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WHY ARE URBAN TRAVEL TIMES SO STABLE?*

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ABSTRACT. Personal travel time in U.S. urban areas has been stable, clashing with the assertion that urban sprawl greatly lengthens travel. Average commute time rises by 7.7 percent with each cross-sectional doubling of Metropolitan Statistical Area (MSA) jobs. Using the RELU-TRAN structural computable general equilibrium model of the Chicago MSA, we simulate the equilibrium effects of a 24 percent population increase projected from 2000 to 2030 by the Chicago Metropolitan Agency for Planning. If no new road capacity is added, then congestion per mile increases. Although the urbanized land area increases by 19 percent, indicating sprawl, the vehicle miles traveled (VMT) per car-trip decreases by 1.31 percent and the VMT per car-trip to work decreases by 2.78 percent. Car travel time increases by only 6.25 percent and commuting time by only 4.54 percent, from 30.3 minutes in 2000 to 31.7 in 2030 or 3.4 seconds per year. We further explore the effects of new road capacity, gasoline prices, public transit speed, fuel economy gains, limits on suburban construction, and importantly, the cross-elasticity of public transit use with respect to car times. The availability of public transportation, economizing on nonwork travel, and land use adjustments that increase job-residence proximity keep times stable.

1. INTRODUCTION

Using a computable general equilibrium (CGE) model, which is empirically calibrated, we show that average time for work travel or for all purposes would remain quite stable as the Chicago metropolitan area grew in population and spread out in land area from 2000 to 2030. To set the stage for the CGE analysis, we will first empirically demonstrate in this Introduction the remarkable stability of travel time across metropolitan areas of different sizes. We will then review how the stability of travel time has been grounded in empirical observations by European and American scholars from within and outside economics and how these observations clash with popular assertions. Then the paper and its results will be summarized.

A Cross-Sectional Look at Travel Time to Work in the United States

The stability of travel time is demonstrated by a log–log regression using year 2000 Census data for the 49 largest MSA/CMSAs. The regression is plotted in Figure 1.¹

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¹Source: Anas (2011).

$$\ln \left(\text{Average one-way commute time (min/day)} \right) = 1.713 + 0.108 \times \ln \left(\text{Workers} > 16 \text{ years} \right) + 0.015 \times \ln \left(\frac{\% \text{ transit ridership}}{\text{work trips}} \right).$$

The intercept and “log workers” (a measure of MSA size) are highly significant at less than 1 percent, whereas “log% transit” is significant at 10 percent. The R^2 is 64 percent. The same regression gives similar results for 1990: the slope of “log workers” is +0.095 again significant at less than 1 percent, whereas the slope of “log% transit” is +0.026 and significant at about 10 percent and the R^2 is 70 percent. New York, Chicago, and Washington, DC sit somewhat above the regression line having higher shares of the slower public transit trips, whereas Los Angeles sits much below, due to its small share of public transit and its proportionally larger highway capacity. Atlanta is a positive outlier relative to its size because it had difficulty expanding its road capacity sufficiently due to Clean Air Act regulations and built a public rail system.

From the regression, the point elasticity of travel time to work with respect to workers is about +0.1. This implies an interval elasticity such that a doubling of workers across MSAs is predicted to cause a 7.77 percent increase in commute times, on average. To see this more descriptively, we look at the observed data and the predictions from the regression: in the year 2000 workers in Louisville were just under half a million and their average one-way commute was 22.7 minutes (predicted as 22.9 by the regression). In Pittsburgh with twice the workers, the commute was 25.5 minutes (predicted as 24.7), and in Houston with twice again, 28.8 minutes (predicted as 26.6). Chicago, with twice as many workers as Houston had 30.5 minutes (predicted as 28.6) and New York with more than twice as many workers as Chicago, 34 minutes (predicted as 30.8). Actual average travel time in this sampling grew by 10.7 percent with each population doubling. Part of the reason the regression implies only a 7.77 percent increase with population doubling is because in the regression public transit share is being kept constant when MSA size (workers) is doubled.

The regression exercise is countered by the common perception, asserted well in The Sierra Club’s website and much of the popular media. This perception is that urban growth results in suburban sprawl, and in longer trips and travel times.

Sprawl spreads development out over large amounts of land; puts long distances between homes, stores, and job centers; and makes people more and more dependent on driving in their daily lives *Sprawl lengthens trips* and forces us to drive everywhere. (Sierra Club, emphasis added.)

According to what can be inferred from Burchfield et al. (2006), from 1972 to 1996, the U.S. urbanized land has sprawled perhaps at an annualized rate of 2.48 percent or 2.5 times the 0.98 percent annualized growth rate of urbanized population. How then, does a doubling of population result in only a 10 percent increase in actual and a 7.7 percent increase in predicted commuting time (keeping transit share constant)?

The incongruity of the popular perception with the apparent facts has been noted more than 20 years ago by Gordon, Richardson, and Jun (1991). They wrote as follows:

A paradox may exist in the widespread reports of congestion in spite of stable average trip durations. Perhaps average commute times are contained by the

location adjustments that households and businesses make. Perhaps there is no paradox. Location adjustments would not be made were it not for the perception of congestion. (p. 416)

We will indeed also argue that there is no paradox. As conjectured by Gordon et al., the reality of higher congestion causes a resorting of the business and residence locations and of the travel choices of consumers that preserves the stability and sustainability of average travel times. But, in the case of Chicago, the process is also aided substantially by the switching of trips to public transit, something that Gordon et al. did not emphasize. They also did not emphasize possible reductions in the lengths and frequencies of nonwork trips as a possible response to higher congestion. More recently, others have also expanded on this theme claiming that residents and workplaces might adjust to congestion in a way that keeps commuting times essentially unchanged. Kim (2008) argues this using the Puget Sound Transportation Panel Data. Sarzynski et al. (2006) do a longitudinal statistical study of the top 50 U.S. metro areas controlling prior levels of congestion and changes in the transport networks to explain subsequent commute times. Our study differs from the above empirical investigations, in that we implement a theoretically consistent and empirically estimated CGE model and explore the relationship between travel time and traffic congestion by making simulations of this model.

The Search for a Law of Constant Travel Time

In noneconomic but empirical research, Hagerstrand (1973) and Zahavi (1977) put forth *laws of constant travel time*. They claimed that daily travel time per traveler is remarkably constant across different population groups, and even independently of the mode of travel and city size and over long periods of time. Zahavi did not reconcile his astute international empirical observations with any theory. Hagerstrand, however, argued informally that the day consists of routine tasks (such as eight hours of sleep, eight hours of work, one hour of personal care) and that the residual becomes so constrained that its allocations to travel and leisure cannot much vary.

Vilhelmson (1990) argued for a biological human need to experience a stable travel time based on habit formation to justify his observations that groups of Swedes from 15 to 84 traveled an average of 79 minutes regardless of city size or mode of travel. But he found huge variation among individuals within groups (Vilhelmson, 1988). He referred to various survey data showing constant travel time over long periods of time, even centuries. He attempted to explain the time-length of a trip as a trade-off between the intrinsic utility stemming from the objective sought by making the trip and the disutility of the travel itself. In a more recent article he offered continued empirical support from the Swedish National Transportation Surveys for 1978, 1984–1985, 1994, 1995, and from the Swedish National Time Use Surveys of 1990 and 1991 (Vilhelmson, 1999).² Hupkes (1982) formulated a rudimentary explanation in which he did not claim travel time to be a constant, arguing that breakthroughs in information technology would cause shorter trips. These observations and informal theories of the *law of constant travel time* do not rely on microeconomic theory, and economists would see no intrinsic psychological law or reason for the daily average time spent in travel to be constant.³

²For my discussion of the sources in the Swedish language, I rely on the summary and discussion by Hojer and Lars-Goran Mattson (2000), and on Vilhelmson (1999), which are in English.

³Kockelman (2001) disputed the hypothesis of constant travel time using an activity analysis approach. Her claim was that making travel opportunities more accessible would reduce the total amount of travel.

The Stability of Travel Time to Work in the United States

A second line of research relies on observations of commuting time in U.S. metropolitan areas over time, but does not systematically include travel for other purposes. Gordon and Richardson (with co-authors) have documented the remarkable stability of average commute time in the United States over recent decades.⁴

Earlier observations became somewhat challenged when the 2000 Census showed an unusual jump in commute times from 1990. McGuckin and Srinivasan (2003)⁵ note that the average one-way commute rose from 21.7 minutes in 1980, to 22.4 in 1990, that is by about 4 seconds per year, but then accelerated to 25.5 in 2000, growing by about 19 seconds annually. They note, however, that the jump from 1990 to 2000 reflects some outlier commutes above two hours, not counted in the older censuses. They claimed that this discrepancy in top-coding accounted for a third of the measured 3.1-minute increase from 1990 to 2000. But, even so, it was still unclear why the average commute time increased by about 2.1 minutes or by 13 seconds per year from 1990 to 2000, a rate thrice as big as in the previous decade.

An income-driven explanation was proposed in Lee et al. (2009), and another based on demographic changes in Kirby and LeSage (2009). Using urbanized area averages from the National Household Transportation Survey, Lee et al. observed that the increase in commute times from 1990 to 2000 is associated with a 3 percent increase in average incomes. They claim that the higher incomes caused more nonwork trips during morning hours which contributed to more peak hour congestion and thus longer average commutes. Average income is insignificant in their regression analysis for 1990, but it is highly significant and its slope is 10 times bigger in their 2000 regression.⁶ Still, they showed that the change in their independent variables explained only about 12 percent of the total change in average commute times during the decade. Kirby and Le Sage (2009) offered an explanation of their own for the jump in average commute times between 1990 and 2000. They use census tract data suggesting that change in household demographics is responsible. An alternative conjecture would be that the jump is caused by new traffic bottlenecks forming during the decade as population increased while traffic capacity did not keep pace. Such a conjecture resembles the observations of traffic gridlocks by Dunphy (1997) and by Downs (2004) and is attuned with the popular view.

The Monocentric City Versus Modern Urban Economics

It is also useful to consider what theory predicts about urban growth and commute times. Unfortunately, the traditional theory relies on the monocentric city with all jobs assumed pinned in the city center. In such a setup, how much increase in average travel time would result from a doubling of the population? Suppose that each person demands a unit of land. Then, the population of a circular city of radius u is equal to its area, and $N = \pi u^2$. Ignoring congestion and assuming that travel time increases linearly with distance from the center, total travel time is $T = \int_0^u 2\pi x^2 dx = \frac{2\pi}{3} u^3$. Average travel time then is $T/N = (2/3)u$, proportional to u . Since $u = \sqrt{N/\pi}$ in this simple model, the point elasticity of average travel time with respect to population is 0.5. This is five times larger than the 0.10 point elasticity implied from the regression of Figure 1.

⁴See Gordon, Kumar, and Richardson (1989), Gordon et al. (1991), Gordon and Richardson (1996), and Lee et al. (2009).

⁵See <http://www.fhwa.dot.gov/ctpp/jtw/contents.htm> (last viewed on February 14, 2010).

⁶The 10-fold change in the slope of income may be because of colinearity between income and the number of multiworker households (they reported a 0.73 correlation coefficient in 2000).

More than 30 years ago, Hamilton (1982) made more extensive calculations (which, however, did not include congestion) and concluded that, “the monocentric model does an almost unbelievably bad job of predicting commuting behavior in samples of U.S. and Japanese cities” (p. 1036).

The monocentric model then is at best a very poor theoretical approximation of the facts on the ground. In fact, casual observation of U.S. suburbanization as documented by Mieszkowski and Mills (1993), suffices to directly refute the assumption of monocentricity:

In the 1950s, 57 percent of MSA residents and 70 percent of MSA jobs were located in central cities; in 1960, the percentages were 49 and 63; in 1970, they were 43 and 55; in 1980, they were 40 and 50; in 1990, they were about 37 and 45. The United States is approaching the time when only about one-third of the residents within an MSA will live in central cities and only about 40 percent of MSA jobs will be located there. (p. 135)

Modern urban economics is now beginning to rely on tractable models in which the locations of jobs and residences is not predetermined, jobs have economic reasons to be located accessibly with respect to their workers and customers, who in turn have economic reasons to locate in proximity to their jobs and shopping places. In a spatial equilibrium, jobs and residences are mixed everywhere within the city, although jobs may be more concentrated around the historical center than are residences. With such a model, Anas and Rhee (2006) showed by nonempirical numerical simulations, that as an urban area decentralizes from a monocentric equilibrium to a new equilibrium with dispersed jobs, commuting time to work falls as the average distance between jobs and residences decreases. They did not, however, investigate how travel time in a dispersed city would respond to urban growth. This paper employs a CGE model with a similar structure to empirically investigate how personal travel time to work and total travel time would evolve if the Chicago MSA, a large metropolis with 65 percent of 2000 jobs in the suburbs and only 14 percent in the Central Business District, would grow and sprawl to 2030.

Summary

The microeconomic structure of the RELU-TRAN CGE model and its calibration, which are used in this study, are described in the Appendix.⁷ Section 2 discusses how the model treats complex travel behavior in a general equilibrium setting, how congestion and public transit are modeled, and the manner in which jobs and population are interdependent. In Section 3, we present the results of a baseline simulation that starts from 2000 and ends in 2030. This baseline shows how the Chicago MSA would evolve under the population growth projected by the planners. In our simulations the growth is driven by all of the following: (i) real MSA wages endogenously responding to an exogenously rising national wage trend; (ii) growing demand for the region’s exports; (iii) technical progress in construction; (iv) planned highway capacity expansions; and in the context of: (v) an upward trend in the price of gasoline extrapolated from the actual increases in 2000–2010. In Section 4, we present the results of six variations around the baseline trend. These variations are: no new road capacity, a gasoline price that stays stable after 2010, improving car fuel economy, faster public transit, exclusion of multifamily and nonresidential construction from the outer suburbs, and a low cross-elasticity of public transit with respect to travel time by car. Taken together, Sections 3 and 4 demonstrate the important adjustments that consumers and businesses make in responding to the

⁷RELU-TRAN: an acronym for “Regional Economy, Land Use and Transportation Model.”

higher congestion that occurs when road capacity does not increase sufficiently, as population and jobs increase. The most important response to the higher congestion is that there is switching to public transit *at the margin* either without changing location or by relocating from the outer suburbs to the CBD, City and inner suburban locations that are all better served by public transit than are the outer suburbs. The second adjustment is the slight moving closer of residence and jobs locations, and a third one is the shortening of aggregate trip lengths by making fewer and shorter nonwork trips. The combined effect of these three adjustments is that travel time per car-trip increases very gently from 2000 to 2030, as population and land area grow much faster.

2. STRUCTURE OF THE RELU-TRAN CGE MODEL

The model structure, equation system, and solution algorithm of RELU-TRAN are described in detail in Anas and Liu (2007). Drawing from that article, the Appendix of this paper describes the model's equations and structural relationships including a new feature whereby the travel behavior of the consumer includes the choice of automobile fuel intensity and equations that calculate gasoline use (Anas and Hiramatsu, 2012).

Representation of the CHICAGO MSA in the Model

In the model, the Chicago MSA is represented by 15 zones (Figure 2a) and by an aggregation of the major and local road network (Figure 2b). The zones make five concentric "rings." Ring 1 (zone 3) is the Central Business District (CBD). Ring 2 (zones 1, 2, 4, 5) together with the CBD complete the City of Chicago, with zone 5 the O'Hare airport job subcenter. Ring 3 (zones 6–10) includes the inner ring suburbs encircling the city with the Schaumburg job subcenter in zone 6, near zone 10. Ring 4 (zones 11–14) comprises the outer ring suburbs and ring 5 (zone 15) is a single peripheral zone representing mostly the rural exurbia, including parts of Northwest Indiana and Southeastern Wisconsin. Residents of the peripheral zone 15 who commute into the first four rings are only 4.7 percent of the total commuters in the region. The model treats this peripheral zone as a spillover area. Some residents would choose to reside there and commute in, but zone 15 is not equilibrated with the rest of the zones.

Table 1 shows the distribution of developable land, floor space by building type, jobs, residents, and trips by origin, destination, and mode by ring in the base year 2000. An important conclusion from this table is that the distribution of jobs is only somewhat more centralized around the CBD than is the distribution of population. The metropolitan area in no way resembles a monocentric city in which all jobs are assumed to be in the CBD. In the Chicago MSA in the year 2000, only 14 percent of the jobs were in zone 3, which is a fairly generous definition of the CBD.

Other salient features from Table 1 are that less than 14 percent of the vacant developable land is located in the City and the inner suburbs, whereas more than 86 percent of it is in the outer suburbs. Hence, opportunities for infill development are significant but limited whereas the opportunity to sprawl outward is limited only by the time and money costs of commuting and the cost and elasticity of new construction. The model does allow the construction of higher density buildings, which can compete somewhat with sprawl in the outer suburbs as well as with infill development.

Also from Table 1 we see that about 58 percent of commutes by public transit and about 72 percent of the nonwork trips by public transit originate in the city; 81 percent of public transit commutes and 76 percent of nonwork trips by public transit terminate in the city; 44 percent of commutes by public transit terminating in the CBD. Side computations from the numbers in the table show that almost 13 percent of the commutes and 10

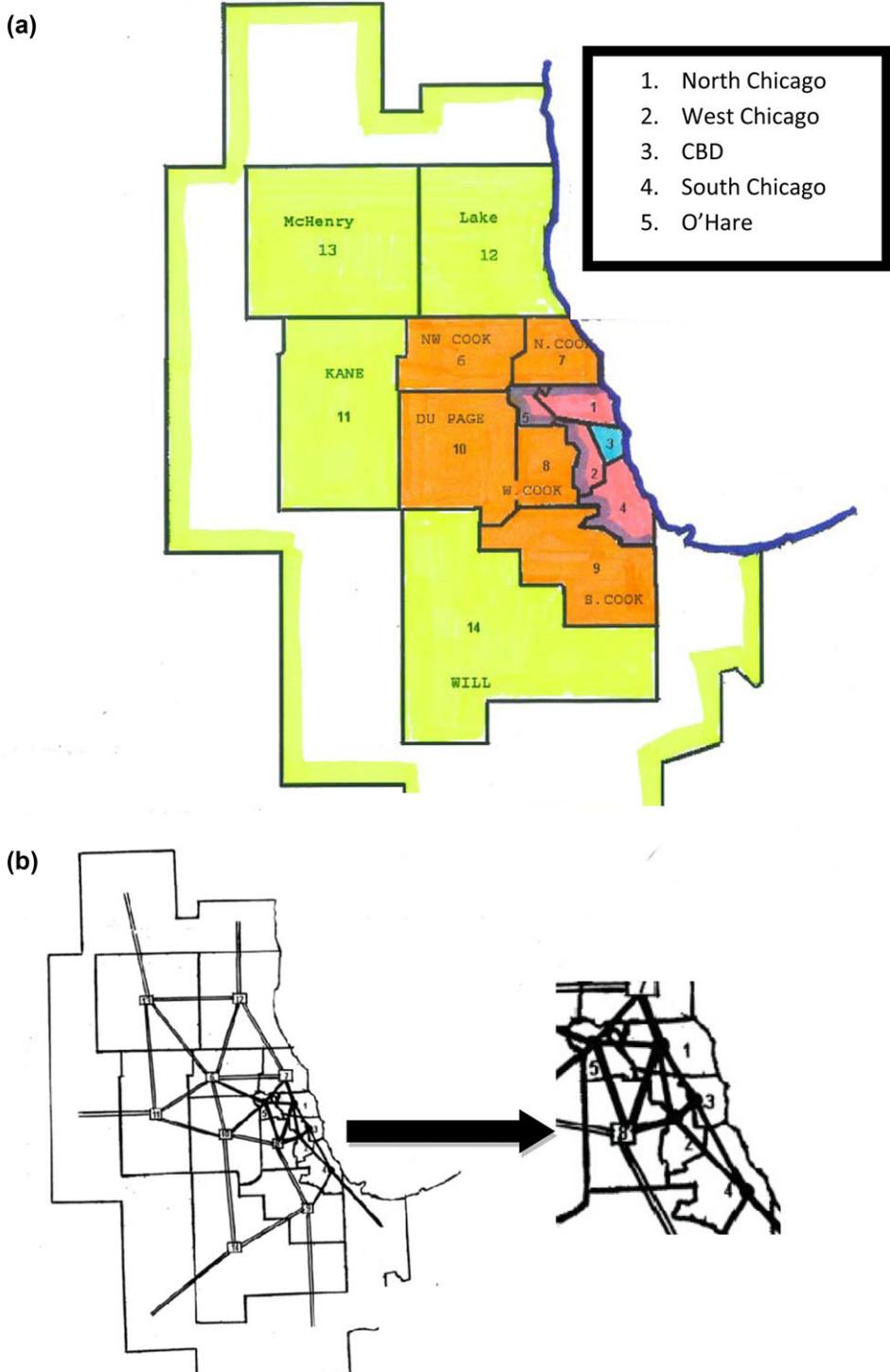


FIGURE 2: (a) RELU-TRAN Model Zones. (b) RELU-TRAN Network of Major Roads.

TABLE 1: Distribution of Land, Floor Space, Jobs, Residents and Trips (Year 2000 of the Baseline)

	MSA Total (14 Zones)	Percent Distribution (%)				
		CBD (Zone 3)	Rest of City (Zones 1,2,4,5)	Inner Suburban (Zones 6–10)	Outer Suburban (Zones 11–14)	Exurban Ring (Zone 15)
<i>Land and floor space</i>						
Undeveloped land		0.15	1.28	12.22	86.35	
Single family housing		0.06	20.70	51.57	27.68	
Multiple family housing		1.71	45.83	40.52	11.94	
Commercial buildings		3.61	34.46	50.01	11.92	
Industrial buildings		3.53	33.80	50.03	12.64	
<i>Jobs and residents</i>						
Jobs	3,745,282	14.35	20.77	45.59	19.29	
Residents	4,690,847	0.82	28.78	43.72	21.94	4.74
Employed residents	3,745,282	0.84	29.84	43.28	21.78	4.26
<i>Trips by trip origin</i>						
All commutes	3,745,282	0.85	29.85	43.28	21.78	4.26
Commutes by car	3,051,279	0.31	24.48	46.13	24.67	4.41
Commutes by transit	484,687	1.73	56.11	31.26	7.42	3.48
Commutes by other modes	209,316	6.42	47.33	29.59	12.85	3.81
All nonwork trips	6,829,013	0.98	30.87	44.79	20.08	3.28
Nonwork trips by car	5,706,355	0.27	24.43	49.07	22.71	3.52
Nonwork trips by transit	580,482	3.38	68.26	20.32	6.31	1.73
Nonwork trips by other modes	542,176	5.87	58.68	25.92	7.10	2.43
<i>Trips by trip destination</i>						
All commutes	3,745,282	14.35	20.77	45.59	19.29	
Commutes by car	3,051,279	9.45	17.42	51.06	22.07	
Commutes by transit	484,687	43.99	36.99	13.84	5.18	
Commutes by other modes	209,316	17.02	32.11	39.38	11.49	
All nonwork trips	6,829,013	2.73	28.36	47.72	21.19	
Nonwork trips by car	5,706,355	1.37	22.15	52.51	23.97	
Nonwork trips by transit	580,482	12.03	63.66	17.99	6.32	
Nonwork trips by other modes	542,176	7.13	55.83	29.13	7.91	

TABLE 2: RELU Calibration

Consumers	Income/Skill Level				
	1	2	3	4	
MRS (disposable income, commute time) (\$/hour/day)	12.48	21.36	36.62	93.88	
Elasticity of location demand with respect to commuting time	-0.615	-0.605	-0.614	-0.574	
Elasticity of housing demand to rent including both housing size and location demand	-1.949	-1.756	-1.568	-1.378	
Elasticity of labor supplied to city with respect to wages in city	+2.818	+2.171	+1.698	+1.212	
Elasticity of labor supplied to suburbs with respect to sub. wages	+1.597	+1.345	+0.967	+0.614	
	Building Type				
Developers	Single Family	Multifamily	Commercial	Industrial	
Elasticity of floor space supply with respect to rent (Short-run)	+0.099	+0.230	+0.268	+0.138	
Elasticity of construction flow with respect to floor price (Long-run)	City	+0.033	+0.056	+0.261	+0.040
	Suburbs	+0.263	+3.404	+2.262	+0.393

Source: Anas and Hiramatsu (2012).

percent of all trips are by public transit. When compared to the 4.9 percent national share of public transit commutes in the year 2000 Census, the 13 percent share reflects the relative importance of public transit in Chicago.

Table 2 shows the key elasticity and other measures of the calibrated RELU-TRAN. How the model's parameters were calibrated by combining different data sources and the goodness of fit measures are explained in detail in Anas and Hiramatsu (2012).

Treatment of Congestion

It is important to understand how traffic congestion is treated in the model. Only road congestion is treated whereas transit travel times are given exogenously and remain uncongested by assumption.⁸ Intrazonal car-trips, those originating and terminating within the same zone, utilize a congestible *local road*, an aggregation of the underlying streets and roads in the zone. Interzonal trips choose a path over the road-links, which are an aggregation of *major roads and highways* (Figure 2b), and use the intrazonal local roads

⁸The assumption of uncongested public transit is approximately valid for rail, but buses travel on roads and therefore share congestion with cars. We are trying to rectify this feature in the applications of the model to Los Angeles and Paris.

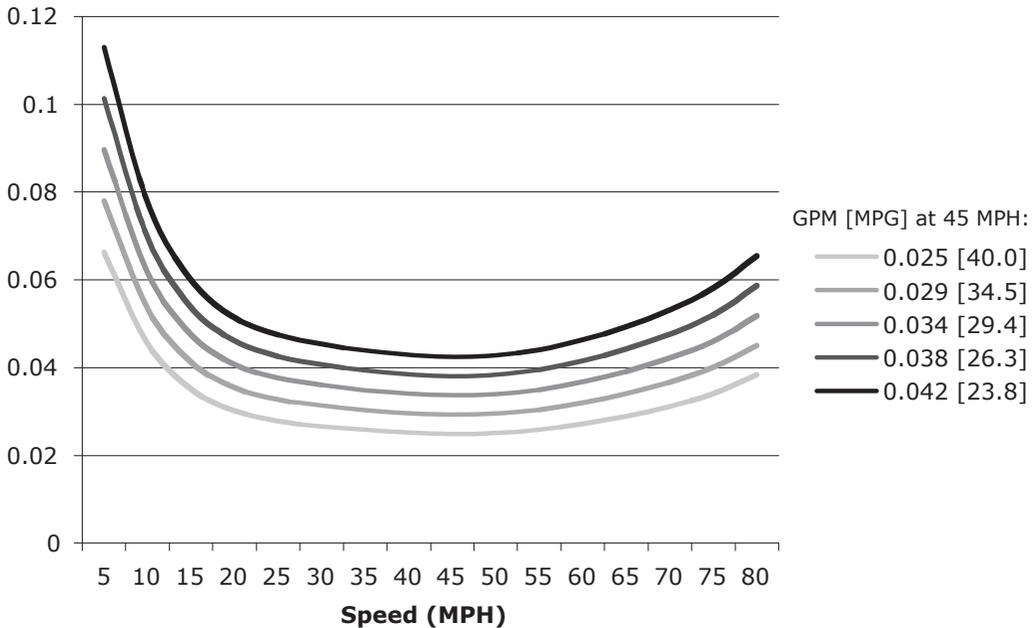


FIGURE 3: Fuel Intensity and Speed for the Five Car Types of RELU-TRAN.

for access to and egress from the major roads. Each interzonal link has a capacity used to calculate equilibrium flow congestion, which determines equilibrium monetary and time costs on the link. The intrazonal local roads which, as already noted, are also congestible, carry the intrazonal traffic and, as noted, the access and egress traffic. The effect of congestion on fuel consumption and hence on the monetary cost of road travel is also treated in the model. As shown in Figure 3, the model allows consumers to choose among five abstract car-types distinguished by their technological fuel intensity (TFI). These correspond to the five curves in the figure, the lower is the curve the higher is the fuel economy at any given speed. The curves are U-shaped and, hence, fuel consumption per mile increases at low speeds and again at very high speeds.⁹ Time of day considerations in traffic flow and congestion are ignored in the model.

Interdependence of Job and Residence Locations

From the microeconomics of the model, the location of jobs influences where residences are located and the location of residences in turn influences where jobs locate. Both processes are constrained by two types of spatial in-homogeneities: the initial distribution of the stock of buildings, and the existing nodes and structure of the transportation networks. The two processes of job and residence location are locked in a feedback loop that is mediated by many factors, most important among them being the level of congestion, the cross-elasticity of public transit ridership to car travel times, the marginal rate of substitution (MRS) between travel time and disposable income, the marginal utility and productivity of floor space, the elasticity of labor demand and supply and the elasticity of construction with respect to floor prices (see Table 2 for the elasticity measures in the

⁹Technical details about the modeling of congestion and the fuel-speed relationships are in the Appendix. Figure 4 is adapted from Davis and Diegel (2004) by fitting polynomials to their data.

model and Anas and Hiramatsu (2012) for the details of the model's calibration). The role of the mode choice elasticity is discussed in more detail later in this section.

The location of residences is determined in part by the proximity to jobs and also by the trip-based accessibility to shops (i.e., to retail production), and it is constrained by the availability of the housing stock in the short run, but less so in the long run when more housing stock is created by new construction. As shown in Table 2, the MRS between travel time and annual disposable income increases with income. Thus higher income consumers value proximity to their jobs and to shopping more highly than do lower income consumers. Richer consumers also have a less price-elastic demand for housing floor space. Given that floor space is a normal good, suburban location is desirable because houses in suburbs are larger. Also suburban public goods are of a higher quality, which means that higher income consumers will be more interested in residing in the suburbs and more resilient to rent increases. These facts, which are included in the model, suggest that as a metropolitan area grows in population more residential suburbanization will occur because that is where most of the vacant land is found and that is where the most new housing will be built. The average commuting and shopping distances and the monetary and time costs of travel would increase as consumers decentralized into new housing constructed in the suburbs where vacant land is available, if firms could not follow. The suburban locations would become more congested as they became more developed.

How would firms respond to residential suburbanization? One response would be to stay put but respond to the higher congestion and travel costs by paying higher wages to attract an adequate labor supply to current production locations. An alternative response would be for the firms to move closer to their workers and retail customers. As residential development piles up in the suburbs, existing or new first mover firms make temporary positive economic profits in the suburbs. These profits are dissipated by more firms and jobs becoming concentrated in the suburbs. The process repeats in a positive feedback loop by more workers and customers finding the suburbs more attractive to reside in, as more jobs and shops locate there. The higher the level of congestion, the stronger is the positive feedback as both consumers and firms strive to overcome the congestion by improving proximity to one another.

The positive feedback loop between residence location and job location is slowed as the rents of suburban floor spaces rise, which restrains the demand for additional new construction. But the higher rents also cause floor prices to rise relative to land prices, which cause developers to launch more construction. The strength of this real estate development response depends on the elasticity of new construction with respect to the price of floor space. At one extreme, pretend that this construction elasticity is zero. Nothing would be constructed. Firms and consumers could only reshuffle their locations in the existing building stock. With population growth, room would be made for newcomers in the intensive margin by the higher rents reducing the allocation of existing floor space per consumer and per job and by a reduction in vacancies. There would be no additional land area sprawl, since there is no new construction, but existing floor space would rise in price and so would traffic congestion as long as road capacity remained constant or increased little. At the other extreme, suppose that construction was very elastic to floor prices. This would make construction respond fast to the higher demands from consumers and firms, there would be more suburban sprawl and rents and floor prices would increase less.

What is the general equilibrium effect of the positive feedback loop on average travel times? On the one hand, with road capacity unchanged, the piling up of more residences and jobs in the suburbs will tend to lower speed, increasing average traffic congestion per mile of road raising monetary and time costs of travel per mile (recall Figure 3). On the

other hand, as the cost of travel per mile increases, firms and residences will respond by locating in closer proximity to each other to economize. The rising congestion per mile is a marginal effect that would cause longer travel times per mile. Distance shortening is another marginal effect that works in the opposite direction. The outcome on average car travel times depends on the tug-of-war between these two marginal effects.

Mode Choice Elasticity and Public Transit

As already mentioned, an important margin in the case of Chicago is the availability of public transit. Key is the cross-elasticity of the demand for public transit with respect to the travel time by car, since population growth would increase congestion, hence travel time by car would increase which, in turn, would increase public transit ridership via the cross-elasticity. In RELU-TRAN, a trinomial logit model is used to model mode choice, where (ignoring here the variation by zone) P_{CAR} , P_{PT} , P_{O} are the aggregate market shares of the three modes (car, public transit, and “other”), respectively. From such a model, the elasticity of the demand for mode m (denoted by η_m) with respect to its own travel time is given by $\eta_m = \theta(1 - P_m)T_m < 0$, where $\theta < 0$ is the coefficient of travel time and T_m the travel time by mode m . The cross-elasticity of the demand for mode m with respect to the travel time of mode n is $\eta_{mn} = -\theta P_n T_n > 0$.

In the model’s calibration, the own travel time elasticity of the demand for the modes (considering all trips both for work and nonwork) from the trinomial logit model of mode choice is -0.73 for drivers, -1.90 for public transit, and -0.64 for the other mode (mostly walking and bicycling). The aggregate mode shares using all model trips are 83 percent car, 10 percent public transit, and 7 percent other modes. Weighted by these mode choice probabilities over the car, public transit, and other modes, the average mode choice elasticity over the three modes is -0.84 . This number agrees with the magnitude mentioned in the textbook by Small and Verhoef (2007) who refer to only one source for time and cost elasticities of travel demand: “. . . time- and cost-elasticities are measured as -0.8 and -0.5 for Boston and Louisville, Kentucky (Chan and Ou, 1978, p. 43)” (Small and Verhoef, 2007, p. 11).

In particular, the cross-elasticity of the demand for public transit with respect to travel time by car $\eta_{\text{PT,CAR}} = -\theta P_{\text{CAR}} T_{\text{CAR}}$ would *ceteris paribus* be higher in cities with a bigger car market share and longer car travel times. In the logit model, the ratio of the cross-elasticity of public transit demand with respect to the travel time by car to the own-elasticity of driving demand with respect to the travel time by car is simply $-\frac{P_{\text{CAR}}}{1 - P_{\text{CAR}}}$. In our case, this is $-\frac{0.83}{0.17} = -4.88$. Hence, our cross-elasticity is $(-0.73)(-4.88) = +3.56$. This means that ignoring other market adjustments, if congestion were to raise car travel times by 1 percent, the use of public transit would increase by about 3.56 percent. In our case, the 1 percent increase in T_a would cause P_{PT} to increase from 10 to 10.356 percent. Correspondingly, the 3.56 percent increase in public transit share is a 0.429 percent decrease in car-trips.

However, as we shall see and as was explained above, adjustments in the other markets and changes in location play a crucial role to moderate the effect of switching to public transit. One obvious question is the extent to which some consumers would locate differently so that they can utilize public transit (or continue to drive) to blunt the effect of the higher congestion on them. Consumers who respond in this way can shorten their travel times by shortening their travel distances since they locate centrally where jobs and nonwork opportunities are more densely available. Alternatively, jobs could move to the suburbs to shorten travel times. Meanwhile, other consumers who switch to public transit to avoid the monetary cost of driving without relocating job or residence could, on average, lengthen their travel times because public transit is the slower of the two modes of travel.

TABLE 3: Changes from 2000 in Exogenous Variables Driving Growth

Exogenous drivers of Urban Growth	Percent Change by Decade from 2000 Baseline			Annualized Compounded Rate 2000–2030 (% per year)
	2000– 2010	2000– 2020	2000– 2030	
Population and jobs ^a	+7.4	+15.4	+24.0	+0.7%
Net export demand	+10.3	+21.4	+33.6	+1.0%
Real national wage	+10.5	+22.0	+34.8	+1.0%
Real rent on undeveloped land	−9.6%	−18.2%	−26.0%	−1.0%
Real productivity gain in construction	+16.3	+35.3	+57.4	+1.5%
Real gasoline price	+28.1	+71.9	+131.3	+2.83%

^aAdapted from population projections of CMAP. Includes working and nonworking adults.

The effect of public transit travel times on average travel times by all modes is therefore ambiguous, but clearly switching to public transit can directly and significantly keep in check road congestion and travel times. In Section 4, we will examine the sensitivity of our simulation results to the mode choice elasticity. We will do so by juxtaposing the high elasticity of Chan and Ou (1978) against the more recent estimates from the literature, which are about 10 times smaller.

3. URBAN SPRAWL, CONGESTION, VMT, AND TRAVEL TIME IN A BASELINE SIMULATION: CHICAGO 2000–2030

To use a CGE model wisely, one must input reasonable values for the trends in the exogenous variables in order to get reasonable trends in the endogenous variables. Although a great deal of uncertainty exists about how a particular MSA might develop in the future, the common expectation for most U.S. MSAs is that in the period of 2000–2030 they will experience more sprawl and suburban development while population, jobs, incomes, and aggregate travel continue to grow. We set up a trend line growth scenario for the time span from 2000 to 2030 for our baseline simulation, which reflects this common expectation. The growth in this baseline is driven in large part by assumed time paths for seven factors, which are exogenous to the model. Of course there is considerable uncertainty around these assumed trends. Hence in the next section, we will report on sensitivity analyses to see how variations around the baseline trend affect the stability of travel time and why. How the exogenous factors trend over time in our baseline scenario is documented in Table 3. We now provide a brief discussion for the rationale supporting our assumptions about these exogenous trends.

- (a) *Population and job growth*: The total MSA adult residents increase at an annual rate of +0.7 percent. The number of employed adult residents also grows at the same exogenous rate and therefore so does the number of work trips since the model assumes that each worker goes to work once daily. These growth paths were taken from those of CMAP¹⁰ and amount to an MSA size that is about 24 percent larger in population and jobs in 2030. The a priori expectation is that land area will expand to accommodate most of the new population and jobs. An obvious reason for this is that only a bit more than 12 percent of the undeveloped land in the MSA is located in the

¹⁰CMAP: Chicago Metropolitan Agency for Planning.

TABLE 4: Projected Road Capacity Additions to 2030 by Area in the Baseline

	Expressway Lane Miles in 2000	Projected Percent Expansion Decade to Decade and Cumulative			
		2000– 2010	2010– 2020	2020– 2030	Cumulative
CBD	38	0	0	0	
Rest of city	640	0	+2.20	0	+2.20
Suburban cook	964	+10.88	+5.05	0	+16.48
Du Page	412	+1.94	+20.20	0	+22.53
Lake	207	+19.30	+23.88	0	+44.11
Kane	176	0	+13.60	+26.30	+43.48
McHenry	50	+10.0	0	0	+10.00
Will	320	+21.25	+40.98	+1.09	+72.80
Total expressway miles	2,823	+10.61	+12.75	+2.58	+20.20
Total other road miles	23,683	+1.79	+0.61	0	+2.41

Source: Derived from CMAP 2030 plan and 1997 conformity analysis.

inner suburbs, whereas 86 percent is in the outer suburbs (Table 1). To accommodate a great deal of the growth of population and jobs in the city or the inner suburbs would require considerable development of buildings at higher densities. Land is cheaper in the outer suburbs and consumer preferences for larger housing sizes are more easily met with outward expansion. The 24 percent exogenous growth in population and jobs from 2000 to 2030 causes *inter alia* a 19 percent expansion of the land area that was already urbanized in the year 2000, and a 14 percent depletion in the MSAs land (in the 14 zones) that was not urbanized in 2000.

- (b) *Price of gasoline*: Real gasoline prices are assumed to increase at a high 2.83 percent annual real rate. The assumption reflects popular beliefs that fossil fuels will become scarcer in the future. However, this is hardly certain. Hence, in the next section we will present an alternative scenario in which the price of gasoline rises at the 2.83 percent rate from 2000 to 2010 (as it actually did) and is assumed to stay flat after 2010.
- (c) *Cost of labor*: Real national wages are assumed to rise at a 1 percent annual rate. In the model, firms use labor that commutes from zones within the MSA to the zone of the model in which the firm produces and wages in each of the model zones are determined by the intra-MSA labor market equilibrium for four skill classes. However, firms in the model can also substitute labor in regions beyond the MSA to enhance local production. Hence, as national wages grow exogenously, the locally substitutable labor's wages that are endogenous also grow despite the increase in the labor supply caused by the population growth. If this were not true, CMAP's population and job growth assumptions could not be sustained, because the increase in population would increase labor supply and cause MSA wages to fall, other things constant.
- (d) *Demand for exports from the MSA*: The rest of the world's exogenous net demand for the MSA's exports is assumed to grow at 1 percent annually, faster than the 0.7 percent growth in the MSA's population and jobs. This growth in exports supports a rising trend in the MSA's endogenous output and factor prices. The model assumes that each zone's output can be exported to the rest of the world directly from that zone.

- (e) *Rent on undeveloped land:* The undeveloped land in the outer suburbs of the MSA is utilized mostly in farming but is available for conversion to urban buildings. In addition, there are smaller amounts of undeveloped urban land in the city and the inner suburbs, even some in the CBD. The peripheral nonurban land's rent is exogenous to the model (a common assumption in urban economics) but the market price of such land is endogenously determined because the model treats the option value of future development. We assume that the rental value of agricultural land decreases in real terms at about 1 percent per year. This reflects rising productivity in U.S. agriculture as more food can be produced over time using less land. The direct effect of lower rents on undeveloped land is to induce sprawl and lower suburban population and job density.
- (f) *Construction costs:* The model's factor-neutral trend in the productivity of construction is +1.5 percent per annum. The direct effect of this technological progress is that the endogenous price of floor space remains affordable, which sustains suburban building construction and more sprawl.
- (g) *Highway capacity:* Additions to roads projected by the region's planners (CMAP) are shown in Table 4. The bulk of these additions are expressways slated for the outer suburbs. The direct effect of the capacity additions is to keep congestion from rising too rapidly, which encourages more long distance driving and a higher rate of location in the outer suburbs.

Results of the baseline simulation by decade are shown in the two-panel Figures 4 to 6. Along the horizontal axis, the zones (which were shown in Figure 2a) are arranged by their zone numbers, where zones 1–5 are the city (with zone 3 the CBD), zones 6–10 the inner suburbs, 11–14 the outer suburbs, and 15 the peripheral zone. Zone numbers increase roughly with distance from the center. Panel a of each figure graphs the percent change from year 2000 and panel b the change in quantity units from 2000 by zone.

Figures 4 and 5 are the growth in jobs and in employed residents by zone. As expected, jobs and employed residents decentralize over time: percent growth is generally higher towards the periphery and lower near the center. Percent job growth is higher in the CBD (zone 3), in Du Page County (zone 10), an inner suburb but near Schaumburg in northwestern Cook County (in zone 6), a historically fast growing subcenter; and in Will County (zone 14) an outer suburb that is currently largely agricultural. Employed residents also decentralize with high percentage growth occurring in the exurban area (zone 15) and in the outer suburbs, but the CBD is also a rapid residential grower though from a very small base (in the year 2000 it had only 0.82 percent of the MSA's residents; see Table 1).

From 2000 to 2030, the MSA's stock of year 2000 undeveloped land in the 14 zones decreases by a total of 14 percent and the initial stock of developed land increases by 19 percent. From Table 1, the core of the region comprised of the City of Chicago and the inner suburbs contained less than 14 percent of the year 2000 undeveloped land stock, the outer suburban counties containing more than 86 percent (mostly farmed land). According to Figure 6, significant parts of the core's undeveloped land would become infill development by 2030. But the bulk of new land development goes to the outer suburbs causing more land area sprawl. Because the outer suburban areas are so large in area, the large quantities of development represent relatively smaller percentages of the undeveloped land available in 2000.

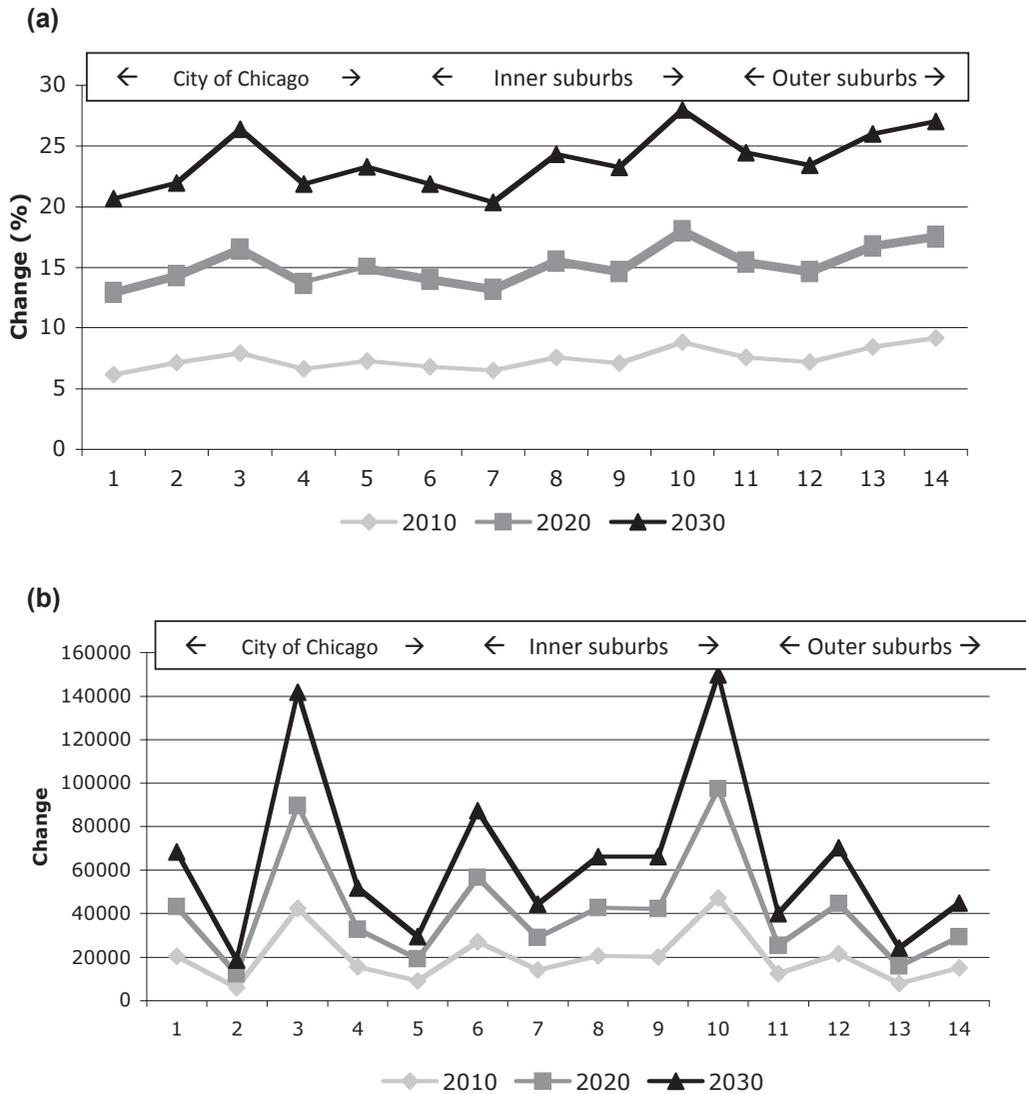


FIGURE 4: (a) Percent Growth in Jobs from 2000. (b) Growth in Jobs from 2000.

In order to understand the outer suburban sprawl in more concrete terms, we can focus, as an example, on McHenry County (zone 13 and home to famous Woodstock, Illinois), which according to Figure 6b would add the largest amount of land to development between 2000 and 2030 in the baseline simulation. The total land area of this zone (excluding water) is about 603 square miles and 63 square miles are exogenously treated by the model as inaccessible to the markets, hence undevelopable. Of the remaining 540 square miles, 80 percent or 432 square miles were undeveloped in the year 2000 being utilized primarily in agriculture. The remaining 108 square miles were developed in some urban use. According to Figure 6b, 53 square miles of the 432 square miles of undeveloped land in McHenry would become built on by 2030, which implies a rate of 1.76 square miles per year on average. That is, a bit over 12.27 percent of the undeveloped but developable land would become suburbanized over the 30-year period. In 2030, the land in McHenry would

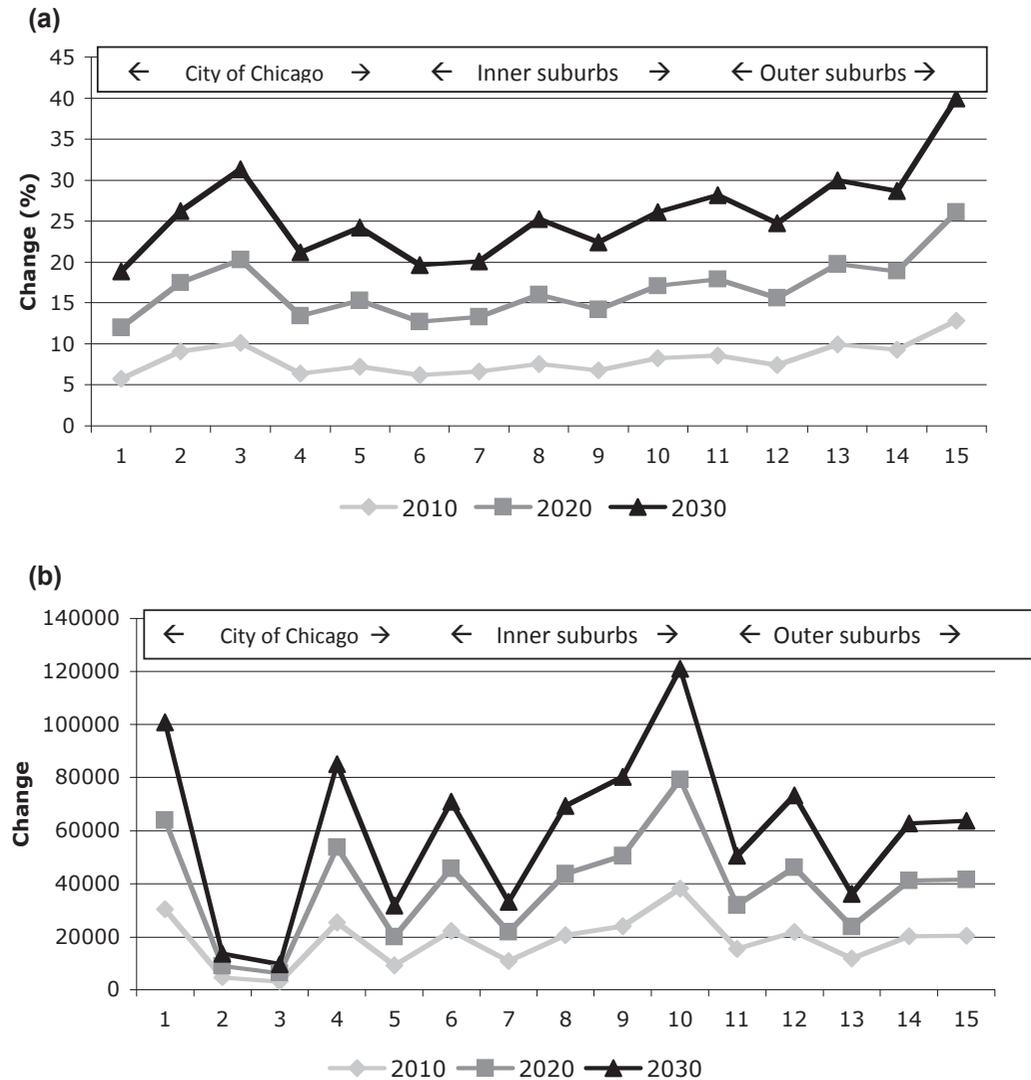


FIGURE 5: (a) Percent Growth in Employed Residents from 2000. (b) Growth in Employed Residents from 2000.

still be 70 percent undeveloped (compared to 80 percent in 2000). By the development out to 2030, McHenry would be adding—according to the baseline simulation—about 80,000 adult residents about half of them employed, and about 25,000 locally located jobs.¹¹

Returning to the region as a whole, it is also instructive to consider the growth in floor spaces by type of building. The single family and multiple family aggregate floor spaces grow a bit slower than population. Because of this, floor space per adult resident decreases on average by about 5 percent over the three decades. The commercial and industrial floor space stock also increases less rapidly than population, the average floor

¹¹According to the U.S. Census Quick facts, McHenry’s population grew by 18.7 percent from 2000 to 2010. For the same period the model predicts a 10 percent growth (Figure 5a).

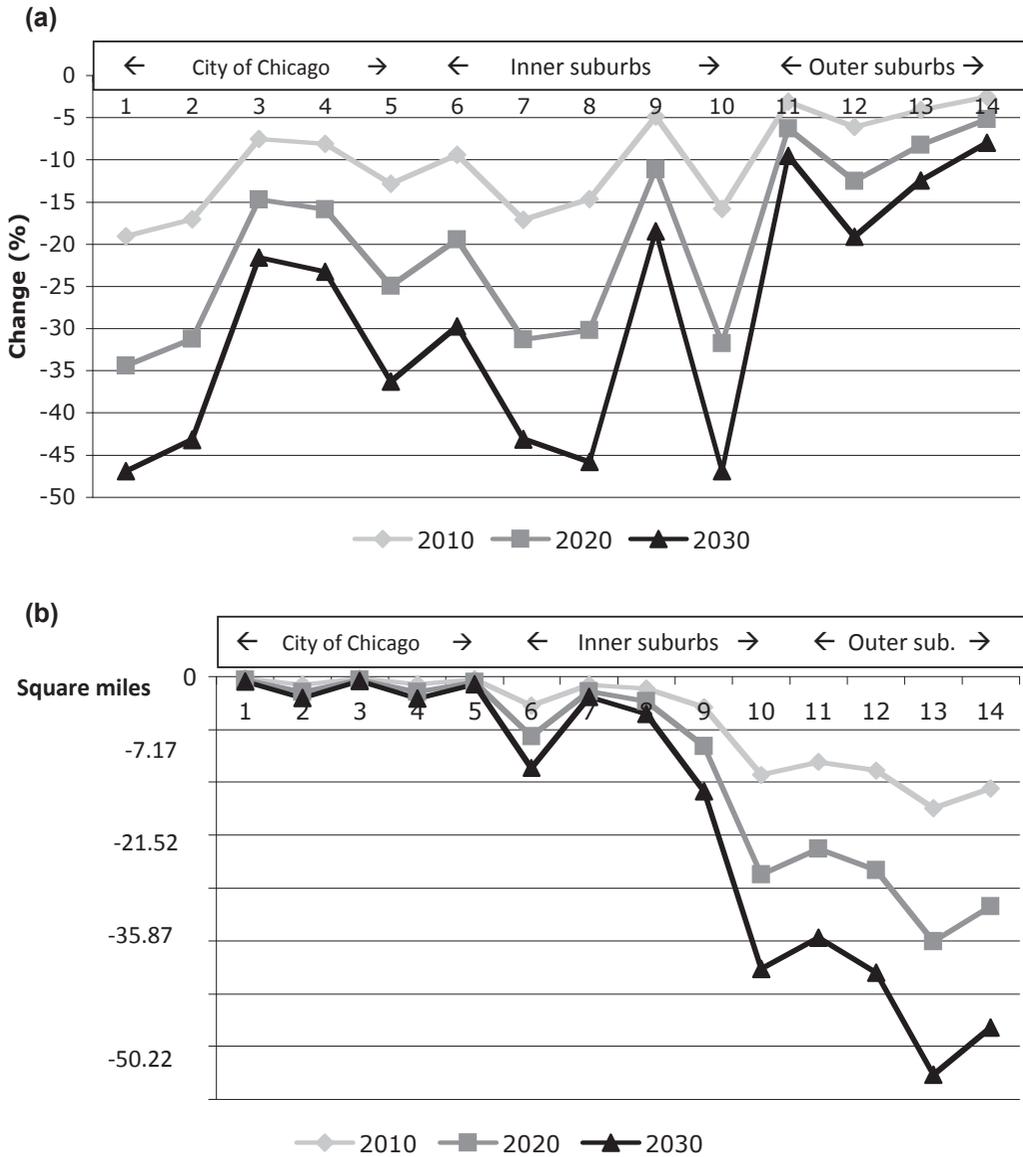


FIGURE 6: (a) Percent Decrease in Undeveloped Land from 2000. (b) Decrease in Undeveloped Land from 2000.

space per job decreasing by about 8 percent. But the floor spaces per resident and per job do increase in the outer suburbs where land is more plentiful and cheaper.

We now turn to the baseline simulation's implications for travel. Figure 7a shows the change in travel-related aggregates in the baseline. Total nonwork trips grow by about 20 percent to 2030, whereas aggregate gasoline consumption rises by about 18 percent and aggregate car VMT (vehicle miles traveled) by about 15 percent; on-the-road fuel economy or MPG (miles per gallon) decreasing by about 3 percent. Because these changes are smaller than the exogenous population and jobs growth rate of 24 percent, quantities

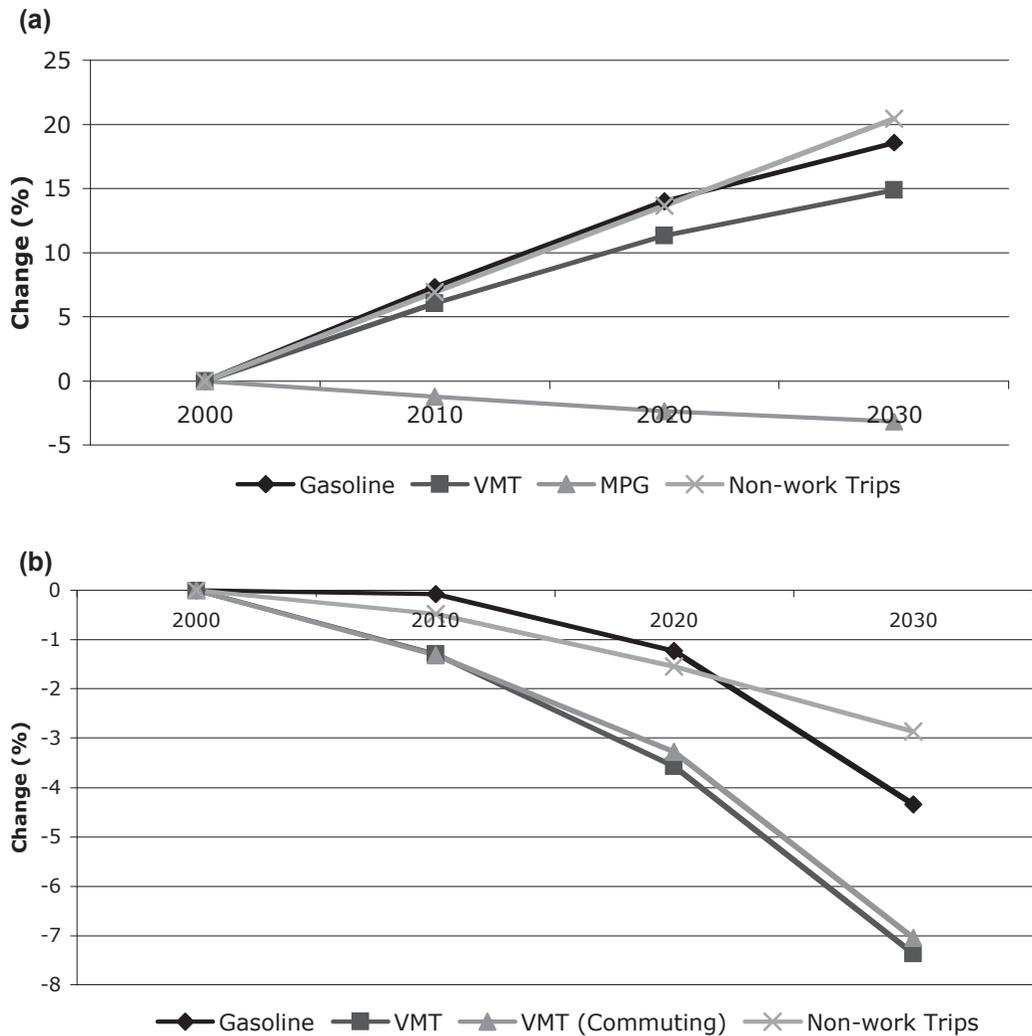


FIGURE 7: (a) Aggregate Gasoline, VMT, MPG, Nonwork trips. (b) Gasoline, VMT, Commuting VMT, Nonwork Trips (All Per Adult Population).

decrease on a per capita basis in Figure 7b. Gasoline, nonwork trips, car VMT for all trips, and car VMT for work trips decrease by 4.4, 3.0, 7.4, and 7.1 percent, respectively, per adult resident.

A key driver of these results is that by 2030 trips by public transit have increased by 55 percent, taking into account the exogenous population growth and any mode switching without relocation, or switching to transit after relocating near it by the existing population. A rough illustrative calculation to separate these effects (ignoring spatial compositional aspects) is as follows. Since car travel time per driver for all car-trips increases by 5.62 percent in the baseline (column 1 of Table 5), and the public transit cross-elasticity was calculated earlier as +3.56, public transit ridership would increase by (5.62 percent) \times (3.56) = 20 percent. Adding to this the 24 percent population growth we get a 44 percent increase in public transit ridership. Since the total transit ridership increases by

TABLE 5: The Effects of Variations Around the Baseline

	Baseline	1 No road expansions	2 Stable gas price after 2010	3 4% better fuel economy per decade	4 Improving public transit times by 5% per decade	5 Only single-family housing construction in outer suburbs	6 10 times lower elasticity of public transit with respect to car travel times
<i>Aggregate quantities</i>							
a	Population (adult residents) and jobs	24.00	24.00	24.00	24.00	24.00	24.00
b	Undeveloped land (acres)	-13.96	-14.13	-14.78	-14.20	-12.26	-13.79
c	Single family housing stock (ft ²)	15.84	16.14	16.35	15.94	16.13	15.66
d	Gasoline (gallons)	18.59	16.40	28.83	8.11	17.97	26.06
e	VMT of all car-trips (miles)	14.86	12.82	22.48	17.62	14.27	20.28
f	VMT of work trips by car(miles)	15.35	12.39	21.10	17.46	15.02	23.29
g	Travel time of all car-trips (min)	21.13	21.47	34.29	25.70	20.43	31.34
h	Travel time of work-trips by car (min)	19.72	20.85	30.79	23.60	19.32	34.14
i	Trips by car	14.68	14.32	21.41	17.05	14.34	19.71
j	Work-trips by car	16.39	15.60	20.56	17.87	16.12	23.16
k	Trips by public transit	54.91	57.00	40.86	50.15	56.09	24.10
l	Nonwork trips by all modes	20.44	20.57	25.36	22.21	20.26	18.53
m	Intrazonal trips by all modes	20.65	21.62	25.12	22.23	20.29	20.25
<i>Per trip quantities</i>							
n	VMT /car-trip for all car-trips (<i>e/t</i>)	+0.16	-1.31	+0.88	+0.49	-0.06	+0.47
o	Work-VMT/car-trip to work (<i>f/f</i>)	-0.89	-2.78	+0.45	-0.35	-0.95	+0.10
p	Travel time/car-trip for all car-trips (<i>g/t</i>)	+5.62	+6.25	+10.61	+7.39	+5.33	+9.71
q	Work travel time/car-trip to work (<i>h/f</i>)	+2.86	+4.54	+8.49	+4.86	+2.76	+8.91

55 percent, the remaining 11.7 percent increase comes from relocation induced increases in public transit trips.

In 2000, 10 percent of all trips (13 percent of work trips) were by public transit. Taking into account the 24 percent exogenous population increase and the 55 percent increase in public transit trips predicted by the model, by the year 2030 the public transit market share would increase from 10 in 2000 to 12.5 percent in 2030 or by a bit less than 0.083 percentage points per year. This pace of increase is also due in part to the steep gasoline price increases assumed for the baseline.¹²

Recall that our main objective is to see whether personal travel time remains relatively constant and sustainable as the urban area grows and sprawls. Abstracting from the model's spatial details, travel time and VMT are related by the equation

$$\text{TRAVEL TIME} = \frac{\text{VMT}}{\text{MPH}},$$

where miles per hour (MPH) being the average road speed determined by congestion. Also, the monetary cost of travel is related to *VMT* and to gallons per mile (*GPM*) by the equation:

$$\text{TRAVEL COST} = \text{GAS PRICE} \times \text{GPM} \times \text{VMT}.$$

Consumers in the model care directly only about their travel times and their (monetary) travel costs and not about their vehicle miles or their speed of travel. As higher congestion causes the per mile speed to fall and the per mile fuel consumption to rise, consumers seek to offset the effect of this on their travel times and their gasoline costs by reducing their miles (VMT). In the model, they can do so by utilizing a number of margins of adjustment. These include switching to public transit or to a more fuel efficient car (that is switching from a higher to a lower curve in Figure 3). To reduce VMT, consumers can also make fewer and shorter nonwork trips, and can change job and/or residence location to reduce their commuting distances. Businesses are indirectly affected by the higher congestion of their workers and customers, and can move closer to them to avoid paying higher wages.

In Figure 8, the average travel time to work for each mode of transportation rises very modestly over the three decades. In particular, travel time per car-trip rises 5.62 percent and travel time to work per car-trip to work by 2.86 percent despite the fact that population and jobs grow by 24 percent and undeveloped land decreases by almost 14 percent (first column of Table 5). This means that in the baseline, the average commute by car, which was 30.3 minutes one-way in 2000 would be 31.17 minutes in 2030, rising at an annual average of 1.74 seconds per year. Figure 9 shows that a similar stability also holds for per-capita daily travel time (commutes and nonwork trips and all modes) in each income group. The average travel time across all modes and all trips is higher by income because most nonwork trips are made to acquire normal goods and, in part, also because many higher income consumers live somewhat farther away from their jobs since they value suburban locations more. The increase in aggregate trips and VMT due to the higher incomes and the higher population result in more congestion per mile if insufficient new highway capacity is added. The intensive marginal effect of the higher congestion per mile results in lower speed (Figure 3), hence higher travel time per mile,

¹²From 2000 to 2010 the public transit share in the Chicago MSA did increase by 2.37 percent according to Census Transportation Planning Package data. In the top 49 MSAs, public transit increased by 4.78 percent on average. The rate of increase varied from 47.69 percent in the Charlotte MSA to -52.85 percent in the New Orleans MSA (caused largely by hurricane Katrina). The likely reasons for the nationwide increase are the rise in gasoline prices and the recession caused by the 2008 financial crisis.

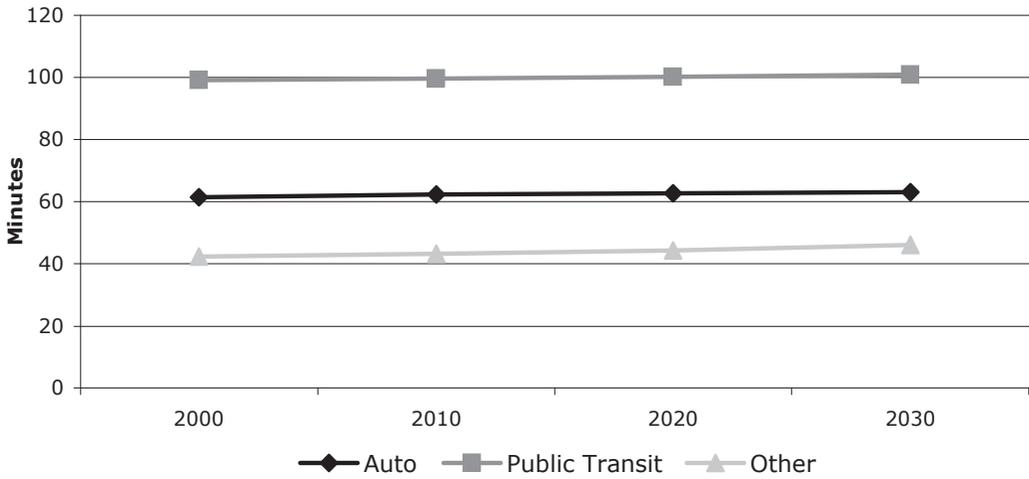


FIGURE 8: Average Daily Round Trip Travel Time to Work by Mode.

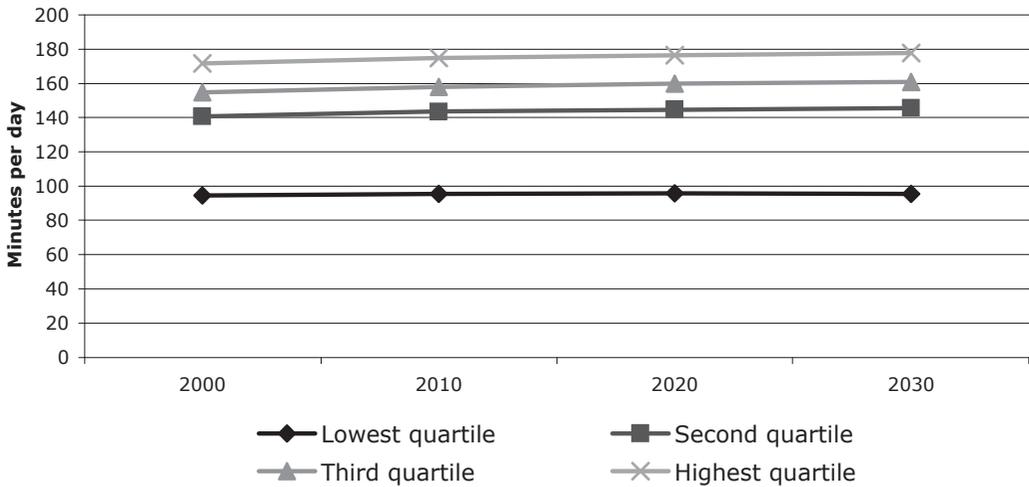


FIGURE 9: Daily Average Travel Time by Income.

but this is partly offset by the extensive marginal effect of less per capita miles caused by switching to transit; and by the intensive marginal effect of trip-distance shortening for nonwork trips. That is why total travel time per person can stay relatively stable. In the next section, we will see that the switching to public transit and the shortening of car distances becomes more dramatic when congestion is higher because road capacity is not increased.

4. EFFECTS OF ROAD CAPACITY, GASOLINE PRICE, FUEL ECONOMY, PUBLIC TRANSIT SPEED, SUBURBAN ZONING, AND THE MODE CHOICE ELASTICITY

To understand better how different changes affect the stability of travel time, we perform perturbations in the most important trends of the baseline simulation by changing them one at a time. We will examine five variations around the baseline while keeping

the mode choice elasticity at -0.84 . In a sixth variation, we will lower the mode choice elasticity taking into account recent estimates cited in the literature. The results are shown in the corresponding columns of Table 5. The variations from the baseline that we examine, numbered by column in the table, are:

- 1 Road capacities stay as in 2000 until 2030 instead of growing according to Table 4.
- 2 Gasoline prices increase from 2000 to 2010 as in the baseline but thereafter remain flat in 2010–2030.
- 3 Fuel economy improves by 4 percent per decade (the five car types in Figure 3 have their curves lowered by about 4 percent each decade).
- 4 Public transit speed improves by 5 percent each decade.
- 5 Only single family housing construction is permitted in the outer suburbs.
- 6 The mode choice elasticity is decreased to one tenth its value.

The top part of the table (rows a–m) gives changes in aggregates of which only population and job growth (row a) is exogenous and unchanged in the variations. The bottom part of the table (rows n–q) show how much VMT and travel time per car-trip change by 2030, both for the total VMT of all car-trips and for the total VMT of car-trips to work (commutes).

The most direct support for the stable travel time hypothesis comes from variation 1 in Table 5. In this simulation, road capacities remain as in the year 2000. This means that by the year 2030 aggregate road capacity is about 22 percent lower than it was in the baseline. Therefore, the population growth without a growth in road capacity would cause congestion per mile to be higher than in the baseline in the outer suburbs where almost all of the road capacity additions go in the baseline. When capacity is not increased, there is less travel and so VMT per person falls, whereas when capacity is increased, there is more travel and VMT per person remains fairly flat. From Table 5 note that travel time per car-trip for all trips and for work trips by car trend a bit higher than the baseline reflecting the congestion, whereas VMT per car-trip for all trips is about 1.31 percent less in 2030 (compared to 0.16 percent more in the baseline), and VMT per car-trip to work 2.78 percent less in 2030 (compared to 0.89 percent less in the baseline). This confirms the expectation based on our intuition explained above that jobs and residences and residences and nonwork travel destinations end up being closer to each other when separation is measured by car-travel-distance. Common intuition may suggest that the lower road capacity would also cause less urban sprawl. But undeveloped land decreases by a somewhat higher percentage than in the baseline. The reason is that as businesses and consumers react to the lower road capacity by reducing the car miles that separate them, they do so in part by moving job or residence (or both) to the suburbs where trips can be shorter, which creates somewhat more sprawl. This is seen by noting that single family housing stock increases by 16.14 percent by 2030 (as compared to 15.84 percent in the baseline), whereas undeveloped land decreases by 14.13 percent (as compared to a 13.96 percent decrease in the baseline).

Variations 2 to 6 provide more confirmation of the tendency for travel time per car-trip to stay in check by reductions in the miles of travel per trip. In variation 2, the lower gas prices cause more sprawl, and more growth in car travel. In this case, travel times by car increase the most among the six variations (by 10.61 percent by 2030), and miles per car-trip lengthen relative to the baseline by 0.88 percent. Trips by public transit increase less than in the baseline and consumers make more nonwork trips and more trips on local roads (intra-zonal trips), which are shorter on average. The fuel economy improvement (variation 3) has qualitatively similar effects on travel times when compared to the lower

gasoline price but is not as powerful, except that—not surprisingly—it results in a much lower increase in aggregate fuel consumption by 2030 relative to the baseline (8.11 percent higher as compared to the 18.59 percent higher of the baseline).

Improving transit speed (variation 4) causes only a bit less urban sprawl than does the baseline. Since public transit service is concentrated in the city and the inner suburbs, some consumers relocate their residences to the center and closer to the transit-served areas where they can make more nonwork trips by transit. Indirectly, this also decreases car distances between homes and workplaces a bit more than in the baseline.

Variation 5 reveals the effects of a hypothetical zoning change, one that would preserve the character of the outer suburbs by restricting new outer suburban development only to single family housing and, perhaps, on the flip side contribute to growth in the city. In this case, it becomes expensive for businesses and apartment dwellers to locate in the outer suburbs since they must squeeze into the floor space already existing in 2000. The price of undeveloped suburban land falls since its effective supply into single family housing has been made larger by the zoning and the elimination of the option to develop into multifamily or commercial uses. Because of the lower land price, more suburban single family development occurs relative to the baseline. The multifamily floor space added during 2000–2030 all goes to the city and the inner suburbs, the distribution of the residential population becoming more centralized on average. As jobs are also more centralized since they are not able to expand in the outer suburbs, average car-mile distance between work and residence at 2030 is a bit lower than in the baseline.

In variation 6, the mode choice elasticity and hence also the cross-elasticity of public transit with respect to travel time by car are reduced 10 times from a cross-elasticity of +3.56 in the baseline to +0.356. The higher value of the cross-elasticity, which is in agreement with the study of Chan and Ou (1978), appears to have come down over the years. The 10 times lower number is in agreement with the more recent estimates cited and surveyed by Frank et al. (2008) and Litman (2012).¹³ Under the lower cross-elasticity, switching to public transit when road congestion increases is greatly reduced as expected. Public transit ridership grows by 24.1 percent to 2030, at the same rate of population increase. Because switching to transit is limited by the weak elasticity, adjustments to the higher congestion occur more by reducing nonwork trips. Gasoline consumption increases by more than the population growth. Car travel distances increase only slightly, but travel times increase by 8.91 percent for work trips by car and by 9.71 percent for all car-trips. These increases are still much lower than the population growth, although considerably higher than the baseline with the 10 times higher mode cross-elasticity.

Finally in another variation not included in the table, we see how the results are changed were consumers to have a lower valuation of their travel time than in the baseline. This causes a bigger increase in trips by transit because the lower valuation favors the slower and cheaper mode, and a bigger increase in nonwork trips and nonwork trip lengths since travel time is less valuable as compared to the base. But the VMT per work-trip by car is essentially unchanged. The reason is that since the slower public transit is now less onerous because travel time is less valuable, those residents who move to the city and the inner suburbs to be able to use the cheaper transit can also get closer to a job. But for others who are less willing to switch to public transit, the lower value of time causes more residential development in the suburbs since more residents with centrally located jobs are now willing to drive farther, again because travel time is less valuable. These two effects essentially offset each other keeping VMT per work-trip by car stable.

¹³Lago et al. (1981) use evidence from demonstration studies as well as from demand models. See also Balcombe et al. (2004).

5. CONCLUSIONS

We have demonstrated by general equilibrium simulations that travel time is relatively stable and sustainable but not constant in the face of urban growth and continuing urban sprawl. The relative stability of travel time that we discovered arises not from a psychological human need or from strict time budgeting assumptions but from rational economic behavior by utility maximizing consumers and profit maximizing businesses that make adjustments in several margins in the face of increasing suburban congestion caused by population growth.

Our empirical explanation of the stable and sustainable travel time relied on a structural microeconomic CGE model founded on the modern assumptions of job dispersal and polycentric urban form. As congestion per mile increases with population growth and slow expansion of road capacity, it is the switching to public transit, the reduction in the lengths and numbers of nonwork trips, and the relocation of jobs and population that keeps travel durations in check as businesses and consumers adjust to the higher congestion. Cause and effect have been established, and there is indeed “no paradox” as correctly conjectured by Gordon et al. more than 20 years ago (see Introduction).

Our results must be tempered by the fact that they are specific to the Chicago MSA, well-served by public transit and in which about a third of the jobs are in three sizeable job centers. Currently, the RELU-TRAN model is being adapted to the Greater Los Angeles region, which differs starkly from Chicago in that about a third of the jobs are dispersed among 30 or so job subcenters and in that public transit ridership share at the MSA level is lower than in Chicago. The expectation is that as population growth causes higher congestion in such a setting, the adjustments could come more from reducing VMT and nonwork trips and much less from switching to public transit. The model is also being applied to the Greater Paris region where road congestion and public transit dependence are both very high: about half of all commutes use public transit and about half of the jobs are concentrated in the central agglomeration consisting of Paris and the near-Paris growth poles. In this situation, an increase in growth coupled with new public transit projects in the central agglomeration could cause jobs and population to concentrate in and around the core agglomeration.

APPENDIX

THE RELU-TRAN CGE MODEL

Consumers, Firms, Developers

The economic agents of the model are consumers, firms, and real estate developers. The RELU submodel treats the housing and labor markets and the markets for the outputs of industries including the construction and demolition of buildings. Consumers, firms, and developers are competitive in all markets, taking prices as given. Choices of route and mode of travel for each trip are treated in TRAN, the transportation submodel.

Consumers. Consumers in RELU choose among discrete bundles (i, j, k, c) ; $i = 1, \dots, 15$ residence zones, $j = 0, 1, \dots, 14$ job zones (where $j = 0$ stands for remaining outside the labor market), $k = 1, 2$ housing types (single family, multiple family structure), and $c = 1, \dots, 5$ car types (by fuel intensity). Conditional on the choice of a discrete bundle, consumers choose (as continuous variables) housing floor space for (i, k) , labor hours supplied at workplace $j > 0$, shopping (nonwork) trips from i to all zones $z = 1, \dots, 15$, and the quantity of retailed goods to buy at each zone z . Consumers regard the retailed goods in different zones as imperfect substitutes and all zones are patronized as

the consumer’s utility exhibits a taste for variety. An hour of travel foregoes the wage, and commuting time creates some disutility.

Formally, each consumer of skill/income level f solves (in an inner nest) the utility maximization problem for the quantities of the retail good to buy $\mathbf{Z} = [Z_1, Z_2, \dots, Z_{14}]$, and the housing floor space, b , to rent. The most-preferred bundle (i, j, k, c) is chosen in an outer nest:

$$(1) \text{Max}_{(i,j,k,c)} \left\{ \begin{array}{l} \text{Max}_{Z_z, b} U_{ijk|f} = \frac{\alpha_f}{\eta_f} \ln \left(\sum_z v_{z|ijf} (Z_z)^{\eta_f} \right) + (1 - \alpha_f) \ln b - \gamma_{1f} G_{ijcf} + \gamma_{2f} m_c + \Lambda_{ijk|f} + u_{ijk|f} \\ \text{s.t.} : \sum_z (p_{Az} + s_{ijf} g_{izcf}) Z_z + b R_{ik} + \Delta_j d g_{ijcf} + K(m_c) = \Delta_j w_{jf} \left(H - \Delta_j d G_{ijcf} - \sum_z s_{ijf} Z_z G_{izcf} \right) + M_f \\ H - \Delta_j d G_{ijcf} - \sum_z s_{ijf} Z_z G_{izcf} \geq 0 \text{ for } j > 0. \end{array} \right\}$$

where $p_{\mathfrak{N}z}$ is the mill prices of the retailed goods (the fourth industry, $\mathfrak{N} = 4$) sold in zone z ; R_{ik} the rent of residential floor space; w_{jf} the wage rate; M_f the nonwage income; G_{ijcf} and G_{izcf} the composite over travel mode and route commuting and shopping travel times (from TRAN); g_{ijcf} and g_{izcf} the composite over travel mode and route monetary costs of commuting and shopping trips (from TRAN); s_{ijf} the shopping trips required to buy a unit quantity of a retailed good; m_c the technological fuel intensity levels of the five car-types $c = 1, 2, \dots, 5$; $K(m_c)$ the annualized acquisition plus maintenance costs of type- c car; H the annual time endowment for work and travel; d the number of days per year for which a commute is required; $\Lambda_{ijk|f}$ the constant effects of the discrete bundle (i, j, k, c) ; $u_{ijk|f}$ a particular consumer’s idiosyncratic taste bias for the bundle (i, j, k, c) ; $v_{z|ijf}$ the constant effects of the retail location z for consumers type f with residence-job locations i, j ; η_f the CES parameter controlling the elasticity of substitution among retail locations; α_f the share of disposable income spent on retailed goods ($1 - \alpha_f$ on renting housing); γ_{1f} the marginal disutility of commuting time; and γ_{2f} is the marginal utility of a larger and safer and more fuel-intensive car.

The right side of the budget constraint in (1) is the money income of the consumer who is paid the wage after travel time for commuting and shopping. If the consumer chooses not to work ($j = 0$), then $\Delta_j = 0$. Otherwise, for any $j > 0$, $\Delta_j = 1$. The left side of the budget is the monetary expenditure on retail goods, commuting, housing floor space, and the annual cost of car-ownership. The prices of the retail goods are effective prices: the mill price at the retail location plus the monetary cost of the travel from home to the retail location.

In the inner stage (inside $\{\}$ in (1)), the Marshallian demands $Z_{ijk|f}$ and $b_{ijk|f}$ are determined. In the outer stage, the consumer chooses the most-preferred discrete bundle (i, j, k, c) given the indirect utility function $U_{ijk|f}^* + u_{ijk|f}$ from the inner stage. Making the usual assumptions about the distribution of $u_{ijk|f}$, the idiosyncratic utilities, the discrete choice probabilities are a nested-logit, with a marginal binary probability for entering the labor market or not ($j = 0$ if not) and a conditional multinomial logit probability, $P_{i,j>0,kc|f}$ for choosing among the bundles $(i, j > 0, k, c)$.

RELU connects with TRAN which determines the mode-and-route-composite trip times and monetary costs that is the matrices $[G_{ijcf}]$, $[g_{ijcf}]$. TRAN does not treat congestion by time of day. Thus, all who use a road experience the same congestion. In TRAN, consumers choose mode of travel (car, public transit, other) and the route of travel for each car-trip, based on the combined monetary cost and travel time of trips.

Monetary cost depends on car fuel intensity because gas consumption depends on traffic speed determined by congestion, and a car’s fuel intensity m_c is a discrete choice. Cars are chosen based on acquisition and gas costs, and on car preferences for comfort and safety, which increase with fuel intensity and with income. The U-shaped curves of Figure 3 were estimated by fitting a polynomial to the performance of the Geo Prizm,

one of the nine car brands in the study by Davis and Diegel (2004), and then multiplicatively shifting this polynomial up and down for the other values of m_c . The Geo Prizm's polynomial curve is $f(t)m_c, m_c = 1, t = 1/s, s$ being the congested speed. Thus,

$$(2) \quad f(t) = 0.12262 - 1.172t^{-1} + 6.413 \times 10^{-4}t^{-2} - 1.8732 \times 10^{-5}t^{-3} + 3.0 \times 10^{-7}t^{-4} - 2.472 \times 10^{-9}t^{-5} + 8.233 \times 10^{-12}t^{-6},$$

where $pf(t)m_c d$ is the fuel cost of driving a road distance d at speed, $s = 1/t$, by a car of fuel intensity m_c when the gas price is p . The congested time per mile, t , on a road-link is given by the "Bureau of Public Roads" (or BPR) function: $t = c_0(1 + c_1(\frac{Flow}{CAP})^{c_2})$, where c_0 is the free-flow (uncongested) travel time per mile, $c_1 = 0.15$ and $c_2 = 4$. $Flow$ is the traffic on the road and CAP is the calibrated road capacity. Disutility (or generalized cost) on a road-link of length d is $(vot_f)(td) + pf(t)m_c d$, where vot_f is the on-the-road value of time that depends on the consumer's income quartile f .

Firms. The four RELU industries are: (a) agriculture, (b) manufacturing, (c) business services, and (d) retail. Goods in the same industry produced in different zones are variants of the same good. Consumers buy all variants of the retail good by shopping them where they are produced. All nonretail variants are intermediate inputs in producing the other goods except for the retail good, which is not an input in production. Each industry also uses primary inputs that are business capital, space in commercial and industrial buildings and labor from each of the skills groups (income quartiles) of the working consumers. All outputs including retail can be exported to other regions from any of the MSA's zones.

Production functions are constant returns to scale and all firms are myopic profit maximizers and perfectly competitive. The number of firms being indeterminate (because of constant returns to scale) the model finds aggregates specific to zone and industry. The first three industries supply their outputs to meet demand from exports and from other firms, whereas retail trade output is shopped or exported. Formally, for industry r located in zone j , the cost minimization problem is:

$$(3) \quad \text{Min}_{K, [L_f], [B_k], [Y_1], \dots, [Y_n]} \rho K + \sum_{f=0}^4 w_{jf} L_f + \sum_{k=0,3,4} R_{jk} B_k + \sum_{s=1}^4 \sum_{n=0}^{14} (p_{sn} + \sigma_s g_{nj}) Y_{sn},$$

with target output $X_{rj} = A_{rj} K^{v_r} \left(\sum_{f=0}^4 \kappa_{f|rj} L_f^{\delta_r} \right)^{\frac{\delta_r}{\theta_r}} \left(\sum_{k=0,3,4} \chi_{k|rj} B_k^{\mu_r} \right)^{\frac{\mu_r}{\theta_r}} \prod_{s=1}^4 \left(\sum_{n=0}^{14} \nu_{sn|rj} Y_{sn}^{\gamma_{sr}} \right)^{\frac{\gamma_{sr}}{\epsilon_{sr}}}$,

where p_{sn} is the price of the output in industry s produced at zone n and $\hat{p}_{snj} \equiv p_{sn} + \sigma_s g_{nj}$ is the delivered price paid by purchasing producers located at j . Recall that g_{nj} is the monetary cost of commuting from n to j . The coefficient σ_s converts this passenger cost to the monetary cost of freight transport per unit of industry s output. ρ is the exogenous price of business capital (the real interest rate), w_{if} are hourly wage rates, and R_{jk} are rents per unit of floor space. K is business capital with cost share v_r . The first group of inputs, L_f with collective cost share δ_r is labor. The industry hires all skills. $f = 0$ stands for labor hired outside the Chicago MSA. The second group of inputs, B_k are buildings with cost share μ_r . $k = 0$ stands for floor space rented outside the region and $k = 3, 4$ are commercial buildings. The cost share of industry r for the intermediate inputs received from basic industry s is γ_{sr} . $n = 0$ stands for intermediate inputs from outside the region. Coefficients $\kappa_{f|rj}, \chi_{k|rj}, \nu_{sn|rj} \geq 0$ allow specifying input-specific biases including the case of zero values to rule out specific inputs. For example, suppose that businesses do not use residential buildings. We would set $\chi_{k|rj} = 0$ when k stands for residential building.

The scale factors, $A_{r,j}$, are constants that we vary by industry and location to capture place-specific Hicks-neutral productivity effects.

Developers. Developers in RELU are based on a perfect foresight model of building conversions with idiosyncratic cost uncertainty. For the purposes of this study, we have simplified. Although buildings can be constructed on undeveloped land or existing buildings can be demolished creating new undeveloped land, in this study we ignore demolition. Hence, once constructed buildings remain unaltered. Second, in this study, we assume that developers have myopic expectations. A third simplification is that we aggregate time into three simulation periods: 2000–2010, 2010–2020, and 2020–2030 during which the building stock can change. We refer to these periods as $\tau = 1, 2,$ and 3 . Assume that land can be developed only in the beginning of a period. Rents are collected annually within the 10-year period. The decision facing a developer is binary: in any 10-year period the developer decides whether to forego developing a parcel with the option to develop it in the future; or whether to develop it into a particular type of building. The present value of profits in period τ , in zone i from developing a type k building ($k > 0$), or not ($k = 0$), are:

$$(4) \Pi_{ik}^\tau = \frac{1}{(1 + \rho)^{10}} (V_{ik}^{\tau+1} - p_{4+k,i}^\tau) a_{ik} + C_{ik} + \zeta_{ik} - V_{i0}^\tau + q_{ik} (R_{ik}^\tau - D_{ik}^\tau) \times \left(\sum_{s=1}^{10} \frac{R_{ik}^\tau - D_{ik}^\tau}{(1 + \rho)^s} \right),$$

$$\Pi_{i0}^\tau = \frac{1}{(1 + \rho)^{10}} V_{i0}^{\tau+1} + \zeta_{i0} - V_{i0}^\tau + \left(\sum_{s=1}^{10} \frac{R_{i0}^\tau}{(1 + \rho)^s} \right).$$

In Equation (4), ρ is the annual interest rate, $p_{4+k,i}^\tau$ is the endogenously determined equilibrium unit construction cost of type k floor space in the zone i ($4 + k$ is the type- k building construction industry), $V_{ik}^{\tau+1}$ is the per square foot sales price of type k floor space in the beginning of the next period, a_{ik} is the structural density (floor space per unit of lot area) of type- k in zone i , V_{i0}^τ is the per square foot sales price of undeveloped land in zone i in the current period, C_{ik} is nonfinancial costs per square foot of land associated with construction of type k building in zone i . R_{ik}^τ is the annual unit rent of type k floor space (or undeveloped land for $k = 0$) in zone i . D_{ik}^τ is the annual cost maintenance per square foot of a type k building that is occupied by a tenant and the function $q_{ik}(R_{ik}^\tau - D_{ik}^\tau)$ is the binary logit probability function that floor space ik will be supplied for rent. The ζ_{ik} , $k = 0, 1, \dots, 4$ are the present value idiosyncratic profits that vary among undeveloped land parcels in zone i . By assuming that these profits are i.i.d. Gumbel with dispersion parameter Φ_i , the probability that a land parcel that is undeveloped in period τ will be developed into type k building in period $\tau + 1$ is the pentanomial logit:

$$(5) \quad Q_{ik}^\tau = \frac{\exp \Phi_i \left(\frac{1}{(1+\rho)^{10}} (V_{ik}^{\tau+1} - p_{4+k,i}^\tau) a_{ik} - V_{i0}^{\tau+1} + C_{ik} \right)}{1 + \sum_{n=1}^4 \exp \Phi_i \left(\frac{1}{(1+\rho)^{10}} (V_{in}^{\tau+1} - p_{4+n,i}^\tau) a_{in} - V_{i0}^{\tau+1} + C_{in} \right)}.$$

The competitive condition that at time τ the expected value of the maximized profit from future development is zero under risk neutrality, is a consequence of the logit calculus and given by:

$$(6) \quad V_{i0}^\tau = \sum_{s=1}^{10} \frac{R_{i0}^\tau}{(1 + \rho)^s} + \frac{1}{\Phi_i} \ln \left\{ \frac{\exp \Phi_i \frac{1}{(1 + \rho)^{10}} V_{i0}^{\tau+1}}{+ \sum_{n=1}^4 \exp \Phi_i \left[\frac{1}{(1+\rho)^{10}} (V_{in}^{\tau+1} - p_{4+k,i}^\tau) a_{in} + C_{in} \right]} \right\}.$$

Since in this application once built, floor space is assumed to be perfectly durable and since we ignore demolition, the unit sales price is the discounted net rents during the period plus the discounted end-of-period unit sale price. Thus,

$$(7) \quad V_{ik}^\tau = q_{ik} (R_{ik}^\tau - D_{ik}^\tau) \times \left(\sum_{s=1}^{10} \frac{R_{ik}^\tau - D_{ik}^\tau}{(1 + \rho)^s} \right) + \frac{V_{ik}^{\tau+1}}{(1 + \rho)^{10}}.$$

The myopic expectations assumption we use in the current application is that developers do not anticipate value increases that will occur in the future. To reflect this for $k > 0$, we set $V_{ik}^{\tau+1} = V_{ik}^\tau$ in (7) and solve it for V_{ik}^τ , which becomes a function of the net unit rent $R_{ik}^\tau - D_{ik}^\tau$ and the interest rate. Plugging this into (6), we solve (6) for V_{i0}^τ . Finally, using all of the V_{ik}^τ for $k = 0, 1, \dots, 4$, in (5) we calculate the construction probabilities and update the stocks by $S_{ik}^{\tau+1} = S_{ik}^\tau + a_{ik} S_{i0}^\tau Q_{ik}^\tau$ for $k > 0$, starting with the observed stocks in 2000. We also update undeveloped land remaining for the future by $S_{i0}^{\tau+1} = S_{i0}^\tau (1 - \sum_{k=1}^4 Q_{ik}^\tau)$.

General Equilibrium

Piecing together the demands of the consumers, the output supplies and input demands of the firms, the travel decisions of the consumers, and the construction by the developers, the model’s equilibrium conditions are derived (Anas and Liu, 2007).

Rental real estate markets. The excess demand for floor space vanishes for each residential and each commercial type of building in each zone:

$$(8) \quad \sum_f N_f \sum_{cj} P_{ijk|f} b_{ijk|f} - S_{ik} q_{ik} = 0,$$

for $k = 1, 2$ (residential buildings), and

$$(9) \quad \sum_r B_{k|ri} - S_{ik} q_{ik} = 0,$$

for $k = 3, 4$ (commercial buildings). N_f is the number of consumers of each type, S_{ik} is the stock of building floor space of each type, $P_{ijk|f}$ are the consumer’s choice probability functions and $b_{ijk|f}$ are the Marshallian demand functions for floor space, $B_{k|ri}$ is the industry’s aggregate demand for commercial floor space, and q_{ik} is the probability function that a unit floor space will be rented rather than kept vacant.

Labor markets. The annual excess demand for the labor hours of each skill group f , summed over the industries vanishes in each zone:

$$(10) \quad \sum_r L_{f|rj} - N_f \sum_{ikc|f} \left(H - dG_{ijfc} - s_{ijf} \sum_z Z_{z|ijcf} G_{izfc} \right) P_{ijk|f} = 0,$$

where $L_{f|rj}$ are the industries’ demands functions for labor, $P_{ijk|f}$ are the consumer’s choice probability functions, and $Z_{z|ijcf}$ are the consumer’s Marshallian demand functions for the retail good while the parenthesis contains the labor hours supplied annually by a consumer after time allocated to shopping and commuting.

Output markets. Letting Ξ_{rj} be the exogenous export demands, the excess demand in each basic industry (agriculture, manufacturing, business services) must vanish in each zone:

$$(11) \quad \sum_{ns} Y_{ri|ns} + \Xi_{ri} - X_{ri} = 0, \quad r = 1, 2, 3,$$

where $Y_{ri|ns}$ are the demands functions for intermediate inputs. X_{ri} is the output of industry r in zone i . For retail:

$$(12) \quad \sum_f N_f \sum_{nsc} P_{nsc|f} Z_{i|nscf} + \Xi_{4i} - X_{4i} = 0,$$

where the summations are the aggregate shopping demands of the consumers.

Construction. Construction of each type of floor space is treated as an industry. Then, the output is simply

$$(13) \quad X_{4+k,i} - S_{i0} Q_{ik} = 0, \text{ for } r=5, \dots, 8,$$

where S_{i0} is the stock of vacant developable land in the beginning of a period.

Zero-profit conditions (free-entry). By free entry, in each period a zero-profit equilibrium exists for each industry in each zone. Then, output prices are found from input prices:

$$(14) \quad p_{rj} = \frac{\rho^{vr}}{A_{rj} \delta_r^{\beta} \mu_r^{\alpha} v_r^{\gamma} \left(\prod_{s=1}^{\beta} \gamma_{sr} \right)} \left(\sum_{f=0}^F k_{f|rj}^{\frac{1}{1-\theta_r}} w_{jf}^{\frac{\theta_r}{1-\theta_r}} \right)^{\frac{\beta_r(\theta_r-1)}{\theta_r}} \left(\sum_{k=0}^N \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{1-\zeta_r}} \right)^{\frac{\mu_r(\zeta_r-1)}{\zeta_r}} \\ \times \left(\prod_{s=1}^{\beta} \sum_{n=0}^{\zeta} v_{sn|rj}^{\frac{1}{1-\varepsilon_{sr}}} \hat{P}_{sn|rj}^{\frac{\varepsilon_{sr}}{\varepsilon_{sr}-1}} \right)^{\frac{\gamma_{sr}(\varepsilon_{sr}-1)}{\varepsilon_{sr}}}.$$

The foregoing add up to 448 RELU equations, which are solved for the output prices, wages, floor rents, and industry outputs, that is for p_{ri} , w_{if} , R_{if} , X_{ri} given the vacant land stocks S_{i0} from the previous period and given the composite output over modes and routes congested travel times and monetary costs from TRAN ($[G_{i,jcf}]$, $[g_{i,jcf}]$). From a RELU equilibrium, commuting and shopping trips are calculated and entered into TRAN. RELU and TRAN are thus linked in a loop, which is cycled to a fully simultaneous and accurately calculated equilibrium (see Anas and Liu, 2007).

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