanne and the cordon area the Greater Lyon. In the first case, a daily fee is charged for any vehicle driving in a public road within the congestion charge zone, regardless of how many times the cordon is crossed. The area wide congestion pricing system occupies about 62 square kilometers. In the two cordon area cases, a fee is charged to travel to the area whatever the origin of trip and the time of the day. The fee is added to monetary cost in (2). In all the versions, a 10 euro fee is charged starting from 2015. With the current French tutelary value of time of 11.4 euro/hour (Commissariat Général du Plan, 2001), this toll price can be compensated by an estimated travel time gain of 53 minutes. Indisputably, this rather high fee is arbitrary and is chosen for illustrative purpose: to clearly see the consequences of urban toll implementation in a fifteen-year period.

In the fourth alternative scenario we simulate what could happen if fuel prices would increase dramatically. It goes without saying that the realism of this scenario is supported by the non-renewable nature of oil resources as well as political and economic instability in many countries with natural deposits. In this scenario, the petrol price is equal to 1.5 euro/liter in 1999-2014, but increases to 3 euro/liter from 2015. With the fuel consumption 0.055 liter/km, the additional 1.5 euro/liter increases the monetary cost in (2) by 0.08 euro/km; therefore hereafter this scenario is called distance based charging.

The simulated scenarios are described below. The effects of the alternative scenarios on population and housing prices are shown in Figures 2 and 3 respectively. As a consequence of the implementation of the area wide toll Lyon-Villeurbanne, accessibility indices within the area are dramatically, more than twice, decreased. Escaping the expensive toll payments, population leaves Lyon, Villeurbanne and many municipalities of the Greater Lyon located closer to the metropolitan core. The Lyon districts lose at minimum 8% of population and at maximum 16% (Figure 2, *a*). There is practically no difference between the income groups of households: all classes seek to avoid living in the centre. The destinations of relocating population are more distant municipalities, mainly outside the Greater Lyon. Some municipalities, which are rural nowadays, located mainly in more than 20 km from the Lyon city centre, experience the unprecedented population growth, up to 35% in comparison with the reference scenario. Housing prices (Figure 3, *a*) dramatically decreases as well reaching their minimum (-37%) in the central districts. Outside Lyon, Villeurbanne and several closest suburbs, real estate prices are slightly decreasing in most municipalities. Modest growth is observed closer to the fringes of the metropolitan area, especially in the east and the north, where some areas experience significant price increase, up to 40%. In general, it is a catastrophic scenario.

The effect of the cordon area Lyon-Villeurbanne is double. On the one hand, inside the area accessibility improves by 1-4%. On the other, outside Lyon and Villeurbanne the consequence is negative everywhere. The most suffering municipalities are those adjacent to the cordon area and their nearest neighbors. Here, accessibility decreases up to 50%. The negative effect is decreasing almost concentrically. Population density within the cordon area is largely increased (Figure 2, *b*) despite high housing prices (Figure 3, *b*). In seven of nine districts of Lyon the relative population growth is 14%-21%. In Lyon 1 and Lyon 4, where no new residential units are constructed, there is no positive demographic effect: the residential vacancy rate is almost zero and further population growth is impossible. In these two districts, the lack of housing supply leads to increasing demand and enormously high prices, reaching the relative growth of 73% in comparison with the reference scenario (Figure 3, *b*). That is why the rich demonstrate here slightly positive demographic dynamics (Figure 4, *a*), while the poor leave these two districts (Figure 4, *b*). Population density in the first belt around the cordon area is dramatically decreasing. Besides Lyon and Villeurbanne, the attractive locations are those outside the Greater Lyon, where many distant areas experience positive relative price dynamics; this effect is observed especially in the eastern direction.

When the toll cordon area covers the Greater Lyon, the overall effect is similar to the previous case, but population growth in many municipalities in the more prosperous western part of the suburban belt is higher than in its poorer eastern part (Figure 2, *c*). Outside the cordon area, population found it cut from the most of working places and is ready for relocation; the influence of this toll on population dynamics is stronger in the western direction with its minimum of -55%. Thus, after the toll implementation, western suburbs attract more people from the other side of the cordon area boundary. The negative effect on housing prices outside the cordon area is more pronounced than in the case of the toll Lyon-Villeurbanne, while within the area the prices have positive relative dynamics, especially in the Lyon districts without construction activities, where the relative growth reaches 37% (Figure 3, *c*).

The scenario of distance based charging has the geographical distribution of its effect opposite to that of the first scenario: a significant share of population, up to 12%, leaves more distant municipalities to move closer to the agglomeration centre (Figure 1, *d*). Outside the Greater Lyon, there are several tens of municipalities, where population is slightly increasing. Nevertheless, neither in the centre nor in the fringe the relative population growth is higher that 10% at maximum. Housing price dynamics is negative almost everywhere, with very few exceptions, among whom there are four Lyon districts (Figure 2, *d*). Thus, urbanized areas are more resilient to petrol price increase than most of rural locations.

For both predicted population and housing price, standard deviation is the highest in the scenario of the toll cordon area the Greater Lyon. Among all the scenarios, even in the most sensitive Lyon districts the 95% confidence intervals do not exceed 4.6% of predicted values. To measure the effects of stochastic variation (see Krishnamurthy and Kockelman, 2002 and Wegener, 2011), we simulate each scenario ten times with different random number seeds. The overall average deviation and the average deviation in Lyon and Villeurbanne are zeros in all the scenarios. Table 6 shows the extreme deviations from the average for population and housing prices in Lyon and Villeurbanne. High extremes for housing prices in the two toll cordon and the distance based charging scenarios belong to the districts without residential development, where prices are rocketing, while in other districts the extreme deviations are not higher than 0.01.

Table 6. Deviations from the average in repeated simulations

Scenario	Population		Housing price	
	Min	Max	Min	Max
Reference	-0.02	0.01	-0.03	0.02
Toll area wide Lyon-Villeurbanne	-0.02	0.02	-0.01	0.02
Toll cordon Lyon-Villeurbanne	-0.01	0.01	-0.06	0.10
Toll cordon the greater Lyon	-0.02	0.02	-0.05	0.04
Distance based charging	-0.01	0.01	-0.05	0.07

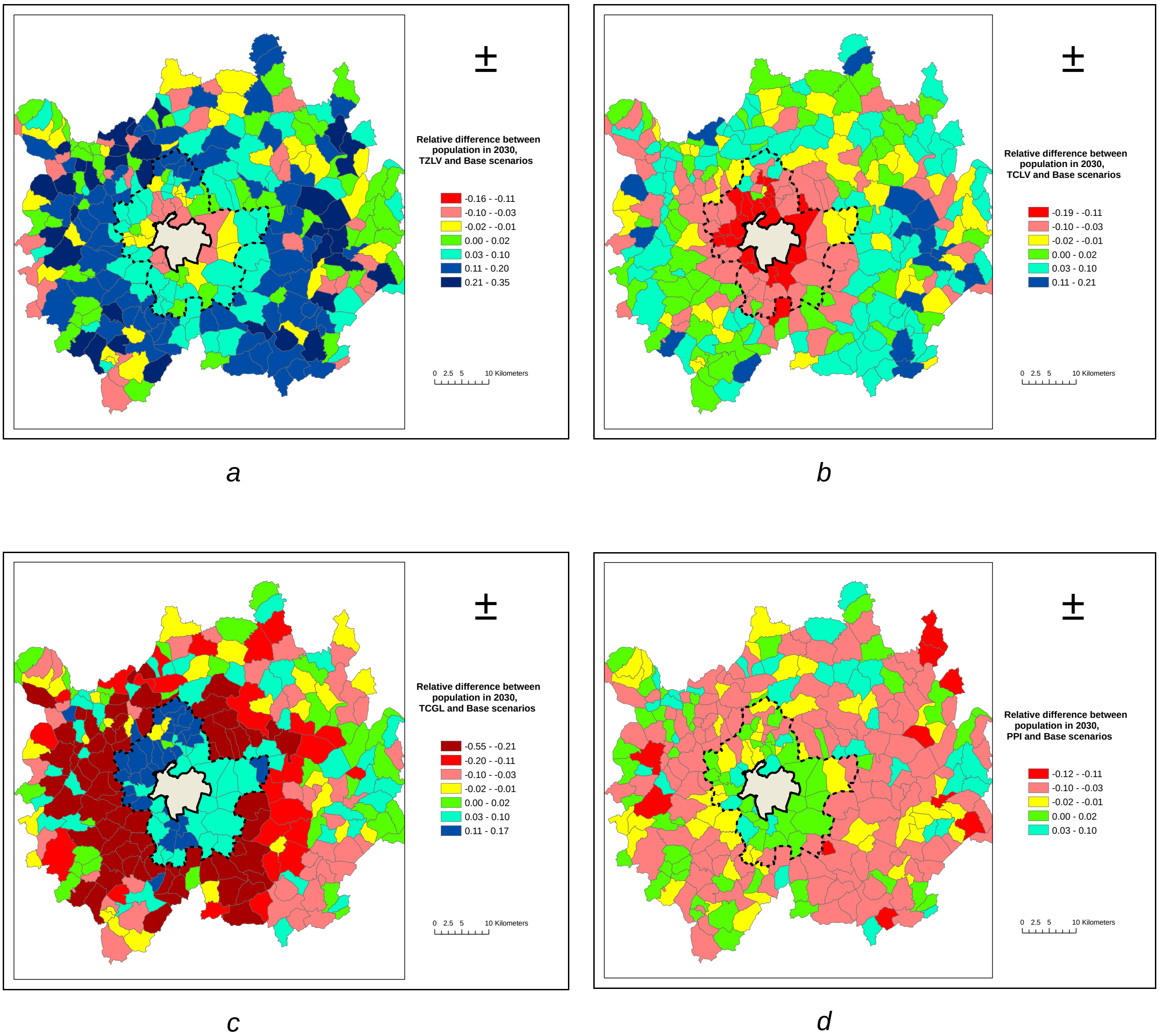
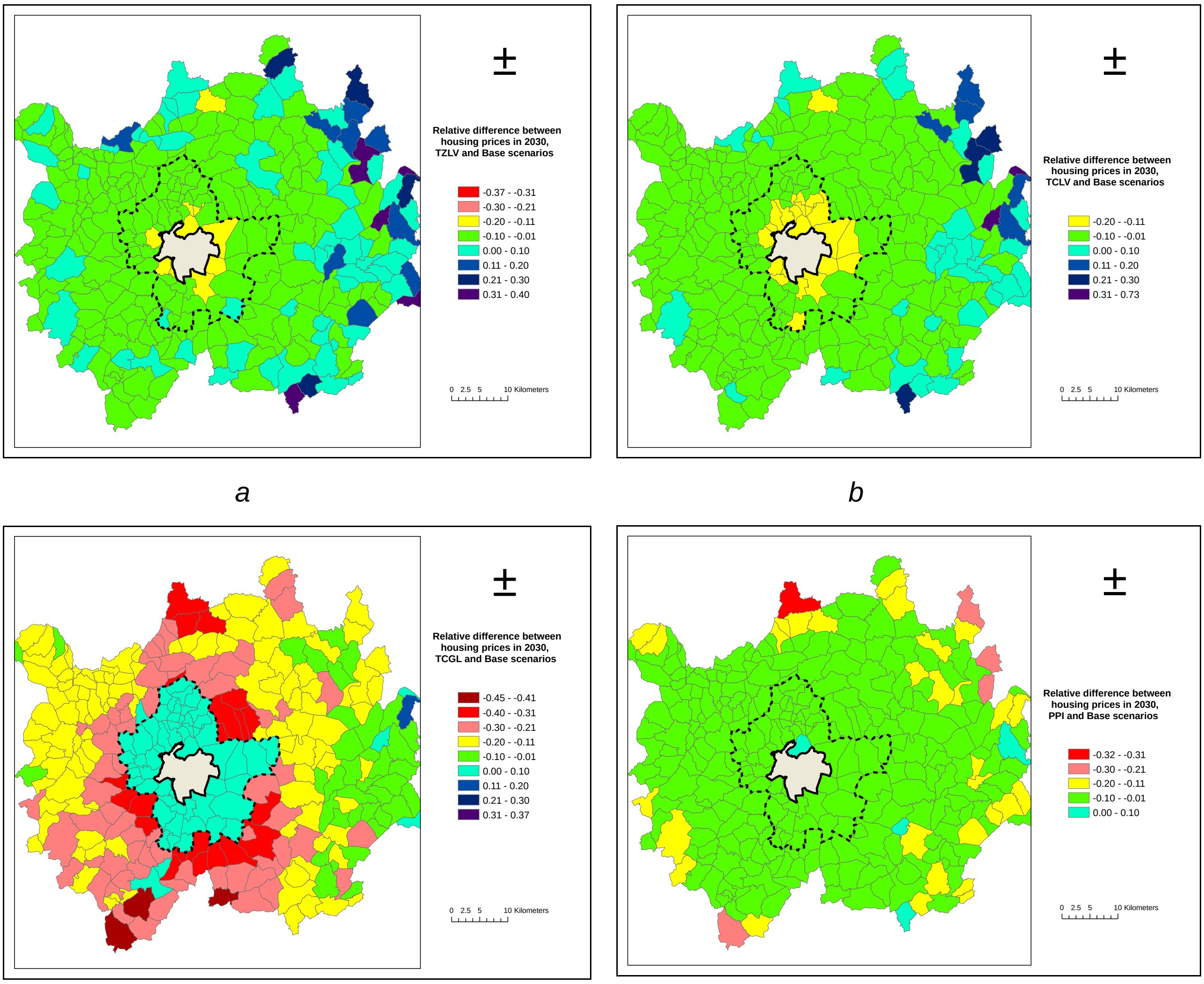


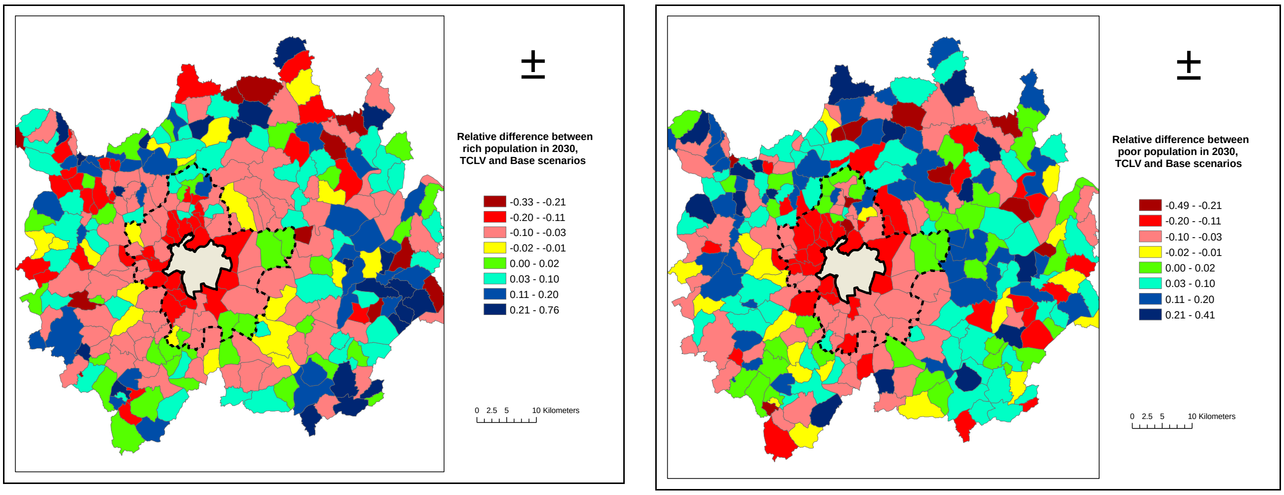
Figure 2. Relative differences between population in 2030, alternative scenarios and the reference (alternative scenarios: toll area wide Lyon-Villeurbanne – *a*; toll cordon area Lyon-Villeurbanne – *b*; toll cordon area the Greater Lyon – *c*; distance based charging *d*)



a *b*

c *d*

Figure 3. Relative differences between housing prices in 2030, alternative scenarios and the reference (alternative scenarios: toll area wide Lyon-Villeurbanne – *a*; toll cordon area Lyon-Villeurbanne – *b*; toll cordon area the Greater Lyon – *c*; distance based charging *d*)



a *b*

Figure 4. Relative differences between population in income groups in 2030, toll cordon area Lyon-Villeurbanne and the reference (rich population – *a*; poor population – *b*)

Ševčiková *et al*. (2007) have developed the Bayesian melding method for assessing uncertainty in urban simulation. Measuring the effects of tearing down a viaduct in Seattle with this method, Ševčiková *et al*. (2011) have obtained the confidence intervals of travel times regarding to which the alternative point estimates do no always fall into. This posterior distribution approach merits attention in future research.

Table 7 compares the effects of the four alternative scenarios on housing price index in comparison with the reference scenario dynamics in the fifteen-year period. It is shown the overall average and the values for Lyon 2, which is an example of a central district without limitation for residential development. The overall effect of any urban toll on housing price dynamics is negative. The negative consequences are more visible at the end of the simulation period. For example, the average effect of the toll area wide Lyon-Villeurbanne is zero in 2016, but decreases to -0.07 in 2030; moreover, in the same period in the city centre, price dynamics decreases from -0.07 to -0.60. In comparison with the toll cordon area Lyon-Villeurbanne, the toll cordon area the Greater Lyon leads to more negative consequences in the overall housing price dynamics and a bit more modest price growth in Lyon 2. Unsurprisingly, the distance based charging scenario always diminishes housing prices on average as well as in the Lyon center.

Table 7. Changes in housing price index dynamics

Year	Toll area wide Lyon-Villeurbanne		Toll cordon area Lyon-Villeurbanne		Toll cordon area the Greater Lyon		Distance based charging	
	Average	Lyon 2	Average	Lyon 2	Average	Lyon 2	Average	Lyon 2
2016	0.00	-0.07	-0.01	+0.01	-0.03	+0.01	-0.02	0.00
2018	-0.02	-0.20	-0.03	+0.03	-0.09	+0.01	-0.05	-0.01
2020	-0.03	-0.30	-0.03	+0.04	-0.12	+0.02	-0.07	-0.02
2022	-0.04	-0.38	-0.05	+0.04	-0.15	+0.02	-0.08	-0.03
2024	-0.05	-0.45	-0.05	+0.04	-0.16	+0.02	-0.09	-0.03
2026	-0.06	-0.51	-0.06	+0.04	-0.19	+0.02	-0.11	-0.04
2028	-0.06	-0.56	-0.06	+0.05	-0.20	+0.03	-0.11	-0.03
2030	-0.07	-0.60	-0.07	+0.05	-0.22	+0.03	-0.12	-0.04

The absolute effects of the road pricing scenarios on the value of housing stock are shown in Figure 5. They are calculated with average housing price per square meter in each municipality under the assumption that all residential units have the same floor area. The total absolute effect is positive only in the toll cordon scenarios, when the central locations are the winners. While the distance based charging has weak positive effect in Lyon and Villeurbanne, the consequence of the toll area wide implementation is negative everywhere.

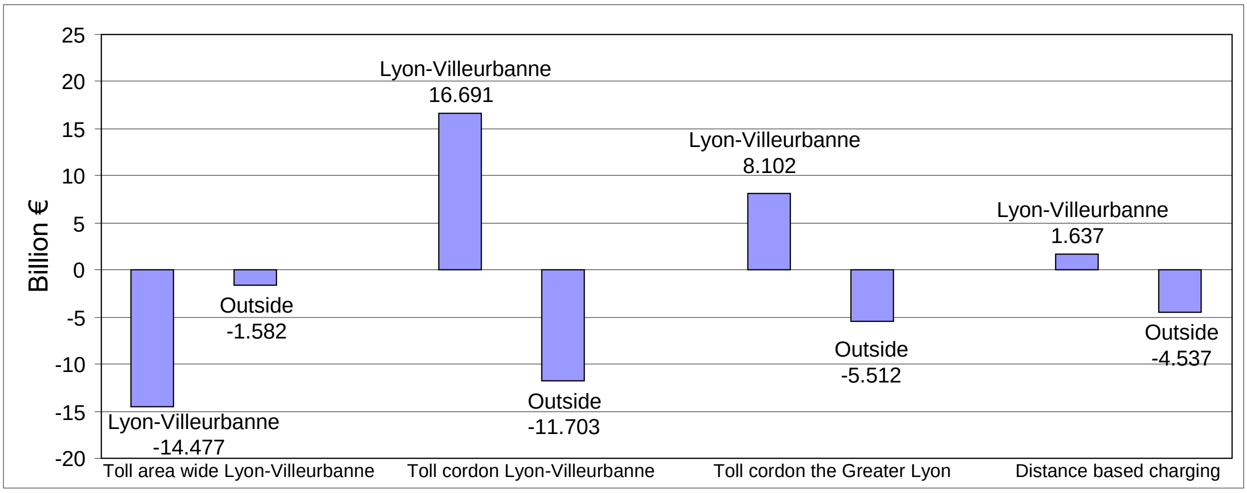


Figure 5. The absolute effects on the value of housing stock in 2030

The effects of urban tolls on housing prices in the central part of the urban area are demonstrated with the classical demand and supply explanations in Figures 5-7. The first two graphs (Figures 5 and 6) show the situations without limitation on residential development. The initial demand (D_0) and supply (S_0) curves intersect in the equilibrium point E_0 with the price P_0.

The implementation of the toll area wide (Figure 5) diminishes the utility of this location and shifts the demand curve down to a new position D_1. Housing supply as a function of a number of households in zones is not increasing, but it also cannot be decreased, because demolition is not foreseen in our simulation. Therefore the supply curve S_0 is not moving. The new equilibrium point is E_1 with price P_1, which is lower than P_0.

The toll cordon area represents the other mechanism (Figure 6): the better utility of location increases the demand (D_1), but the supply is increasing as well (S_1) and instead of intersection E_1 with much higher price P_1 the new equilibrium point occupies the position E_2 with lower price P_2, which is however higher than P_0. Note that despite relatively elastic housing supply the effect of the toll cordon area on price is positive. This happens due to growing population, higher accessibility indices and price lag included in the REPM (Table 2).

Figure 7 shows the effects of the two kinds of toll in the central area without new residential development, i.e. with inelastic supply, S=const. If the demand is decreasing (D_1), the price is decreasing as well to P_1. If the demand is increasing (D_2), the price is increasing to P_2. As the supply is not changed, there is no counterbalance to price decrease or increase. Under this condition the price is more sensitive to scenarios and reaches its minimum or maximum. The examples of Lyon 2 and Lyon 4 correspond to these extreme cases.

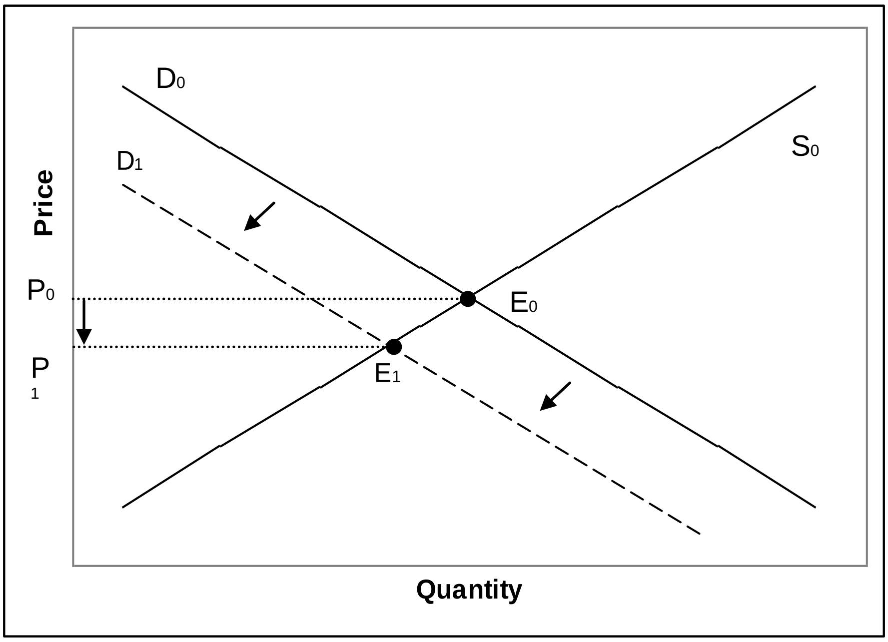


Figure 5. Toll area wide effect with residential development

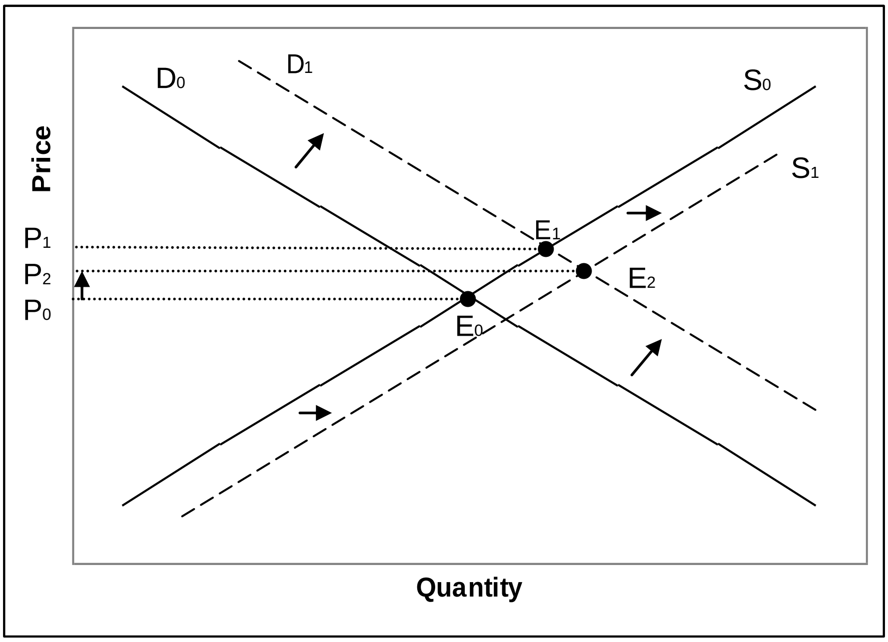


Figure 6. Toll cordon area effect with residential development

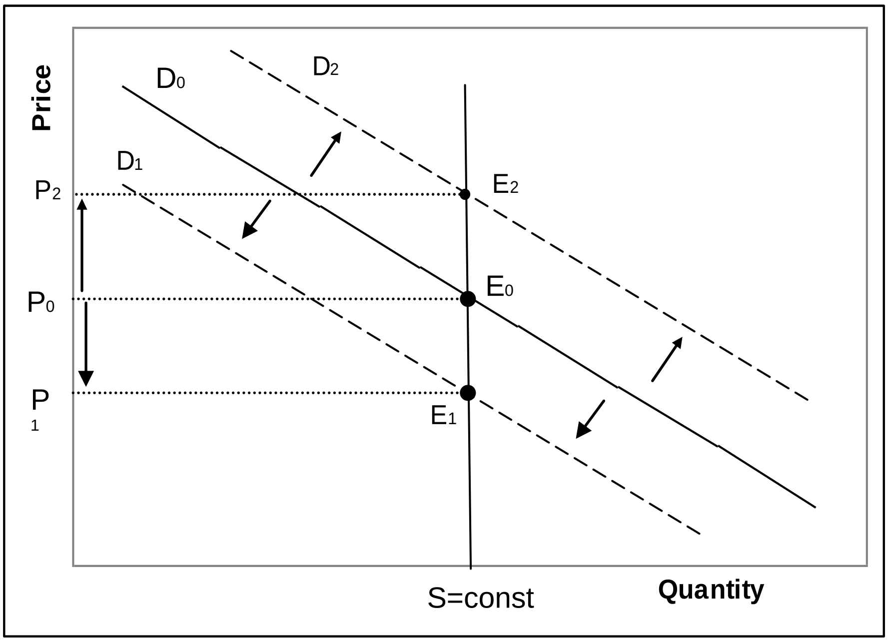


Figure 7. Toll area wide effect (1) and toll cordon area effect (2)
without residential development

Conclusion

Road pricing scenarios have been evaluated with the UrbanSim application. The reference scenario of a thirty-year urban simulation is compared with the four alternative scenarios, where mobility cost increases in the middle of the simulation period. The dynamics of spatial distribution of population and housing prices are focused.

The implementation of the toll area wide in the central part of the agglomeration is a catastrophic scenario: accessibility dramatically decreases and a considerable share of population leaves the urbanized areas. Within the toll cordon area, positive demographic dynamics is provided; when this area covers the bigger territory of the Greater Lyon, the better attractiveness of western suburbs is evident.

Districts without new residential development are more sensitive to changes in housing demand than other areas: inelastic housing supply provides extreme shifts in prices that in the case of growth can lead to income segregation patterns. The same districts have extremes in stochastic variations when housing prices are enormously increasing.

The implementation of any of the three versions of urban tolls leads to negative average effect on housing prices. Moreover, average prices are decreasing during simulation and reach their minimum in the final year. In the policy implication context, it is important to see the absolute effects of the scenarios on housing values, even if they are calculated on the base of some assumptions. The total absolute effect is positive only in the toll cordon scenarios, and the central locations are the winners. The scenario of distance based charging demonstrates that urbanized areas are more resilient to its negative influence than most of rural locations.

The alternative scenarios show that population distribution and housing price dynamics are sensitive to changes in transportation system and respond intuitively correctly in different locations. The effects are illustrated with classical demand and supply curves explanations. We can conclude that the UrbanSim application in Lyon is capable to capture changes in transport policy on urban development and to simulate these effects at geographical dimension. The interaction between the land use framework UrbanSim and the transportation model MOSART is able to provide decision-makers with information, which is necessary for development of comprehensive integrated plans. Thus, describing the working tool simulating the consequences of policy scenarios, the paper contributes to urban sustainability.

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References

Anas, A., Arnott, R. and Small, K. A. (1998). Urban spatial structure, *Journal of Economic Literature*, Vol. 36, No 3, pp. 1426-1464.

Ben-Akiva, M. and Lerman, S. R. (1985). *Discrete Choice Analysis: Theory and Application to Travel Demand*. Cambridge (MA), London: MIT Press.

Bonnafous, A., Crozet, Y., Mercier, A., Ovtracht, N., Péguy, P.-Y. and Puech, F. (2011). MOSART et le projet PLAINSUDD : une plate-forme de modélisation et simulation de l'accessibilité pour l'aide à la décision et l'aménagement du territoire, in: J.-P. Antoni (Ed.) *Modéliser la ville : formes urbaines et politiques de transport*, pp. 186-210, Economica.

Bonnafous, A., Kryvobokov, M., Bouf, D. and Ovtracht, N. (2010). *Simulating residential location choice in the Lyon Urban Area*. Conference paper, 57th Annual North American Meetings of the Regional Science Association International, Denver, Colorado, 10-13 November.

Bonnafous, A. and Masson, S., (2003). Evaluation des politiques de transports et équité spatiale, *Revue d'Economie Régionale et Urbaine*, 4, pp. 547-572.

Borning, A., Waddell, P. and Förster, R. (2008). *UrbanSim: Using Simulation to Inform Public Deliberation and Decision-Making*, in: H. Chen *et al*. (Eds.) Digital Government: E-Government Research, Case Studies, and Implementation, pp. 439-463. New York: Springer-Science+Business Media, LLC.

Chang, J. S. (2006). Models of the Relationship between Transport and Land-use: A Review, *Transport Reviews*, 26 (3), pp. 325-350.

Cho, E. J., Rodriguez, D. A. and Song, Y. (2008). The role of employment subcenters in residential location decisions, *Journal of Transport and Land Use*, 1 (2), pp. 121–151.

Commissariat Général du Plan (2001). *Transports : choix des investissements et coût des nuisances*. La documentation française, 322 p.

Crozet, Y., Marchal, F., Ovtracht, N., Thiebaut, V., Yvon, C. and Bischoff, P. (2008). *Mise en place d'un outil d'aide à la décision et à l'aménagement du territoire : MOSART (MOdélisation et Simulation de l'Accessibilité aux Réseaux et aux Territoires)*, Conference paper, SAGEO Conference, Montpellier, France, 24-27 June.

Delons, J., Coulombel, N. and Leurent, F. (2009). *PIRANDELLO: an integrated transport and land-use model for the Paris area*. Paper presented at the 88th TRB meeting, January 11-15, Washington, DC, 23 p.

de Palma, A., Motamedi, K., Picard, N. and Waddell, P. (2005). A model of residential location choice with endogenous housing prices and traffic for Paris region, *European Transport*, 31, pp. 67-82.

Geurs, K. T. and van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions, *Journal of Transport Geography*, 12 (2), pp. 127-140.

Felsenstein, D. and Ashbel, E. (2010). Simultaneous modelling of developer behavior and land prices in UrbanSim, *Journal of Transport and Land Use*, 3 (2), pp. 107-127.

Geerlings, H. and Stead, D. (2003). The integration of land use planning, transport and environment in European policy and research, *Transport Policy*, 10 (3), pp. 187-196.

Handy, S. L. and Niemeier, D. A. (1997). Measuring accessibility: an exploration of issues and alternatives, *Environment and Planning A*, 29 (7), pp. 1175-1194.

Hunt, J. D., Kriger, D. S. and Miller, E. J. (2005). Current Operational Urban Land-use-Transport Modelling Frameworks: A Review, *Transport Reviews*, 25 (3), pp. 329-376.

Iacono, M, Levinson, D. and El-Geneidy, A. (2008). Models of Transportation and Land Use Change: A Guide to the Territory, *Journal of Planning Literature,* 22 (4), pp. 323-340.

Johansson, B., Klaesson, J. and Olsson, M. (2002). Time distances and labor market integration, *Papers in Regional Science*, 81 (3), pp. 305-327.

Kelly, E. D. (1994) The Transportation Land-Use Link, *Journal of Planning Literature*, 9 (2), pp. 128-145.

Krishnamurthy, S. and Kockelman, K. (2002). Uncertainty propagation in an integrated land use-transport modeling framework: Output variation via UrbanSim, *Transportation Research Record* (1805), pp. 128-135.

Kryvobokov, M., Mercier, A., Bonnafous, A. and Bouf, D. (2011). *Simulating housing prices in Lyon with UrbanSim: Predictive capacity and sensitivity analysis*, Conference paper, 41st Ce.S.E.T. Meeting "Appraisals – Evolving Proceedings in Global Change", Rome, 14-15 November.

Lee, B. H. Y., Waddell, P., Wang, L. and Pendyala, R. M. (2010). Reexamining the influence of work and nonwork accessibility choices with a microanalytic framework, *Environment and Planning A*, 42 (4), pp. 913-930.

Mercier, A. and Stoiber, T. (2010). Improving accessibility measurement combining transport modelling and GIS analysis: two examples from France and Germany, in: J. M. Viegas and R. Macario (Eds.) *Selected Proceedings of the 12th World Conference on Transport Research*, Lisbon, ISBN 978-989-96986-1-1.

Nguyen-Luong, D. (2011). *SIMAURIF : un modèle dynamique de SIMulation de l'interAction transport-Urbanisation en Région Ile-de-France*, in : J.-P. Antoni (Ed.) Modéliser la ville. Formes urbaines et politique de transport, pp. 78-118. Paris: Economica.

Nicolai, T. W., Wang, L., Nagel, K. and Waddell, P. (2011). *Coupling an urban simulation model with a travel model – A first sensitivity test*, Working paper, Technical University of Berlin and University of California, Berkeley, 24 p.

Patterson, Z., Kryvobokov, M., Marchal, F. and Bierlaire, M. (2010). Disaggregate model with aggregate data: Two UrbanSim applications, *Journal of Transport and Land Use*, 3 (2), pp. 5-37.

Raux, C. and Souche, S. (2004). The Acceptability of Urban Road Pricing: A Theoretical Analysis Applied to Experience in Lyon, *Journal of Transport Economics and Policy*, 38 (2), pp. 191-215.

Ravulaparthy, S. and Goulias, K. G. (2011). *Forecasting with Dynamic Microsimulation: Design, Implementation, and Demonstration*, Geotrans research report 0511-01, University of California Transportation Center, Santa Barbara.

Ševčiková, H., Raftery, A. E. and Waddell, P. (2007). Assessing uncertainty in urban simulation using Bayesian melding, *Transportation Research Part B: Methodological*, 41 (6), pp. 652-669.

Ševčiková, H., Raftery, A. E. and Waddell, P. (2011). Uncertain benefits: Application of Bayesian melding to the Alaskan Way Viaduct in Seattle, *Transportation Research Part A: Policy and Practice*, 45 (6), pp. 540-553.

Simmonds, D., Waddell, P. and Wegener, M. (2011). *Equilibrium versus dynamics in urban modelling*. Conference paper, Symposium on Applied Urban Modelling (AUM 2011) "Innovation in Urban Modelling", University of Cambridge, 23-24 May.

Waddell, P. (2002). UrbanSim: Modelling Urban Development for Land Use, Transportation and Environmental Planning, *Journal of the American Planning Association*, 68 (3), pp. 297-314.

Waddell, P. (2011). Integrated Land Use and Transportation Planning and Modelling: Addressing Challenges in Research and Practice, *Transport Reviews*, 31 (2), pp. 209-229.

Waddell, P., Borning, A., Noth, M., Freier, N., Becke, M. and Ulfarsson, G. (2003). Microsimulation of Urban Development and Location Choices: Design and Implementation of UrbanSim, *Networks and Spatial Economics*, 3 (1), pp. 43-67.

Waddell, P., Ulfarsson, G., Franklin, J. and Lobb, J. (2007). Incorporating land use in metropolitan transportation planning, *Transportation Research A*, 41 (5), pp. 382–410.

Waddell, P., Wang, L., Charlton, B. and Olsen, A. (2010). Microsimulating parcel-based land use and activity-based travel: Development of a prototype application in San Francisco, *Journal of Transport and Land Use*, 3 (2), pp. 65-84.

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

Wegener, M. (2011). From Macro to Micro – How Much Micro is too Much? *Transport Reviews*, 31 (2), pp. 161-177.

West, S.G., Finch, J.F. and Curran, P.J. (1995). *Structural equation models with nonnormal variables: problems and remedies*, in Hoyle, R.H. (Ed.) Structural Equation Modeling: Concepts, Issues and Applications, pp. 56-75. Newbury