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Journal

Environment and Planning B: Planning and Design, 40(6)

Author

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Publication Date

2013-07-27

Peer reviewed

A summary of the applications to date of RELU-TRAN, a microeconomic urban computable general equilibrium model[†]

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Received 14 November 2011; in revised form 27 July 2013

Abstract. RELU-TRAN (Regional Economy Land Use and Transportation) is a spatial computable general equilibrium (CGE) model treating endogenous road congestion, housing and labor markets, and real-estate development consistent with microeconomic theory. The model has been calibrated and used for the Chicago Metropolitan Statistical Area and the Greater Paris Region, and is currently being implemented for the Greater Los Angeles metropolitan area. In the Chicago application the model has been used: (i) to examine the impact of an increase in the price of gasoline on travel and location patterns; (ii) to study how travel time, gasoline consumption and automobile emissions would evolve over time as the area grows in population and land area and as employment continues to disperse into the suburbs; (iii) to evaluate the effects of cordon tolling; and



[†] This paper does not include original material but is a summary of existing papers and ongoing work by the author and his coauthors. An earlier and shorter version of this paper was presented at the Symposium on Applied Urban Modeling 2011, held at the University of Cambridge, Cambridge, United Kingdom, 23–24 May 2011, and a shorter and partially overlapping version appeared in *International Public Policy Studies* 16(1), 2011, a publication of Osaka University. The research reported here benefited from support over the years some of it still ongoing. Acknowledged especially is the support from research award RD-83184101-0, United States Environmental Protection Agency's 2004 Science to Achieve Results (STAR) competition, and the Multi-campus Research Program and Initiative (MRPI) grant from the Office of the President, University of California's award 142934. Initially, the development of RELU-TRAN was funded under a competition sponsored by the United States National Science Foundation's Urban Research Initiative solicitation. This resulted in a \$450 000 research award (NSF number SES 9816816) to Alex Anas at the State University of New York at Buffalo and led to RELU-TRAN1, the fifteen-zone Chicago prototype version which was completed in 2005. The National Science Foundation and the State University of New York at Buffalo have assigned intellectual property rights to Alex Anas. Subsequent support to the research of Alex Anas came from a \$675 000 research award RD-83184101-0, from the United States Environmental Protection Agency's 2004 Science to Achieve Results (STAR) competition. This project which started in 2006 and ended in 2010 extended the Chicago application of the model and resulted in RELU-TRAN2 which enriched RELU-TRAN1 by adding a traffic environmental emissions component among other things. Because of this, RELU-TRAN2 (hereafter simply RELU-TRAN) is now suitable also for the analysis of urban traffic on CO₂ and other emissions from urban driving, hence relevant to analyses and policies that relate to global warming (Hiramatsu, 2010). In 2009 Alex Anas was awarded a Multi-campus Research Program and Initiative (MRPI) grant from the Office of the President, University of California (award 142934, approximately \$ 2 600 000 over five years.) Under this research award, scholars, postdoctoral fellows, and graduate students at the University of California at Riverside, the University of California at Santa Barbara, and recently at the University of California at Berkeley are collaborating since January 2010 with the team at Buffalo to apply the RELU-TRAN2 model to the Greater Los Angeles Metropolitan region. The RELU-TRAN L.A. consists of 97 zones. Alex Anas who holds a visiting research economist appointment at the University of California, Riverside from 2010 to 2014 is acting as the scientific director of the project. The Paris study is funded by Societe du Grand Paris.

(iv) of road congestion versus a tax on gasoline. The main findings from these applications of RELU-TRAN are reviewed in this paper. The recent application to the Greater Paris region was aimed to study the effects of projected growth and of planned rail investments on concentrating jobs in growth poles around the City of Paris.

Keywords: computable general equilibrium, urban economics, land use and transportation

1 Introduction

RELU-TRAN is a spatial computable general equilibrium (CGE) model. CGE models are structural as opposed to reduced-form economic models. Structural models can be based solidly in microeconomic theory (Anas and Liu, 2007)—since they do not require a departure from the underlying fundamental functional forms of demand and supply—and therefore they are free of the commonly known pitfalls of reduced-form models.⁽¹⁾

RELU-TRAN simulates the workings of key urban markets and their interactions with each other in a manner that is consistent with economic science. In the model, consumers choose their residential–workplace locations and the fuel economy of their cars, their housing type and floor space quantity, labor supply, and their consumption of goods and services which entail shopping trips. Consumers also choose their destination, mode, and route for each work and nonwork trip. The congestion is determined endogenously. Producers, developers, and landlords are the other economic agents in the model.

The markets modeled in RELU-TRAN are:

- (i) The market for land and existing (already built) floor space in each model zone, where the built floor space can be residential or commercial–industrial.
- (ii) The market for labor in each model zone.
- (iii) The ‘generalized retail’ market in each model zone in which households acquire goods and services from the firms that provide these goods and services and also from government agencies.
- (iv) The markets in which goods and services are exchanged between firms engaged in production within the region that is the procurement of intermediate inputs by firms in different industries from other firms within and by importing into the region, and the export of their outputs beyond the region.
- (v) All of the above markets are connected by the regional mass transit and road networks. Therefore, the monetary cost and travel times that occur on these networks play key roles in determining how these markets clear, reaching a new equilibrium. Transportation is thus a key factor in determining indirectly the response of wages in the labor markets, prices in the goods markets, and rents and market prices of real-estate floor space and for developable land in the land markets.

How all these markets interact and the structure of the RELU-TRAN solution algorithm are described in Anas and Liu (2007). The footnote to the present paper’s title describes in detail the history of the model’s development.

The purpose of this brief paper is to summarize, from my perspective, the key economic and policy-analytic results from the application of RELU-TRAN to the Chicago Metropolitan Statistical Region (MSA) and to the Grand Paris region. In the first of these studies (described in section 2), RELU-TRAN was used to examine the impact of an increase in the price of

⁽¹⁾These pitfalls in a nutshell are that in reduced-form models certain parameters are not identified in calibration or econometric estimation. Hence, changes in these parameters cannot be modeled even though it may be important to be able to do so; reduced-form models cannot be used to do a proper cost–benefit analysis. Structural models are therefore much more preferable if the analyst is serious about understanding the effects of complex changes or doing cost–benefit analyses to support various policies.

gasoline on travel and location decisions in the Chicago MSA (Anas and Hiramatsu, 2012). In section 3 a second study is described in which the model was used to study how travel time, gasoline consumption, and automobile emissions would evolve over time to the year 2030 as the Chicago MSA were to grow in population and expand in land area (Anas, 2011). In section 4 we describe the results of a study to evaluate the effects of cordon tolling in the Chicago MSA (Anas and Hiramatsu, 2013). In section 5 we describe how the model was applied to understand the effects of a gasoline tax versus Pigouvian congestion tolling in the Chicago MSA (Anas, 2013). In section 6 the application of the model to the Île-de-France, the Greater Paris region, is described (Anas, 2012). Finally, section 7 outlines a list of additional applications on my agenda, regarding the treatment of agglomeration economies, welfare analysis with taxation, and redistribution; and dynamics.

2 Effects of the gasoline price

RELU-TRAN, as a spatial CGE model of the Chicago MSA was used to understand how gasoline use, car-vehicle miles traveled (VMT), on-the-road technological fuel intensity (TFI), trips and location patterns, housing, labor, and product markets respond to a gasoline price increase. This application is described in detail in Anas and Hiramatsu (2012). For this purpose the model was calibrated to the base year of 2000. The approach in deciding on the model's parameters was a mixture of fixing some parameters and calibrating others in such a way that the model's elasticity relationships concerning location demand, housing demand and supply, and the labor market are within reasonable ranges of estimates by various econometric studies in the literature.

Since RELU-TRAN includes choice among five car types differing by TFI and precise calculations of gasoline use, VMT, miles per gallon (MPG), and speed, it required a calibration adjustment that draws on additional data from the Illinois Travel Statistics on these aggregates (IDOT, 2000). In particular, data targets for RELU-TRAN to be matched by the calibration were constructed as follows. The data were used to target the number of jobs and residents by zone, the work-trip pattern by mode of commuting and the average travel speed. The VMT, aggregate gasoline consumed, and MPG targets were constructed from the Illinois Travel Statistics (IDOT, 2000) as annual totals for the year 2000. This source gives regionwide VMT as 55 923 million miles/year composed of 15 820 million miles/year on interstates and 40 103 million miles/year on principal and minor arterials, collectors, and local roads and streets. Using the same dataset, we took 90% of these in an effort to exclude miles of travel generated by trucks (since they are not explicitly modeled in RELU-TRAN). Then, our targets for total, major-road, and local-road VMT per day were 137.9, 39.0, and 98.9 million miles, respectively. The calibrated model simulating an equilibrium for the base year predicts these as 132.51 (3.9% less), 32.71 (16.1% less), and 99.80 (0.9% more), respectively.

From the Illinois Travel Statistics, aggregate motor fuel consumption for the State of Illinois in the year 2000 was 4329 million gallons. Chicago's consumption of fuel is estimated as 61% of this and 54.9% after the adjustment for trucks or 6.51 million gallons per day. The calibrated model predicts 6.17 million gallons per day or 5.2% less. The Illinois Travel Statistics also give the average miles per gallon that is the fuel economy that applies to cars in the region as 21.2 miles per gallon. The calibrated model predicts 21.48 or 1.3% more. The model's predictions were also evaluated by how well they fit the zonal location distribution pattern, by computing the average of absolute value percentage errors. Thus, for example, given equilibrium rents and wages and zone-to-zone travel times predicted by the model, the equilibrium distribution of employed residents by zone is predicted with an average error of 6.1%, and the distribution of jobs with 4.9%. The distribution of work trips is predicted with an average error of 5.9% and of trips by car with 6.1%. Car-type choices are predicted with an average error of 5.3%.

Table 1. Compositional analysis of the long-run elasticity (Anas and Hiramatsu, 2012).

Elasticity with respect to gasoline price of	Base values	Elasticity by stage of adjustment (each stage includes earlier stages)								
		short-run			long-run					
		1	2	3	4	5	6	7	8	9
		routes	modes	trips	car fuel economy	residential location	job location	price adjustment	stock adjustment	TFI improves 2%
GAS (<i>million gallons/day</i>) (a)	6.169	0.000046	-0.035	-0.042	-0.043	-0.046	-0.047	-0.078	-0.081	-0.251
Vehicle miles traveled (VMT) (<i>million miles/day</i>) (b)	132.5	-0.000084	-0.027	-0.033	-0.033	-0.036	-0.037	-0.061	-0.064	-0.041
GPM (<i>gallon/mile</i>) (c)	0.047	0.000038	-0.008	-0.009	-0.010	-0.010	-0.009	-0.017	-0.017	-0.211
Speed (<i>miles/hour</i>)	21.7	0.000012	0.020	0.023	0.023	0.024	0.025	0.039	0.040	0.025
TFI index (<i>gallon/mile</i>) (VMT-weighted) (d)	0.0405	-0.000003	-0.001	-0.001	-0.002	-0.002	-0.002	-0.003	-0.003	-0.202
Fuel cost per mile (fuel price × GPM)	0.074	1.000041	0.991	0.990	0.989	0.989	0.990	0.981	0.981	0.768
<i>Composition by extensive margin (VMT), intensive margin (GPM); composition of intensive margin by congestion and technological fuel intensity (TFI)</i>										
VMT effect (extensive margin) in price elasticity of GAS (b)/(a)	1.826	0.777	0.785	0.760	0.786	0.797	0.784	0.793	0.793	0.163
GPM effect (intensive margin) in price elasticity of GAS (c)/(a)	-0.826	0.223	0.215	0.240	0.214	0.203	0.216	0.207	0.207	0.837
TFI effect in GPM (d)/(c)	-0.079	0.101	0.110	0.227	0.241	0.248	0.165	0.165	0.170	0.957
Congestion effect in GPM [(c)-(d)]/(c)	1.079	0.899	0.890	0.773	0.759	0.752	0.835	0.835	0.830	0.043

We found a long-run elasticity of gasoline consumption by cars with respect to the price of gasoline (with congestion endogenous) of -0.081 , keeping constant car prices and the technological fuel intensity of car types but allowing consumers to choose from available car types. By running the model in stages (which correspond to the columns of table 1), we are able to decompose this elasticity into parts that are due to various market-adjustment processes. So we found that 43% of this long-run elasticity is from switches to public transit; 15% from trip, car-type, and location switches; 38% from price, wage, and rent equilibration; and 4% from building stock changes. Of the long run elasticity 79% is from changes in car-VMT (the extensive margin of travel demand) and 21% from savings in gasoline per mile (the intensive margin); with 83% of this intensive margin from changes in congestion and 17% from the substitution of less fuel-intensive cars. An exogenous trend-line improvement of the technological fuel intensities of the car types available for choice raises the long-run gasoline consumption response to a percentage increase in the gasoline price from -0.081 to -0.251 . Thus, only a third of the long-run response to the gasoline price stems from consumer choices and two thirds from progress in fuel intensity. These results are shown in table 1 and figure 1 which are borrowed from Anas and Hiramatsu (2012).

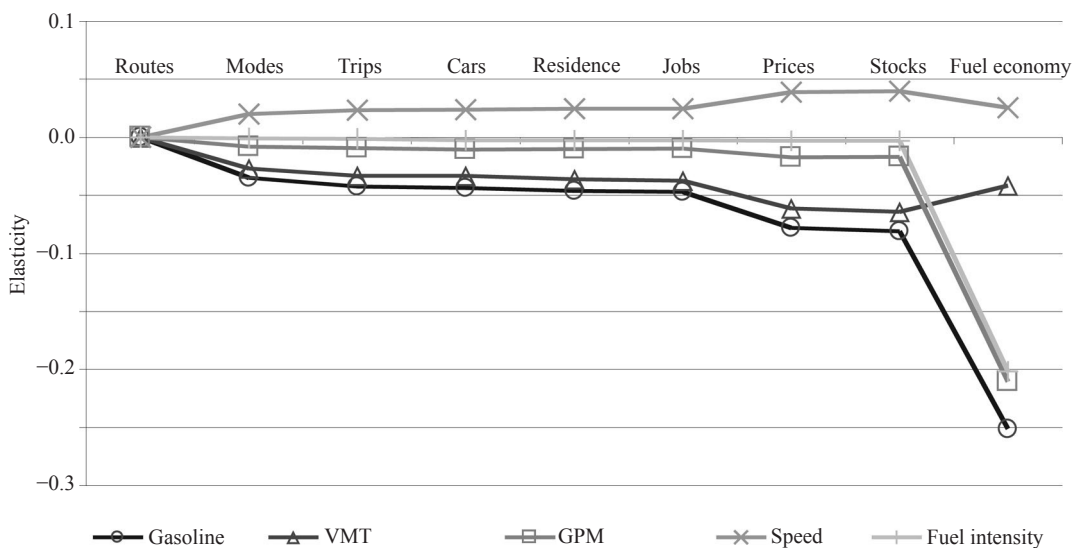


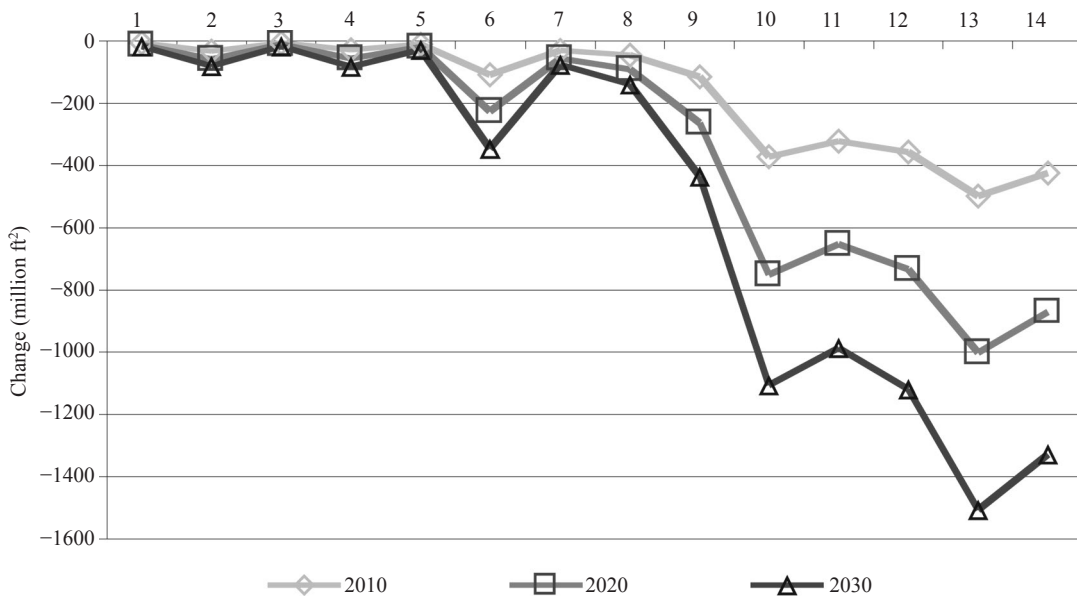
Figure 1. The elasticity of gasoline, vehicle miles traveled (VMT), gallons per mile (GPM), speed, and fuel intensity by stage of adjustment (Anas-Hiramatsu, 2012).

By running an additional simulation we captured the effects on gasoline demand, VMT, trips, etc from changes in the gasoline price in trend-line fuel-intensity improvements and in the prices of cars in this period. In the period 2000–07, real gasoline prices rose 53.7%, the average car fuel intensity improved 2.7%, while car prices fell about 20%. The model predicts that from these changes, but keeping other things constant, gasoline consumption in this period would have fallen by 5.2%.

3 Sustainability of sprawl and travel time

In a second study RELU-TRAN was applied to simulate the growth of the Chicago MSA from 2000 to 2030 (Anas, 2011). According to forecasts, the metropolitan area is expected to grow in population and jobs by about 24% during the period 2000–30. In the model this growth is induced by appropriate growth in exports, a rise in national wages, in gasoline prices, etc. In this context, the interdependent suburbanization of jobs and households will lead to an increase in suburban land development and sprawl, but at the same time it will keep the per-worker travel time in car commuting very stable.

Congestion per road mile increases on average as more jobs and residences suburbanize, but the average road distance traveled between job and residence and between home and shop decrease as the decentralization of firms and workers' residences adjust to the higher congestion per mile. A number of sensitivity tests show that these results are robust in the face of changes in the baseline scenario. On the one hand, these results provide a microeconomic-theory-based explanation of empirical observations made by others in the last twenty years. On the other hand, they provide the first empirical test of the predictions of theoretical models in which the locations of jobs and residences are interdependent and simultaneously determined. The results imply that suburban development in the US, contrary to popular expectations, is likely to remain sustainable in the face of additional metropolitan decentralization in the future. These results are highlighted here in figures 2 to 4. Figure 2 shows the projected increase in urban sprawl over the three decades whereas figure 3 shows



Note: Horizontal axis numbers are model zones arranged roughly by distance from the center.

Figure 2. Decrease in undeveloped land in square feet as a measure of urban sprawl in the baseline simulation 2000–30 (Anas, 2011).

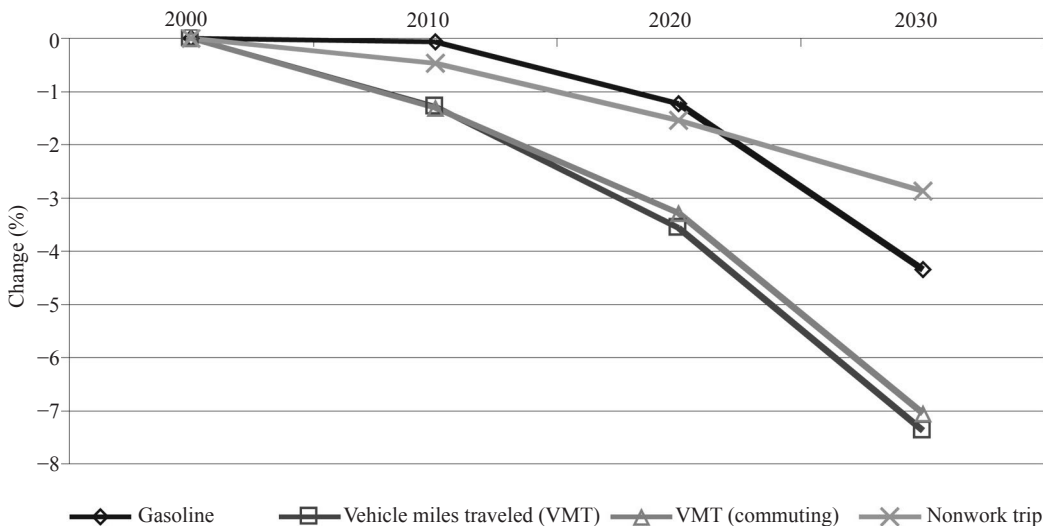


Figure 3. Percentage change in per-capita driving-related variables in the baseline simulation 2000–30 (Anas, 2011).

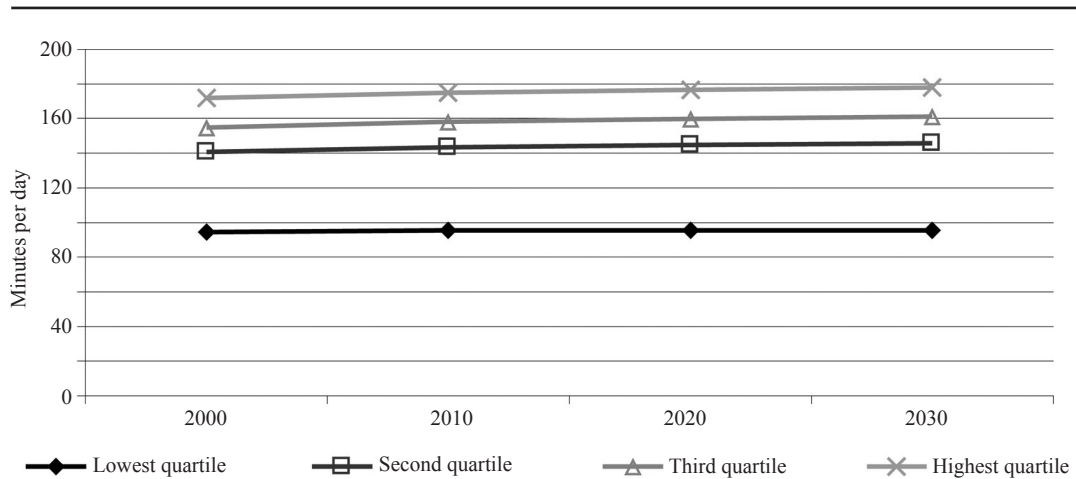


Figure 4. Per capita travel time by income quartile in the baseline 2000–30 (Anas, 2011).

the slight decrease in per capita gasoline, per capita VMT, etc over the same time span and figure 3 the stability of travel time per capita.

4 Cordon tolling

In Anas and Hiramatsu (2013) we report on the effects of cordon tolling to price road congestion in the RELU-TRAN general equilibrium model of the Chicago MSA. We examine in detail how adjustments in the travel, housing, and labor markets by consumers and firms blunt the toll's impact. Toll-avoiding changes in residence locations drive changes in job location and vice versa. Faced with a downtown cordon, some jobs and residents leave, but the outflow is kept in check by switches from car to public transit. Downtown wages increase and rents rise too as producers substitute floor space for labor. Some richer consumers avoid the toll by taking up downtown residence rather than by switching to transit or to a job outside the downtown. Floor space density per land area inside the cordon rises by the demolition of low-density houses and the construction of higher density apartment and commercial buildings. Higher production outside the downtown exceeds downtown output losses and the total real and nominal gross product rises.

A \$14 toll per crossing maximizes welfare, achieving 65% of the gains from Pigouvian pricing on all major roads. About 16% of the downtown cordon's welfare gains are from toll revenue, 34% from annualized real-estate value gains, and 50% from consumer utility. Bigger cordons around the City of Chicago and around the city and its inner suburbs are also studied. In the case of the last cordon, encircling the city and its inner suburbs, toll avoidance causes jobs, residences, and real output to increase within the cordon. The results illuminate issues that were raised in the 1990s about whether road pricing to internalize congestion would centralize economic activity in US central cities or whether it would cause activity to decentralize to the suburbs. Our findings show that both patterns can be observed, depending in a major way on the location of the cordon and the level of the toll. In the case of downtown-London-type and the Stockholm-type cordons which encircled the CBD or the City of Chicago, respectively, there was a net outflow of economic activity both productive and residential, from the cordoned area to the suburbs, while in the case of the hypothetical cordon that encircled both the city and its inner suburbs, activity on the net concentrated within the cordon area.

Figure 5 shows the components of welfare as functions of the cordon level for the case of the CBD cordon. Total welfare increases sharply with the level of tolling, reaching a peak around a toll of \$14 per crossing. One of the encouraging things seen in this figure is that a wide range of tolls (from \$10 to \$18) around the optimum toll can capture the bulk

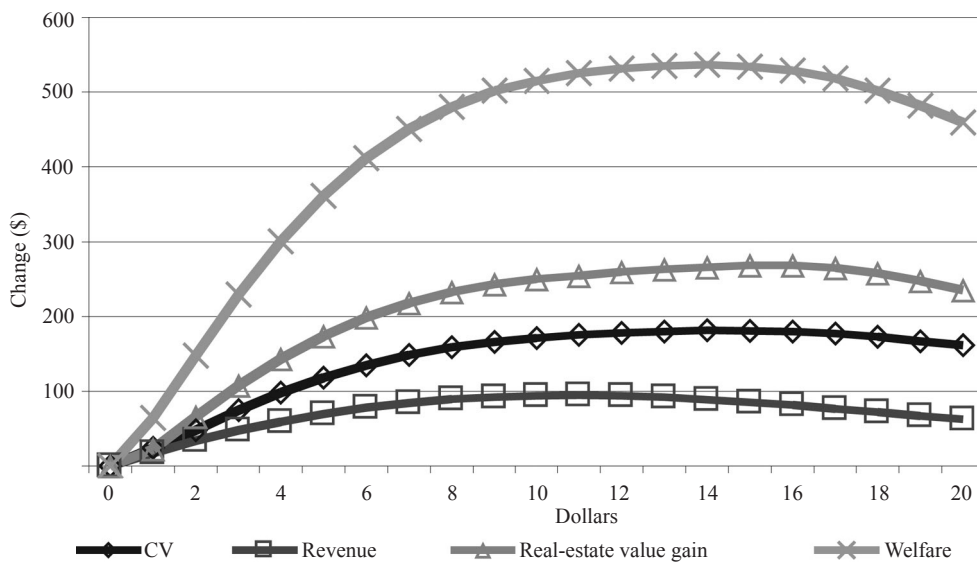


Figure 5. Annual per capita welfare components under the CBD cordon (Anas and Hiramatsu, 2013). CV is the compensating variation as a measure of benefit received per consumer.

of the benefits, so the policy is highly beneficial. However, the optimal toll or the highly beneficial range cannot be found using a simple formula and has to be estimated with a CGE model like RELU-TRAN.

5 Congestion tolling versus the gasoline tax

In Anas (2013) a study sponsored by the Lincoln Institute of Land Policy, the impacts of anticongestion policy on urban sprawl, fuel consumption, and CO₂ emission were analyzed using again the RELU-TRAN version calibrated to the Chicago MSA circa 2000. We model Pigouvian tolling of traffic congestion on all roads or only on major roads, versus (in each case) a revenue-neutral fuel tax per gallon of gasoline. The important difference between the two taxes is that consumers cannot avoid the gasoline tax by moving to less congested areas since the gasoline tax is much more strongly correlated with travel distance, whereas the congestion toll is paid only if the travel is congested and it is higher the more the congestion.

It was found that Pigouvian congestion tolls can both centralize and decentralize the location of jobs and residences, but that fuel taxes much more strongly centralize the location of jobs and residences. The reason is that, under Pigouvian congestion tolling, some jobs and residences minimize the impact of such tolling by relocating to the suburbs which are on average less congested than more central locations.

Under Pigouvian congestion tolling of only the major roads, jobs were found to be weakly centralized in the CBD while a much stronger movement of jobs to the outer suburbs was also observed. Average wages, rents, and real-estate prices increase under all of these policies. Urban sprawl, measured as the depletion of undeveloped land, can increase under all policies, but there are significant differences among the policies. A conclusion that emerges from these results is that the road road-pricing policies, and especially the fuel tax, can indeed help significantly concentrate jobs and population in the central city and toward the downtown and thus may help somewhat central city revitalization.

6 The Greater Paris application

In the case of Paris (Anas, 2012), the objective was to use the model to evaluate the effects of investments in public transit planned for 2025 and 2035. These investments are aimed at connecting the ten inner-suburban growth poles surrounding Paris to each other and to Paris. Unlike the traditional radially oriented public transit projects, these rail and subway investments are meant to make easier the peripheral circulation around the City of Paris. The City of Paris itself is essentially locked out of future redevelopment. As it is now, there is very little empty land inside Paris and increasing the city's capacity to accommodate more jobs and residences would come at the expense of much congestion and taller buildings that would ruin the skyline. There is, however, a vacancy rate of about 8% which means that some more job and population growth can be accommodated without increasing aggregate floor space. These assumptions were built into the model.

The expectations from the planned public transit investments are that sprawl will be contained and that public transit ridership will increase and, more importantly, that as much as possible of the new job growth will concentrate in the ten growth poles surrounding Paris. The results supported these expectations and are illustrated in figures 6–8. The City of Paris is the white area in the middle.

The growth in total population and jobs from 2005 to 2035 increases road congestion and as a result of this and also because of an assumption of higher gasoline prices, the locations in the poles and closer to public transit attract the biggest part of the new growth in jobs and a smaller part of the growth in population. Furthermore, the improved accessibility provided by the new projects additionally concentrates jobs in the growth poles but concentrates residences less so. Rents per square meter of floor space increase and more so in the growth poles than elsewhere. Rents also generally increase in the City of Paris (but this is not shown in figure 8). In summary, as more public transit is built near the center, the central agglomeration (Paris plus the ten poles) becomes a more attractive location and more dominant, and the Paris metropolis comes closer to resembling more a 'monocentric city'.

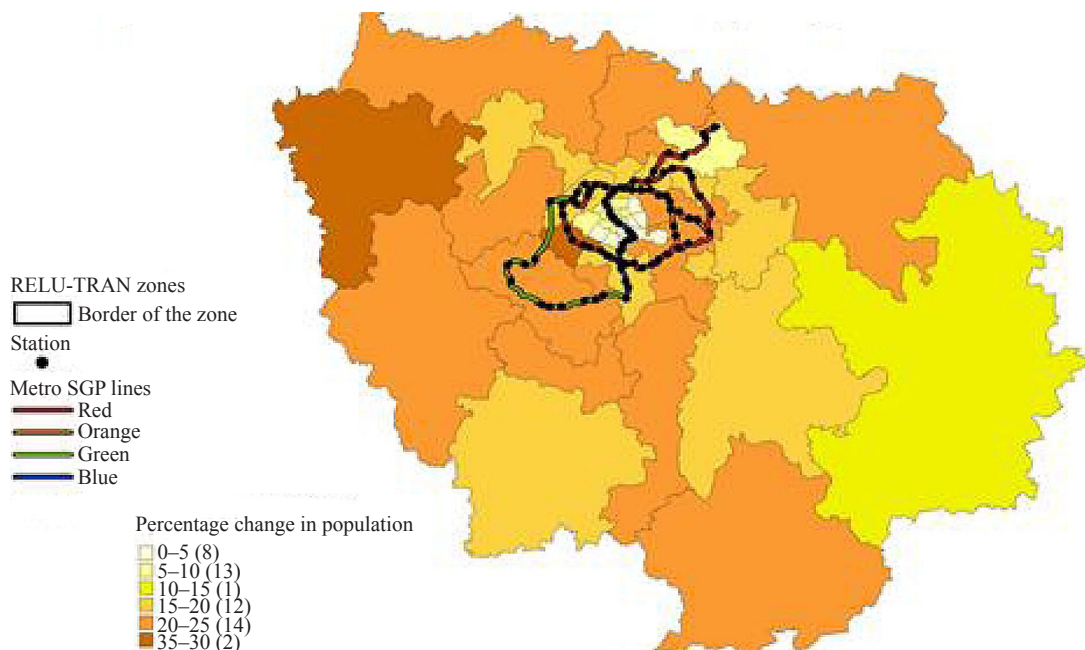


Figure 6. [In color online.] Percentage change in population by zone in the context of growth and the new projects (2005–35).

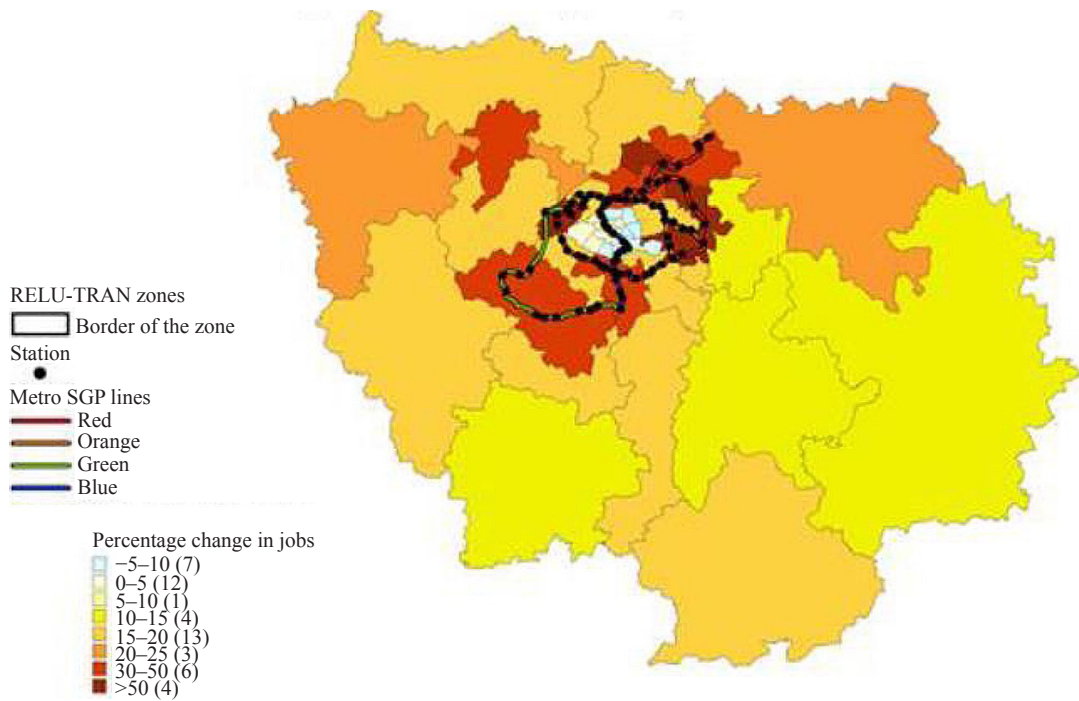


Figure 7. [In color online.] Percentage change in jobs by zone in the context of growth and the new projects (2005–35).

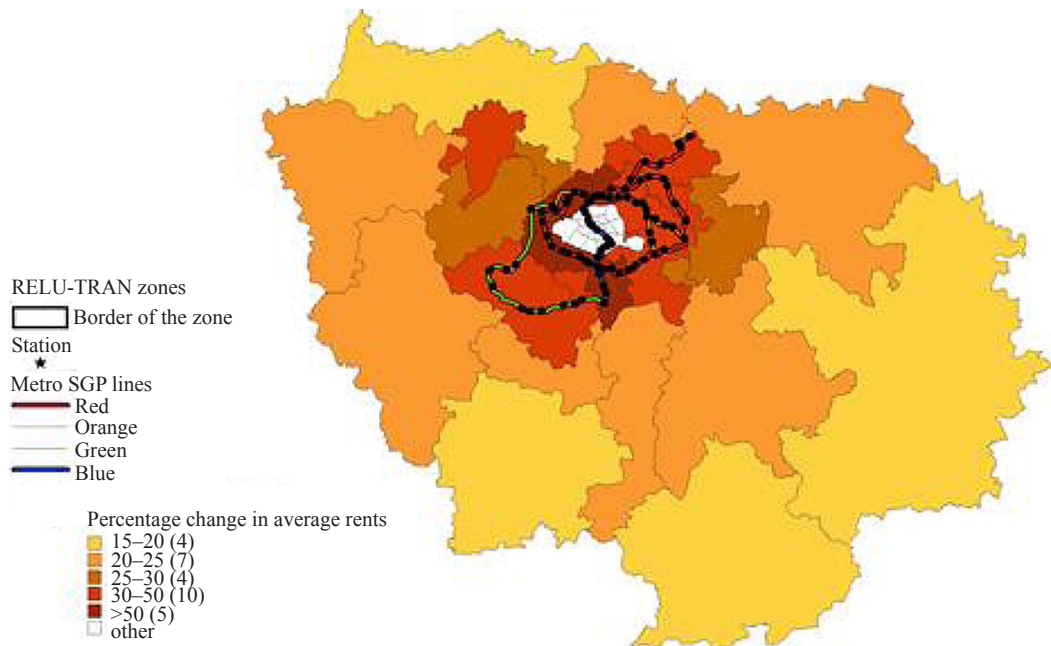


Figure 8. [In color online.] Percentage change in average housing rents by zone in the context of growth and the new projects (2005–35).

7 Extensions

In the continual development of a model such as RELU-TRAN we have a list of additional applications and methodological improvements that can be pursued. Here we will briefly discuss three that are on our agenda. These are: (i) the treatment of agglomeration economies; (ii) welfare analysis with taxation and redistribution; and (iii) dynamics.

7.1 Treatment of agglomeration economies

Agglomeration economies are cost reductions or productivity improvements that result from the spatial proximity of economic agents. A question that is frequently asked is whether RELU-TRAN treats agglomeration. The answer is that yes it does, but there is more to do.

There are three layers of agglomeration. The first is that economic agents will locate in proximity to one another because they will seek to locate around natural or manmade inhomogeneities in space. In this case a higher productivity may result because the spatial inhomogeneity imparts a benefit to each economic agent even though the agents may not directly benefit from being proximal to one another. An example is exporting firms locating near a natural or a manmade harbor facility. RELU-TRAN has two types of spatial inhomogeneity. One arises from the presence of transport networks which give rise to nodes of accessibility. A second arises from the fact that building space of one or another type is historically concentrated in various locations, providing a reason why residential or business activity may also concentrate there.

The second layer of agglomeration arises from the fact that various economic agents engage in market interactions with one another. In RELU-TRAN various such interactions exist and are endogenous to the model. For example, consumer/workers locate close to firms which employ them, and customers locate in areas with good accessibility with respect to shops. Conversely, the firms need to be close to their workers and their customers. This interdependence between firms and consumers creates concentrations in space. Similarly, firms exchange inputs with one another; hence such firms must locate near others with which they exchange those inputs and this in turn gives rise to spatial concentrations as well.

The third layer of agglomeration, not currently treated in RELU-TRAN, would arise from nonmarket interactions and externalities between firms and consumers, among consumer types, and between firms. Anas and Kim (1996) provided a nonempirical spatial CGE model that provided a framework for treating agglomerations arising from nonmarket interactions. As was well demonstrated in that paper, multiple equilibria often arise from nonmarket interactions that are sufficiently strong. That is, under the same parameter values there will be more than one equilibrium configuration of employment centers or any type of market concentration. It is on the agenda to add such interactions to RELU-TRAN and to explore whether the third layer of agglomeration is empirically significant on top of the first and second.

7.2 Welfare analysis with taxation and redistribution

The presence of taxes affects the performance in both equity and efficiency of the urban economy. In the applications discussed in the earlier sections, sales and property taxes were turned off. In the application of the model to congestion pricing, we imposed congestion tolls, cordon tolls, or gasoline taxes in an environment free of other taxes. In addition, the revenues from these taxes were counted as part of the benefit of the anticongestion policies. We plan to do more realistic welfare analyses by redistributing the tax revenues but not necessarily in a first-best manner. It is in our agenda to do more thorough welfare analysis where the surplus or deficit from all taxes some of which are distortive and others such as Pigouvian taxes which are efficiency improving are redistributed optimally in either a first-best or a lower-best sense.

7.3 Dynamics

RELU-TRAN is a dynamic model. However, in the applications summarized here the dynamics occur in a stationary environment or in a long-run equilibrium. In the model the sources of the dynamics are limited to real estate development (Anas and Arnott, 1991; 1997). The developers build or demolish floor space under perfect foresight in the stationary state. In the application of section 2 the model is not stationary, but developers are treated

as being myopic in their expectations of the future. In the future, we intend to treat in more detail dynamics in the nonstationary state under both myopic foresight and perfect foresight. Also, the addition of nonmyopic behavior by consumers by the modeling, for example, of overlapping generations would be a worthwhile extension that is farther away on the horizon.

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