



The effect of the price of gasoline on the urban economy: From route choice to general equilibrium

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ARTICLE INFO

Keywords:

Gasoline price
Urban structure
Travel

ABSTRACT

RELU-TRAN2, a spatial computable general equilibrium (CGE) model of the Chicago MSA is used to understand how gasoline use, car-VMT, on-the-road fuel intensity, trips and location patterns, housing, labor and product markets respond to a gas price increase. We find a long-run elasticity of gasoline demand (with congestion endogenous) of -0.081 , keeping constant car prices and the TFI (technological fuel intensity) of car types but allowing consumers to choose from car types. 43% of this long run elasticity is from switching to transit; 15% from trip, car-type and location choice; 38% from price, wage and rent equilibration, and 4% from building stock changes. 79% of the long run elasticity is from changes in car-VMT (the extensive margin) 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 in favor of lower TFI. An exogenous trend-line improvement of the TFI of the car-types available for choice raises the long-run response to a percent increase in the gas price from -0.081 to -0.251 . Thus, only 1/3 of the long-run response to the gas price stems from consumer choices and 2/3 from progress in fuel intensity. From 2000 to 2007, real gas prices rose 53.7%, the average car fuel intensity improved 2.7% and car prices fell 20%. The model predicts that from these changes alone, keeping constant population, income, etc. aggregate gasoline use in this period would have fallen by 5.2%.

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1. Introduction

How does the urban economy respond to an increase in the price of gasoline? Since the mid 1970s econometric studies have measured the price elasticity of the demand for gasoline, using state, national and international cross-sectional or time series data. These studies tell us how a change in the gasoline price would affect total vehicle miles traveled (VMT), changes in the stock of vehicles owned and the average fuel economy of cars being operated. From these studies, we know the probable ranges of the price elasticity of the aggregate demand for gasoline, and the “rebound effect”, the propensity to drive more as the fuel economy of cars improves in response to higher gasoline prices.

Small and Van Dender (2007) estimate that both the price elasticity of the demand for gasoline and the rebound effect declined over time (except, perhaps, in recent years not yet studied). Hughes et al. (2008) agree on the elasticity but not necessarily on the decline of the rebound effect, although differences between the two studies appear to be explainable by differences in specification. One reason for the declining elasticity is the fact that since the oil embargo of 1975, incomes have risen but gasoline prices have remained stable or declining (except for recent years). Another reason is that CAFE standards and the fuel economy of cars on the market have improved.

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In this paper, we will evaluate the effect of a higher gasoline price in a computable general equilibrium (CGE) model of a spatially disaggregated urban economy (the Chicago MSA) as it responds from the very short run of travel route adjustments to the long run of location and building stock changes. The structural model treats explicitly aspects that are suppressed in reduced form econometric modeling. This advantage of CGE models sheds more light onto our understanding of how the gasoline price affects urban form and structure.

1.1. Econometric studies and CGE modeling

We consider some limitations of reduced-form econometric specifications and explain how our CGE model, RELU-TRAN2, attempts to compensate for them:

- (a) *Endogenous congestion*: Road congestion indirectly affects gasoline consumption but is hard to treat well in an econometric model. Efforts to capture the congestion effect are few and have relied on very rough aggregate proxies of congestion such as the level of urbanization in a state or the ratio of adults to lane miles of highways (Small and Van Dender, 2007); or the average metropolitan-wide congestion delay indices of the Texas Transportation Institute (Hymel et al., 2010). In our spatially disaggregated CGE model of the Chicago MSA, route choices on a spatial road network are modeled explicitly for different incomes and values of time, taking into account monetary cost (e.g. gasoline) as well as travel time, as these times and costs are endogenized by congestion.
- (b) *Effects of adjustments in urban markets*: Labor, housing, and land markets are changed by travel behavior and in turn affect travel behavior. But the indirect changes in gasoline consumption from endogenous changes in wages, rents and goods prices, in location decisions and in building stocks are not explicitly treated in econometric studies. Our CGE model treats travel and car use decisions for commuting and for discretionary (non-work) trips and also treats labor supply, location of work and residence, location of firms, housing type and market adjustments in rents, wages and retail prices, the asset prices of buildings and the adjustment of building stocks. These adjustments are simulated in stages. Thus, we are able to trace the change in elasticity from the very short run to the long run, decomposing the effect of each stage on the long run elasticity.
- (c) *Sorting out and decomposing various rebound effects*: In the econometric literature, the commonly held definition of the “rebound effect” seems to be the increase in the use of an appliance when its fuel intensity falls. In the case of cars most authors have measured use of the car by VMT (vehicle miles traveled), although TRIPS (number of trips made), HOURS (total hours of travel) or GAS (gasoline burned) would all also be equally valid measures of use in the extensive margin. A car’s use in the intensive margin can be measured by MPG (miles per gallon), by MPH or speed (miles per hour), by GPM (gallons per mile) or by monetary cost (dollars per mile). Our CGE model predicts all of these indicators of car use and the trade-offs among them that consumers make when they allocate their time and income between travel and other activities and when they choose a bundle of trips to maximize utility. In the literature, GPM is normally used as a measure of fuel intensity. But we distinguish between the TFI (technological fuel intensity) of a car’s engine and its on-the-road fuel intensity which is determined by the car’s speed under congested conditions given its TFI. The TFI of cars actually driven improves by technological progress in the car industry or by consumer choice of more fuel efficient cars. Then, as the price of gasoline rises, TFI and/or speed improve indirectly and the monetary cost of driving a mile rebounds. From this, rebounds occur not only in VMT, but also in GAS, HOURS and TRIPS, taking back from the initial reductions in these variables induced by the higher gasoline price.
- (d) *Changes in fuel intensity*: A reduction over time in average fuel intensity is a well-observed trend. Fig. 1 plots the national trends for 1980–2009.² Improvement comes in part from consumers choosing more fuel efficient vehicles in response to a higher gas price. This would raise the demand for such cars causing imperfectly competitive car-makers to produce more of them while marking-up prices. At the same time, in the used car market, fuel intensity is higher on average and the relative prices of used cars would fall, offsetting in part the adoption of the more fuel efficient vehicles. Changes in the supply of vehicles by fuel intensity could also be driven in some measure by CAFE standards. Bento et al. (2009) have attempted to model the effects of these standards in a national model with endogenous car production, but their model does not include urban structure and markets.

Our CGE model is focused on metropolitan structure. It treats as endogenous consumer choices among car-types but does not treat car-production as endogenous. In the model, five abstract car types shown in Fig. 2 are available to consumers, and differ by their TFI. Each higher curve in Fig. 2 represents a car type of higher TFI. Each curve also captures that for a given car type on-the-road fuel intensity falls with car speed, making a relatively flat bottom and rising at high speeds.³ We assume that higher TFI cars are larger, more comfortable, safer but also more expensive to own. The choice of a car type trades off higher ownership and gasoline cost for car size, comfort and safety. Average on-the-road fuel intensity is determined by the distribution of the consumers among the car types and by the traffic congestion which determines speed. In the legend of Fig. 2, the

² The MPG data for Fig. 1 was not available post 2007.

³ The empirics of the curves in Fig. 2 will be discussed in Section 3.

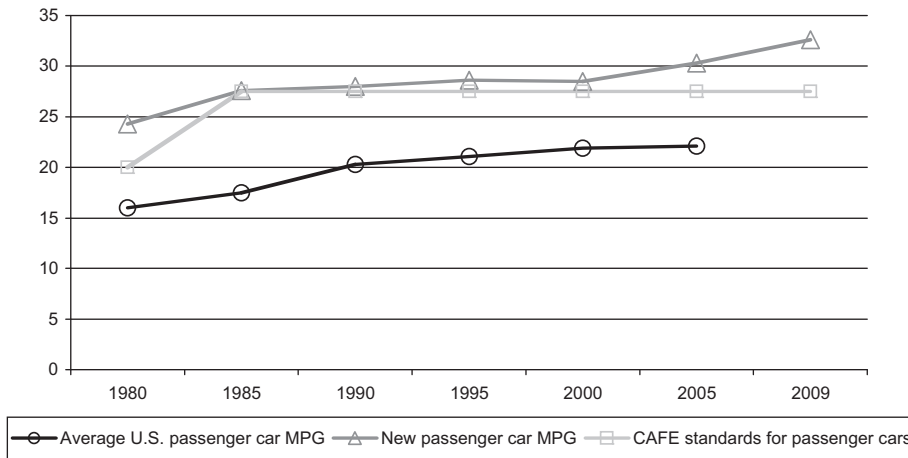


Fig. 1. Time trends of miles per gallon (1980–2009). Source: Bureau of Transportation Statistics.

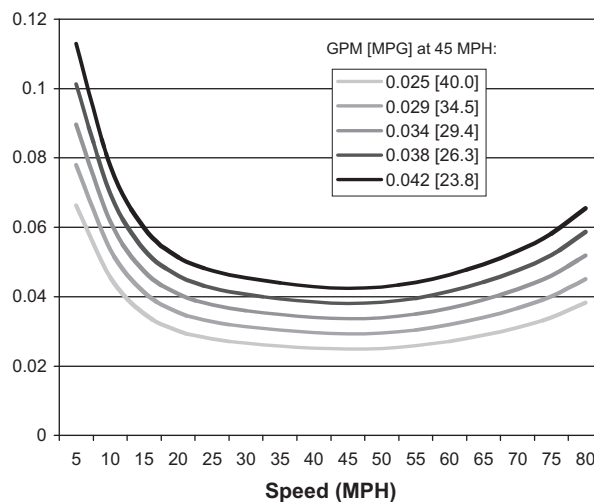


Fig. 2. Technological fuel intensity (TFI) of the five car types in RELU-TRAN2.

gallon per mile (GPM) of the car types is compared at a speed of 45 mph to show how GPM increases (MPG decreases) by the car type's TFI which is the height of the curves. The supply of cars of any of the five fuel intensities to the Chicago MSA is assumed perfectly elastic. This is justified, at least in part, by the fact that any metropolitan area is small in the national car market and that consumers can choose TFI by mixing new and used cars. Trend line progress in car TFI is treated in the CGE model by exogenously shifting (downward) the curves shown in Fig. 2.

1.2. How the simulations are structured

We design a series of nested simulations in which relevant processes of the CGE model are solved while higher level processes are turned off. The consumer in the CGE model completes a hierarchically ordered sequence of choices in response to an increase in the price of gasoline. Short term adjustments are completed fairly quickly. The fastest is changing one's travel route on each car trip, changing the mode of travel of a trip to or from auto to public transit and non-motorized, changing the number and length of non-work trips, and changing one's car type by selecting one of the curves in Fig. 2. Changes in location of residence and/or workplace are longer term as are market clearing adjustments in wages, rents, prices and building stocks.

At every stage in the hierarchy, we endogenously calculate congestion and thus speed on the roads of the network. The endogenous congestion requires a re-statement of the standard microeconomic textbook definition of the demand function for gasoline. In the standard definition aggregate gasoline demand falls with the per gallon price, keeping constant all other prices, consumer incomes and travel times. The demand for gasoline with endogenous congestion is the aggregate gasoline

demanding keeping all other prices and consumer incomes constant, when travel times are re-equilibrated via congestion, as the per gallon price changes. Thus, the textbook aggregate demand for gasoline would be $d(p|t, X)$, where p is the per-gallon price, t is (average) travel time and X is other variables (variables after the vertical bar being kept constant). The demand with endogenous congestion is $D(p|X) \equiv d(p|t(p), X)$, where $t(p)$ is the congested travel time re-equilibrated as the gasoline price p changes. We calculate the shortest-run demand for gasoline (with endogenous congestion) if consumers adjusted only their route choices. The demand curve for gasoline becomes more elastic as consumers adjust route-and-mode choices, route-mode-and-non-work trips and then car TFI and location choices and so on, congested travel times being endogenously determined for each such adjustment.

1.3. Summary and results

The econometric literature on the price elasticity of gasoline is reviewed in Section 2.1. In Section 2.2 a theoretical analysis is presented, as a short-hand for the CGE model. The purpose of this is to clarify the main channels of causation in the demand for gasoline. The analysis combines the extensive margin of VMT with the intensive margin of GPM, and separates the direct effect of the gasoline price from the rebound effects. We show that there is a rebound in GPM and in the gasoline cost per mile. These rebounds stem from two indirect effects of the higher gas price: the consumer's choice of a lower TFI car-type (a lower curve in Fig. 2) and the reduction in congestion as fewer miles are driven on aggregate.

In Section 3, the CGE model's specification is described, with most of the attention on the consumer's utility maximization and the choice structure. In Section 4, we describe the data sources used to calibrate the CGE model, how the calibrated model was fitted to the data to validate it, and how well the elasticity measures and the value of time used in the calibrated model agree with values from the literatures. Section 5 is the key section. There we report on the structured simulations with endogenous congestion and the composition in stages of the price elasticity of the demand for gasoline. The results are discussed in the context of the econometric studies and show that our long run price elasticity agrees well with those of the most recent. The advantage of our approach, however, is that we can decompose the price elasticity by stage of adjustment, and by the extensive margin (VMT) versus the intensive margin (gallons per mile, GPM), quantifying direct and rebound effects.

Our long run price elasticity of gasoline is -0.081 , keeping constant the TFIs of the model's five car-types and the car prices. Decomposing this long-run elasticity by stage of adjustment, about 43% is due to switches from cars to transit; 15% due to changes in trips made and in car-type choices, and job and residence locations. Another 38% is induced by changes in rents, wages and prices in the urban markets. About 4% is induced by long run adjustments in building stocks. Looking at the composition of the elasticity from a different angle, the extensive margin of car miles traveled (VMT) accounts for 79%, while the intensive margin of gallons per mile (GPM) contributes 21%, about 17% of which is from congestion improvement and about 4% from the substitution of lower TFI by consumers, constant the cost of owning the car-types and their TFIs.

Our understanding of the long run response to a gasoline price increase is extended by two more simulations of the CGE model. In the first simulation, the long run response of the demand for gasoline to its price, in the presence of a 2% trend line improvement in the TFI of cars on the market (roughly similar to what has been experienced over a recent 5 year period) and assumed to occur concurrently with the long run adjustments is -0.251 per percent increase in the gas price. Then, since the long-run elasticity (constant TFI) was -0.081 , 2/3rd of the long run response is caused by the modest trend-line improvement in TFI and only 1/3rd by the endogenous choice of TFI by consumers.

In the second simulation, we model the impact of changes in the period 2000–2007. Over this period, the real annual average price of gasoline in the Chicago MSA increased by 53.7% while the TFI of cars on the market improved by 2.7% on average, car acquisition costs decreasing from 19.2% for fuel efficient cars to 23% for the less fuel efficient cars. We report the separate and cumulative long run effects from these changes on gasoline consumption, VMT, speed, gallons per mile and number of work and non-work trips. The gas price increase by itself causes a 4.21% decrease in gasoline use, but the TFI improvement extends this decrease in gasoline use by half as much to 6.34%. But the decrease in car prices takes back about 18% of the combined effect of the TFI and the gas price. The overall effect of all three changes together is a 5.2% drop in gasoline use keeping constant other trends such as population and income.

In Section 5, we also report on how consumers in different commuting arrangements in the model respond to the gas price increase by switching arrangement. Those car commuters most impacted by the gas price would be suburban residents working in the central city and those least impacted suburb-to-suburb car commuters. Conversely, those hurt most by the gasoline price increase benefit the most from a change in TFI. The result is that a gas price increase causes switches to suburb-to-suburb commuting and could result in more suburbanization of car commuters. But this is offset as other suburban commuters switch to transit and do so by moving to a residence in the central city, where transit is more accessible.

In Section 5, sensitivity analyses of the model's elasticities with respect to key parameters of the CGE model are also reported. We focus on increasing or decreasing idiosyncratic consumer taste dispersion to see how the elasticity of GAS, VMT and GPM with respect to the gas price changes. Less (more) idiosyncratic heterogeneity increases (decreases) the elasticity. In the short run a 20% change in taste dispersion causes a just less than 20% change in the elasticity, but in the long run as more choice margins become available, the elasticity converges back towards its original value. That is the long run elasticity is about three times as robust as the short run elasticity in the face of perturbations in consumer heterogeneity. Section 6 concludes.

2. Background

2.1. The econometric literature

Econometric studies that measure the price elasticity of the demand for gasoline date back to at least 1973.⁴ A 1982 article by Wheaton reviews the prior literature and presents estimates of its own. In the earlier studies by DRI (1973), Wildhorn (1974), CRA (1975), Sweeney (1978), and Pindyck (1979) it was customary to specify a single regression equation to estimate the price elasticity which ranged from -0.07 to -0.37 . These studies used US national data consisting of time series of states from 1950 to 1973. Wheaton (1982) used a 1972 cross section of 42 countries and estimated three equations in which the dependent variables were gasoline consumption, miles driven and MPG. He obtained a high gasoline price elasticity, -0.94 , and a VMT price elasticity of -0.483 to -0.547 . All of the estimates are of the short run price elasticity. Estimates of the long run price elasticity ranged from -0.23 to -2.07 .

The more recent work was published between 1992 and 2007 and has been focused in part on the rebound effect, and is surveyed – among others – by Small and Van Dender (2007) and Hymel et al. (2010) who report their own estimates as well, based on data from 1996 to 2001 that treats US states as sample points. Based on theirs and other recent work, they find that the price elasticity of gasoline in the U.S. has decreased in more recent periods, as do also Hughes et al. (2008). This, as they note, is explained largely by the increase of income relative to the gas price since the energy crisis years of the mid seventies (except for more recent steep increases in gas prices after 2001 that do not affect their estimates). Their estimates for the short run (long run) price elasticity are -0.09 (-0.48) for gasoline consumption, -0.045 (-0.22) for VMT, -0.044 (-0.20) for MPG. They calculate rebound effects (not including congestion-related) of 4.5% in the short run and 22% in the long run. Other studies are by Greene (1992), Jones (1993), Schimek (1996), Haughton and Sarkar (1996), Goldberg (1998), Pickrell and Schimek (1999), Greene et al. (1999) and West (2004). The rebound effects found in these studies range from 4% to 23% in the short run (West’s is an outlier at 87%) and from 12.7% to 23% in the long run.⁵

2.2. Theory

Any valid CGE model must be based on an explicit theory. We use a short-hand simplified model (in this section only) abstracting from the details and spatial disaggregation of the RELU-TRAN2 model, but treating rigorously how gas consumption is determined by congestion, car fuel intensity and the demand for travel. In the CGE model (simulations of Section 5), VMT and HOURS are determined from the consumer’s utility maximizing choices of TRIPS, but the short-hand model treats the congestion and the relationship $GAS = GPM \times VMT$ suppressing TRIPS and HOURS of travel. The short-hand model is:

$$GAS = \underbrace{f(t)m}_{GPM} V \left(\underbrace{t, \underbrace{pf(t)m, m}_{\equiv g}}_{VMT} \right) \tag{1}$$

$$t = F \left(V \left(\underbrace{t, \underbrace{pf(t)m, m}_{\equiv g}}_{VMT} \right) \right). \tag{2}$$

$V(t, g, m)$ is the derived demand for VMT. It decreases with the time per mile t , and the monetary cost per mile, g ($V_g < 0$, $V_t < 0$), but assumed to increase with the car’s comfort and safety and so with TFI (denoted by m), so $V_m > 0$. Monetary cost per mile is $g = pf(t)m$, where p is the price of gas; m is an index of the car’s TFI (a curve’s height in Fig. 2 viewed here as a continuous variable) as well as the car’s comfort-safety. From $f(t)$, gas per mile increases with t (or decreases with the congested speed $1/t$).⁶ In (2), $t = F(V)$ is the congestion function by which travel time increases with VMT, given road capacity, that is $F'(V) > 0$.

Using η_{XY} for the elasticity of X with respect to Y , we totally differentiate (1) and (2) with respect to t , m , and p . We will see first how an increase in p affects GPM and g , the monetary cost per mile. Since $GPM = f(t)m$ and $g = pf(t)m$, we get:

$$\eta_{GPMm} = 1 + \eta_{ft} \eta_{tm} > 0, \tag{3a}$$

⁴ Graham and Glaister (2002) provide a survey.

⁵ Greening et al. (2000) provide a survey of the rebound effect’s estimates.

⁶ In the CGE model $f(t)$ will be a U-shaped polynomial function (curves in Fig. 2), but in this theoretical model we consider only the low speed portion of the U in which gasoline per mile decreases with speed.

$$\eta_{gp} = 1 + \eta_{GPMm}\eta_{mp} = 1 + \eta_{mp} \underbrace{(1 + \eta_{ft}\eta_{tm})}_{(3a)} > 0. \tag{3b}$$

Eq. (3a) says that as TFI, m , increases, GPM increases, “1” being the direct effect of m . $\eta_{ft}\eta_{tm} < 0$ is the indirect (rebound) effect in GPM. That is, indirectly a higher TFI causes less driving, less congestion, hence less travel time and less fuel per mile. The sign of (3a) is positive, by the indirect effect being smaller than one. If this were not true, as TFI increases GPM would decrease which is not reasonable. In (3b), the “1” is the direct effect of p on per mile monetary cost g and says that if t and m did not change, then g would be unitarily elastic with respect to p . The last two terms are indirect (rebound) effects showing how the change in p affects g by inducing changes in m which, in turn, also changes $f(t)$. That the sign of (3b) be positive simply means that the absolute value of the indirect effects does not exceed the direct effect. We will see below that if this were not so, then VMT could increase with p .

Now, from (1) we can see how a change in p determines gas use in the intensive (GPM) and extensive (VMT) margins:

$$\eta_{GASp} = \underbrace{\eta_{mp} + \eta_{vt}\eta_{tp}}_{\substack{\equiv \mathbf{A} < 0 \quad \equiv \mathbf{B} < 0 \\ = \eta_{GPMp} < 0 \\ \text{Intensive margin}}} + \left(\underbrace{\eta_{Vg}(1 + \eta_{mp} + \eta_{vt}\eta_{tp})}_{\substack{< 0 \quad (3b) = \eta_{gp} > 0}} + \underbrace{\eta_{Vm}\eta_{mp}}_{\equiv \mathbf{D} < 0} + \underbrace{\eta_{Vt}\eta_{tp}}_{\equiv \mathbf{E} > 0} \right) < 0, \tag{4}$$

$\underbrace{\hspace{15em}}_{\substack{= \eta_{VMTp} < 0 \\ \text{Extensive margin}}}$

First, note that $\eta_{GASp} < 0$ is asserted because the demand for gasoline with car choice and endogenous congestion is negatively sloped. We will indeed see this to be true in our CGE model, without directly assuming it. The term **A** in the intensive margin is from substituting a lower-TFI car and **B** is from the fuel saved per mile as the change in p reduces congestion. The terms in brackets, the extensive margin effect, are the effects of p on vehicle miles through g , m and t :

- (i) $\eta_{Vg}\eta_{gp} < 0$, **C**, is the direct effect of p on V .
- (ii) $\eta_{Vm}\eta_{mp} < 0$, **D**, is the indirect effect of p through car TFI choice. The sign follows by $\eta_{Vm} > 0$ since $V_m > 0$, and by $\eta_{mp} < 0$, substitution of a lower TFI car.
- (iii) $\eta_{Vt}\eta_{tp} > 0$, **E**, is the indirect effect of p through congestion relief. The sign follows because $\eta_{Vt} < 0$ since $V_t < 0$, and by $\eta_{tp} < 0$ (below). Even though this last effect in the bracket is positive, the sign of the bracket is negative. Otherwise VMT would increase with a higher gas price. $\eta_{tp} < 0$ is from (2), the congestion function. Working through the algebra:

$$\eta_{tp} = \frac{\underbrace{\eta_{FV}}_{> 0} \left(\underbrace{\eta_{Vg}}_{< 0} \underbrace{\eta_{gp}}_{> 0} + \underbrace{\eta_{Vm}\eta_{mp}}_{< 0} \right)}{1 - \underbrace{\eta_{FV}}_{> 0} \left(\underbrace{\eta_{Vt}}_{< 0} + \underbrace{\eta_{Vg}}_{< 0} \underbrace{\eta_{gf}}_{=1} \underbrace{\eta_{ft}}_{> 0} \right)} < 0. \tag{5}$$

Congestion means $\eta_{FV} > 0$. Then, the denominator of (5) is positive and the numerator negative.

3. The RELU-TRAN2 CGE Model⁷

The CGE model’s detailed structure, equation system and solution algorithm are described in Anas and Liu (2007). RELU-TRAN2 is an extension of RELU-TRAN in which the travel behavior of the consumer includes the choice of automobile fuel intensity (TFI) and equations that calculate gas use from car travel (Hiramatsu, 2010). In the model, the Chicago area is represented by a system of 15 zones and by an aggregation of the major and local road network.

3.1. Representing the Chicago MSA

Figs. 3 and 4 illustrate the 15 zones and the aggregated road network. The zones make up 5 “rings”. Ring 1 (zone 3) is the Central Business District (CBD). Ring 2 (zones 1, 2, 4, 5) together with the CBD completes the rest of the City of Chicago, with

⁷ RELU-TRAN: Regional Economy, Land-Use and Transportation.

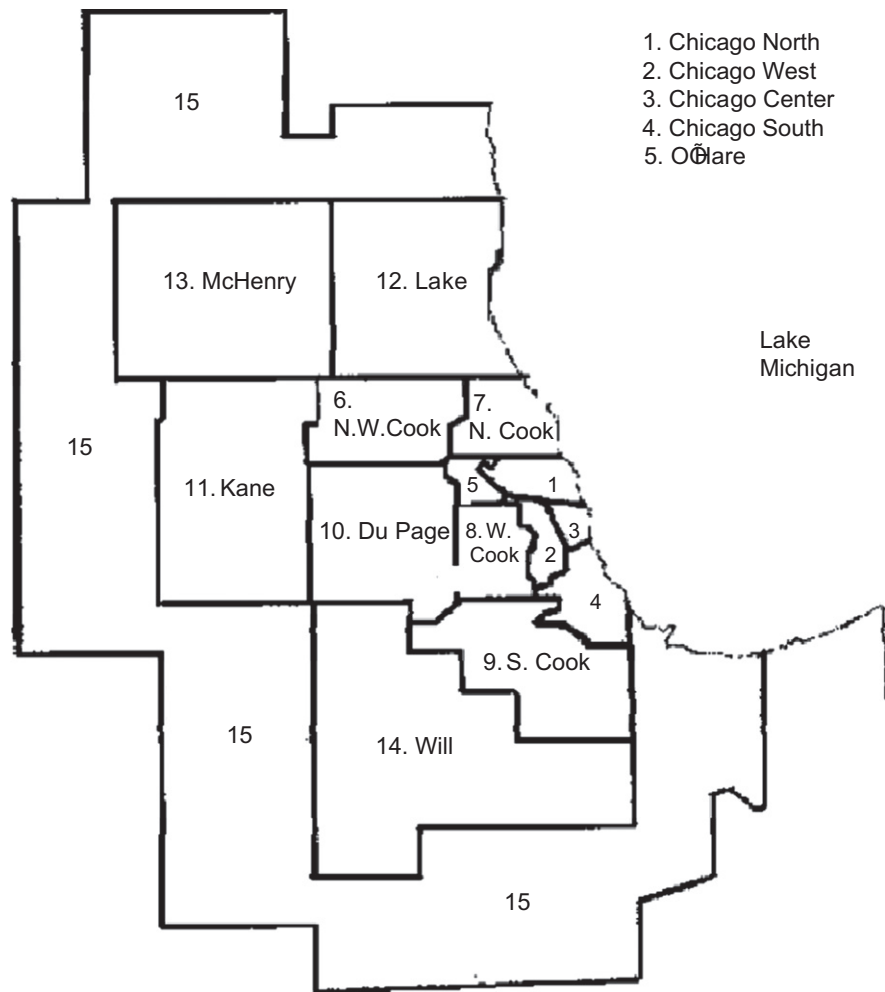


Fig. 3. RELU-TRAN zones for Chicago MSA.

zone 5 the O'Hare airport job sub-center. Ring 3 (zones 6–10) includes the inner ring suburbs encircling the city with zone 10 including the Schaumburg job sub-center. Ring 4 (zones 11–14) comprises the outer ring suburbs and ring 5 (zone 15) is a single peripheral zone representing the primarily rural exurban areas, including parts of Northwest Indiana and Southeastern Wisconsin.

The model can be computed in two ways. In both, the total number of consumers is given exogenously. The first way is that of a “closed MSA”.⁸ In this case, the model consists of only the 14 zones and allocates the given aggregate population of consumers among those zones only. All of the simulations we report here use this way since we did not find that the two ways are substantially different in results. Residents of the peripheral zone 15 are only 5% of the total and so the two versions yield fairly similar results.

All intra-zonal trips, trips that originate and terminate within the same zone, utilize a congestible *local road* that is an aggregation of the underlying street and minor road system. Trips choose a path over the road-links which are an aggregation of *major roads and highways*, shown in Fig. 4, and use the intra-zonal local roads for access and egress. Each one-way inter-zonal link is represented by a capacity used to calculate equilibrium flow congestion which determines equilibrium monetary and time costs on the link (below).

3.2. Model structure: consumers, firms, developers

The economic agents are consumers, firms and real estate developers. RELU treats the housing market, the labor market, and the markets for the outputs of industries including the construction and demolition of buildings. Consumers and firms

⁸ In the second way, “the partially open MSA”, consumers choose from all 15 zones, but for those choosing the exurban zone 15, the wages they earn or the rents they pay in 15 are treated as exogenous.

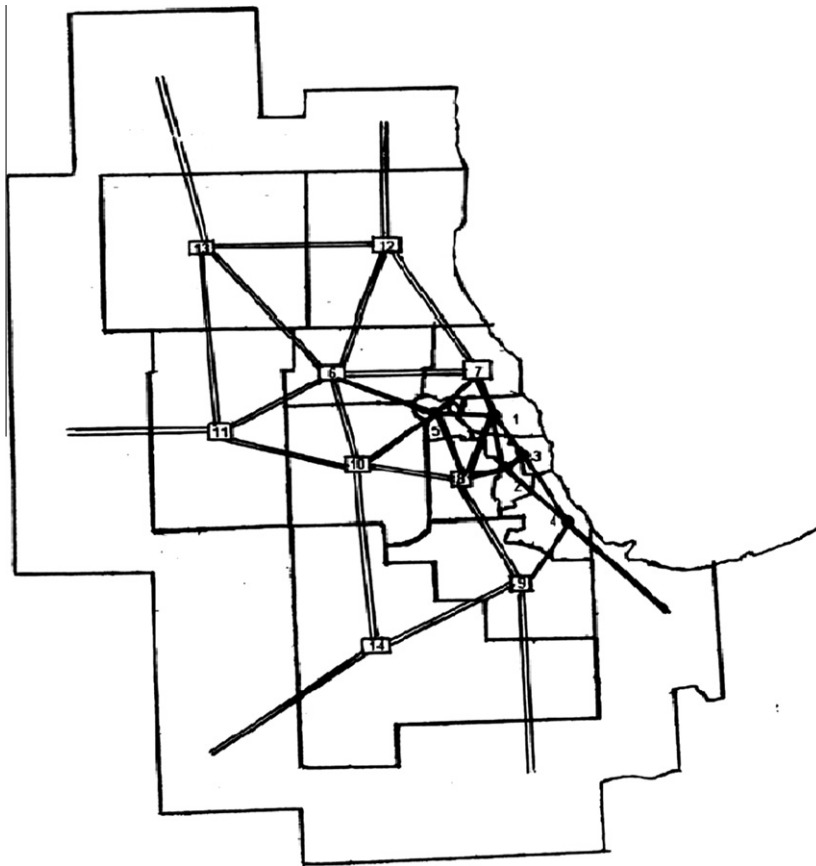


Fig. 4. Network of major roads in RELU-TRAN.

are competitive in all markets, taking prices as given. Choices of travel route and mode for each trip are treated in TRAN, the transportation sub-model. RELU and TRAN are linked sequentially, but are cycled to a fully simultaneous equilibrium (see Anas and Liu, 2007).

Consumers in RELU choose among discrete bundles (i, j, k, c) ; $i = 1, \dots, 14$ residence zones, $j = 1, \dots, 14$ job zones, $k = 1, 2$ housing types (single family, multiple family structure), and $c = 1, \dots, 5$ car types (the TFI levels of Fig. 2). Continuous variables, conditional on each discrete bundle are the housing floor space for (i, k) , labor hours supplied at j , shopping trips from i to all zones $z = 1, \dots, 14$, and the quantity of retail goods to buy at each z . Consumers regard the retail goods in different zones as imperfect substitutes and all zones are patronized as the consumer's utility exhibiting a taste for variety. Travel time is valued at the wage (an hour of travel foregoes the wage). But commuting time creates some disutility and the marginal rate of substitution between disposable income and commuting time is more than the wage.

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

$$\text{Max}_{\forall(i,j,k,c)} \left\{ \begin{array}{l} \text{Max}_{\forall Z_z, b} U_{ijkcf} = \frac{\alpha_f}{\eta_f} \ln \left(\sum_{\forall z} I_{zijf} (Z_z)^{\eta_f} \right) + (1 - \alpha_f) \ln b - \gamma_{1f} G_{ijcf} + \gamma_{2f} m_c + \Lambda_{ijkcf} + u_{ijkcf} \\ \text{s.t.} : \sum_{\forall z} (p_{zcf} + q_{ijf} g_{izcf}) Z_z + b R_{ik} + \Delta_j d g_{ijcf} + K(m_c) = \Delta_j w_{jf} (H - \Delta_j d G_{ijcf} - \sum_{\forall z} q_{ijf} Z_z G_{izcf}) + M_f \\ H - \Delta_j d G_{ijcf} - \sum_{\forall z} q_{ijf} Z_z G_{izcf} \geq 0 \quad \text{for } j > 0. \end{array} \right. \quad (6)$$

p_{zcf} : the mill prices of the retail goods sold in zone z .

R_{ik} : the rent of residential floor space.

w_{jf} : the wage rate.

M_f : non-wage income.

G_{ijcf} , G_{izcf} : mode and route composite commuting and shopping travel times (from TRAN).

g_{ijcf} and g_{izcf} : mode and route composite monetary costs of commuting and shopping trips (from TRAN).

q_{ijf} : shopping trips required to buy a unit quantity.

m_c : the technological fuel intensities (TFI) of the available car-types $c=1,2,\dots,5$ (see Fig. 2).

$K(m_c)$: annualized costs of type c car ownership (acquisition plus maintenance).

H : the annual time endowment for work and travel.

d : the number of days per year for which a commute is required.

A_{ijkclf} : constant effects of the discrete choice bundle (i, j, k, c) .

u_{ijkclf} : the idiosyncratic tastes for the choice bundle (i, j, k, c) .

ι_{zijf} : constant effects of the retail location z for consumers type f at residence-job locations i, j .

η_f : CES parameter controlling the elasticity of substitution among retail locations.

α_f : share of disposable income spent on retail goods ($1 - \alpha_f$ on renting housing).

γ_{1f} : the marginal disutility of commuting time.

γ_{2f} : the marginal utility of a larger and safer and more fuel-intensive (higher TFI) car.

The right side of the budget constraint in (6) is the money income of the consumer who is paid the wage after travel time for commuting and shopping. But 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 and housing space and annual costs 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 the $\{\}$ in (6)), the Marshallian demands Z_{ijkclf}^* and b_{ijkclf}^* are determined. In the outer stage, the consumer chooses the most-preferred discrete bundle (i, j, k, c) , given the indirect utility function $U_{ijkclf}^* + u_{ijkclf}$. By making the usual assumptions about the distribution of the idiosyncratic utilities u_{ijkclf} , 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, $P_{ij>0,kclf}^*$ for choosing among the bundles $(i, j > 0, k, c)$.

RELU connects with TRAN via the mode-and-route-composite trip times and monetary costs, that is the matrices $[G_{ijclf}]$, $[g_{ijclf}]$. How these composites are determined is described next. RELU-TRAN2 does not treat congestion by time of day, and all who use a road, experience the same congested time. Monetary cost depends on car TFI since gas consumption depends on traffic speed determined by congestion, and since TFI is a discrete choice responsive to car acquisition and gas costs, and on car preferences for comfort and safety which increase with income in the indirect utility function. In TRAN consumers make choices of mode of travel (car, mass transit, other) for each trip and choose the route of travel for each car trip, based on the combined monetary cost and travel time of trips (that is generalized cost).

The money cost of car travel depends on the gas price, the car type's TFI, which together with the speed determine gas use. The U-shaped curves of Fig. 2 were estimated by fitting a polynomial to the Geo Prizm, the third curve in Fig. 2, 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 . The Geo Prizm's polynomial curve is $f(t)m_c$, where $m_c = 1$ and, $t = 1/s$, s being the congested speed. Thus:

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

$pf(t)m_c d$ is the fuel cost of driving a road distance d at speed, $s = 1/t$, by a car of TFI m_c when the gas price is p . The congested time per mile, t , on a road-link is given by the BPR function: $t = c_0(1 + c_1(\frac{Flow}{CAP})^{c_2})$, where $c_1 = 0.015$, $c_2 = 4$, and c_0 is the free-flow (uncongested) travel time per mile. $Flow$ is the traffic on the road and CAP is the calibrated 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 .

RELU industries are: (a) agriculture, (b) manufacturing, (c) business services, and (d) retail. All variants of a good (a)–(c) are used as intermediate inputs in producing other goods. The retail good is produced by the input of the other goods, but is not itself an input for other goods. Each industry also uses business capital, space in commercial and industrial buildings and labor from each of the skills groups (income quartiles) of the working consumers. Outputs can be exported to other regions directly from the zone of production.

Production is constant returns to scale and firms are myopic profit maximizers and perfectly competitive. The number of firms is therefore indeterminate, and the model finds aggregate output, employment, etc. by zone and industry. The price of each good is endogenous in the model and from the zero profit condition of long run competition and free entry, it is a function of the wages, rents and intermediate product prices.

Developers in RELU are investors buying and selling real estate with zero transactions costs, and landlords renting out land and floor space, as well as contractors who either build or demolish. Developers operate with perfect foresight and are risk neutral and competitive. Asset prices for vacant land and for each type of building are determined so that the expected discounted economic profit including net rental income is zero. Developers who own land decide whether to continue to hold it vacant or to construct on it, and those who own buildings decide whether to demolish or not.

3.3. Model structure: general equilibrium

The equilibrium conditions are pieced together from the demands of consumers, the output supply and input demands of firms, the travels of consumers and the floor spaces supplied by developers. The relevant markets are the labor market for each labor skill level in each zone (56 equations, that is 14 zones by 4 skill levels), the residential rental market for single-family and multiple-family floor space (28 equations, that is 14 by 2), the business rental market for commercial and industrial floor space (28 equations, that is 14 by 2), and the goods markets for each industry (56 equations, that is 4 industries by 14 zones). Solving these equations determines in each zone, the rental price (per square foot) of each type of floor space, the hourly wage for each skill level and the output price for each industry. See [Anas and Liu \(2007\)](#) for details.

4. Data and calibration

Deciding on the model's parameters was a mixture of fixing some at reasonable values and calibrating others so that the elasticity relationships concerning location demand, housing demand and supply and the labor market are within ranges of estimates in the literature. We first discuss the data sets used to calibrate, then how the calibrated model fit the data, and lastly the model's calibrated elasticity relationships.

4.1. Data

A variety of data sets were utilized to calibrate RELU-TRAN1. Travel times and work trips from residences (origins) to workplaces (destinations) by income and by mode of travel (car, mass transit and non-motorized) came from the year 2000 Census Transportation Planning Package (CTPP). From the CTPP jobs by zone of workplace, and estimates of wages by place of work were also determined. Non-work trip frequencies from residence location trip origins were estimated from the Home Interview Survey for the Chicago MSA. Residential housing stock is from the year 2000 Census, and non-residential building stock and floor space prices from COSTAR data. Residential housing prices and rents for floor space in single and multiple family housing were inferred by an imputation procedure that used the Public Use Micro Sample data. The land use files of the Northeastern Illinois Planning Commission were used for the vacant developable land and land use by building type in each model zone and from that the structural density of buildings by type was constructed as a zone-average floor area per acre. The industries and inter-industry trade-flow relationships were obtained by following the IMPLAN's economic modeling system as were also expenditure shares by intermediate input categories. Car costs are from the American Automobile Association ([AAA, 2005](#)) and the Bureau of Labor Statistics.

4.2. The model's fit to the data

Since RELU-TRAN2 is an extension of RELU-TRAN that includes choice among five car-types differing by TFI ([Fig. 2](#)) and precise calculations of gasoline use, VMT, MPG and speed, it required a calibration adjustment that draws on additional data. Data targets for RELU-TRAN2 to be matched as closely as possible by the calibration were constructed. The [RTAMS \(2000\)](#)⁹ 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, gas use and MPG targets are from the Illinois Travel Statistics ([IDOT, 2000](#)). The targeted car distribution by TFI was constructed from the [NHTS \(2001\)](#). [Table 1](#) shows how well the calibrated model fit the targets.

4.3. Elasticities

[Table 2](#) shows the key calibrated elasticities and values of time calculated from the model's predicted equilibrium for the year 2000. Here, we discuss how these elasticities compare to values from the relevant literature and if they differ we explain why.

Our MRS between disposable income and commuting time from the choice of job-residence is higher than the wage rate because of our specification of the consumer's utility: the consumer gives up the wage for commuting, but there is also disutility from the commuting time. This specification ignores that a consumer's dislike for hours spent at work may be higher than his dislike of commuting, which would result in a value of time lower than the wage. It is consistent with recent empirical evidence that the value of time in commuting exceeds the wage rate due to job market frictions ([van Ommeren and Fosgerau, 2009](#)).

The elasticity of location demand with respect to commuting time was estimated in the 1970s by [Charles River Associates \(1972\)](#), [Atherton et al. \(1975\)](#), [Train \(1976\)](#), and [Lerman \(1977\)](#). The in-vehicle time elasticity ranged from -0.36 to -1.40 for transit and from -0.55 to -1.77 for the drive-alone mode. The out-of-vehicle time elasticity ranged from -0.23 to -2.7 for transit. As shown in [Table 2](#), our workers' travel time elasticity of location demand in RELU-TRAN2 ranges from -0.54 to -0.62 and is in the range of these estimates.

⁹ Regional Transportation Assets Management System (RTAMS) <http://www.rtams.org/ui/homepage.asp> contains an aggregated version of the year 2000 CTPP data for the Chicago MSA.

Table 1

Fit of the calibrated RELU-TRAN2 to targets constructed from data.

Data items	Source	Percent (%) over-under-prediction (average absolute value % error)	Calibration target
Region wide car-VMT (mill.mi/day)	IDOT (2000)	−3.9	137.90
Interstate car-VMT (mill.mi/day)		−16.1	39.00
Other car-VMT(mill.mi/day)		+0.9	98.90
Fuel use by cars (mill.gall./day)		−5.2	6.51
MPG by cars (mi./gall.)		+1.3	21.20
Employed residents by zone	RTAMS (2000)	+6.1%	
Jobs by zone		+4.9%	
Work trips by origin-to-destination		+5.9%	
Work trips by car origin–destination		+6.1%	
Distribution of cars by TFI level	NHTS (2001)	+5.3%	

Table 2

Calibrated elasticities in RELU-TRAN2 (Chicago, MSA).

Consumers	Income quartiles			
	1	2	3	4
MRS (disposable income, Commute Time) (\$/h/day)	12.257	20.934	35.910	92.625
Elasticity of location demand with respect to commuting time	−0.618	−0.606	−0.612	−0.546
Elasticity of housing demand with respect to rent	−1.949	−1.756	−1.568	−1.378
Elasticity of labor supply in city with respect to city wage	2.818	2.168	1.694	1.199
Elasticity of labor supply to suburbs with respect to wage in suburbs	1.602	1.352	0.973	0.626
Developers	Building type			
	1 Single family	2 Multi-family	3 Commercial	4 Industrial
Elasticity of floor space supply with respect to rent (Short-run)	0.099	0.230	0.268	0.138
<i>Elasticity of construction flow with respect to asset value</i>				
Overall	0.052	0.421	0.420	0.074
City	0.033	0.056	0.261	0.040
Suburbs	0.053	0.681	0.452	0.079
<i>Elasticity of demolition flow with respect to asset value</i>				
Overall	−1.612	−0.982	−0.176	−0.523
City	−0.055	−0.528	−0.346	−0.667
Suburbs	−1.719	−1.375	−0.073	−0.465
<i>Elasticity of floor space stock with respect to asset value</i>				
Overall	0.0535	0.0147	0.0054	0.0087
City	0.0010	0.0068	0.0064	0.0079
Suburbs	0.0672	0.0218	0.0048	0.0092

Anas and Arnott (1993) found that the average rent elasticity of housing demand, the rent elasticity of white households and the rent elasticity of non-white households in the Chicago MSA for 1970–1980, are -0.55 , -0.52 and -0.68 respectively. In our model, the rent elasticity of housing demand is more negative than -1 , because of the functional form of the utility function, and ranges from -1.38 to -1.95 . But our elasticity combines two margins, one is the demand for housing floor space and the other the number of consumers who demand housing. Thus our elasticity is higher than that in Anas and Arnott (1993), who estimate a model in which the demand for housing in the first margin is inelastic.

Kimmel and Kniesner (1998) studied nationwide US data for the period 1983–1986. Their nationwide average wage elasticity of labor supply (hours worked) is $+0.51$. In our case, the model is at the metropolitan level and an average elasticity can be calculated for each zone and each income-skill level as the increase in labor hours per consumer times the number of consumers wishing to work at a zone. Table 2 shows the average wage elasticity of labor supplied to the City of Chicago versus the suburbs. These wage elasticities of labor supply decrease with income-skill group, and are lower for suburban zones.

In Anas and Arnott (1993), the elasticity of housing floor space supply with respect to rent is $+0.10$ and $+0.114$ for single-family and multiple-family housing in the Chicago MSA. It is the percent of stock that will be offered for rent by the landlords (than kept vacant). Our corresponding values are $+0.099$ and $+0.23$. While our single-family housing is similarly elastic, our multiple-family housing supply is more elastic than theirs and similar to Anas (1982).

The methodology used in the literature to estimate the supply elasticity of housing is not robust. There are important data-driven or definitional differences between any two studies. DiPasquale and Wheaton (1994) report that the long run price elasticity of the aggregate housing stock of $+1.2$ to $+1.4$. Blackley (1999) reports that the construction elasticity ranges from $+1.0$ to $+1.2$, and that the long-run price elasticity of new housing supply (in value terms) for 1950–1994 ranges from $+1.6$ to $+3.7$. Green et al. (2005) report a price elasticity of housing supply in the Chicago MSA for 1979–1996 as $+2.48$, but

not significantly different from zero. Their supply is the number of housing units for which building permits were issued, multiplied by 2.5 (average household size), divided by the population. They cover a bigger region than does our model. By 2000, our region was more developed than during their period, and the available land would have decreased significantly. The definition of our elasticity of construction is different than theirs and measures the percent by which the construction flow would increase. In addition, there are two assumptions that could be affecting our elasticity in real estate variables.

First, is the assumption that our building structural density (in floor space per unit of land), is constant by building type and zone. Our average structural density is not constant, however, and changes over time by demolishing low structural density and constructing higher structural density buildings. If the building's floor space could be directly chosen by the developer, the stock could be more elastic when the building value increases. This would be especially true in the zones where the vacant land is scarce. Smith (1976) reports that the price elasticity of density is +5.27, where their density is the number of dwelling units built on a unit land area, from Chicago MSA cross-section data between 1971 and 1972. The second assumption is the equilibrium condition that the construction and demolition flow of each building stock in each zone is equalized in stationary equilibrium. In reality, the construction flow would be larger than demolition and stock in a growing economy.

This suggests that it is better to evaluate the reasonableness of our housing supply elasticity by simulating the model in a comparative static exercise, observing how the housing stock responds. In Hiramatsu (2010), an urban growth scenario is simulated, in which the total population and the net exports are increased 10%. The vacant land stock decreases in both the city and the suburbs. The single family housing stock decreases in the city and increases in the suburbs. The multiple family housing stock increases in both the city and the suburbs, and increases more in the suburbs than in the city. The single and multiple family housing stock increases less than the 10% population growth and the average floor space per person decreases. Industrial and commercial floor space also increase in the city and suburbs. The increase is higher in the city, but not as high as that of the housing stock. In the city, where the available land is limited, some single family housing is demolished and multi-family housing, industrial and commercial buildings are constructed. In the suburbs where there is plenty of land, both single and multiple family housing is constructed. Industrial and commercial buildings are also constructed in the suburbs. Thus the building stocks respond reasonably with respect to the increase of population and net exports. In the city the rent of single family housing increases by more than 10% as the supply decreases. The other building rents also increase since demand increases by more than supply does. We conclude that the building markets, including stocks, rents and values, respond reasonably under the calibrated elasticities.

5. General equilibrium analysis in stages

Table 3 and Figs. 5–10 show results from the baseline simulations. To obtain the numbers in the table, the model was run in stages by increasing the base (year 2000) gas price by 10%. The numbers in the first eight columns of Table 3 (plotted in Fig. 5) are the elasticities (percent change in the row variable per 1% higher gas price, – the simulation's result divided by 10). The first eight columns are discussed in 5.1. The ninth column shows the percent change in the row's variable when the 2% trend line improvement in TFI occurs for each car type alongside the 10% increase in the gas price or, alternatively, assumed caused by the 10% increase in the gas price. The results of column 9 are discussed in Section 5.2.

5.1. Composition of elasticity by stage of adjustment

Columns 1–4 quantify the short-run gasoline price elasticity by stage. In column 1 is the elasticity when consumers change only their route of travel for all trips by minimizing generalized cost, keeping their higher level choices and all prices, wages and rents unchanged. In column 2 only the choice of mode and route are flexible. In column 3, non-work trip destinations and frequencies, modes and routes change; and in column 4 the choice of one of the five car fuel intensities is added. Columns 5–8 report longer term responses. In column 5, consumers are adjusting their residential locations (and housing type) on top of the lower-level choices, but their job locations, all prices, wages, rents and housing stocks are fixed at base values. In column 6 job locations are adjusted on top of all preceding adjustments; in column 7 all prices, wages and rents are re-equilibrated but building stocks remain at base values. Finally in column 8, building asset prices are updated and building stocks are adjusted by developers. Traffic congestion is endogenous in each stage. That is congestion on the road network responds simultaneously with route choice, the lowest stage.

The results (columns 1–8) are summarized as follows. First, as expected, the absolute value of the calculated elasticity becomes bigger, as more choices are allowed. This is true for gasoline, for speed (determined by the endogenous congestion), and for GPM (or inverse MPG) when car-choice and higher level choices are allowed. More precisely, gasoline consumption decreases as more choices are allowed, speed increases, VMT decreases and fuel efficiency (MPG) improves (GPM decreases).

The only one exception is GPM at the route choice level. The relevant number in Table 3 shows a small increase in GPM per 1% higher gasoline price when consumers switch routes but mode choice and higher level choices are fixed. The subtle reason this can happen is demonstrated by means of a simple example. Suppose that there are two parallel road links connecting two points and the total demand for trips between the points is perfectly inelastic. In a stochastic equilibrium both routes will be utilized. Suppose initially that only money cost matters in route choice (zero value of time). Assume

Table 3
Compositional analysis of the long run elasticity by stage of adjustment.

Elasticity with respect to gasoline price of	Base values	Short-run				Long-run				
		1 Routes	2 Modes	3 Trips	4 Car fuel economy	5 Resid. locat.	6 Job locat.	7 Price adjust.	8 Stock adjust.	9 TFI improves 2%
<i>Elasticity by stage of adjustment (each stage includes earlier stages)</i>										
GAS (mill.gall./day) (a)	6.169	-0.000046	-0.035	-0.042	-0.043	-0.046	-0.047	-0.078	-0.081	-0.251
VMT (mill. mi./d) (b)	132.5	-0.000084	-0.027	-0.033	-0.033	-0.036	-0.037	-0.061	-0.064	-0.041
GPM (gall./mi.) (c)	0.047	0.000038	-0.008	-0.009	-0.010	-0.010	-0.010	-0.017	-0.017	-0.211
Speed (mi./hr)	21.7	0.000012	0.020	0.023	0.023	0.024	0.025	0.039	0.040	0.025
TFI index (gall./mi.) (VMT-weighted) (d)	0.041	-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 TFI</i>										
VMT effect (extensive margin) in price elasticity of GAS (b)/(a)		1.83	0.77	0.79	0.77	0.78	0.79	0.78	0.79	0.16
GPM effect (intensive margin) in price elasticity of GAS (c)/(a)		-0.83	0.23	0.21	0.23	0.22	0.21	0.22	0.21	0.84
TFI effect in GPM (d)/(c)		-0.08	0.13	0.11	0.20	0.20	0.20	0.18	0.18	0.96
Cong. effect in GPM[(c)-(d)]/(c)		1.08	0.87	0.89	0.80	0.80	0.80	0.82	0.82	0.04

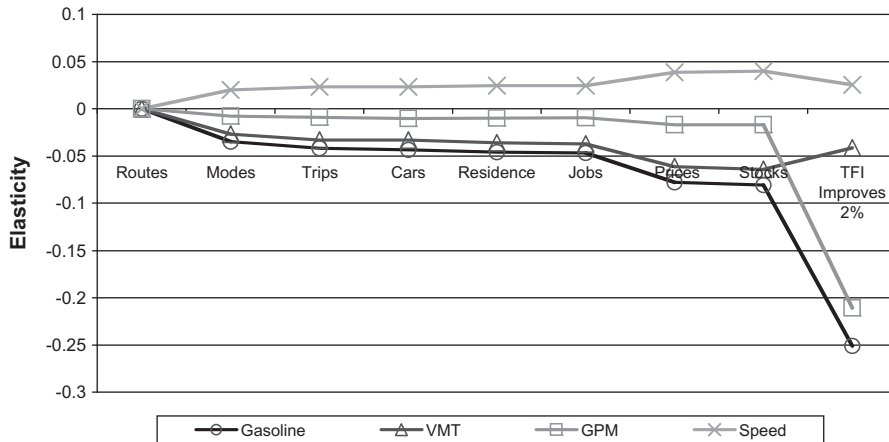


Fig. 5. The gasoline price elasticity of VMT, GPM, speed and GAS.

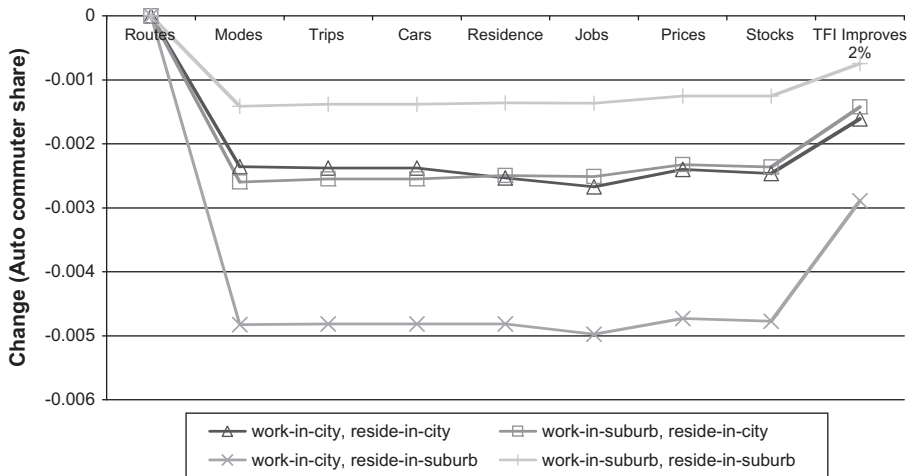


Fig. 6. Auto commuting shares when gas price rises 10%.

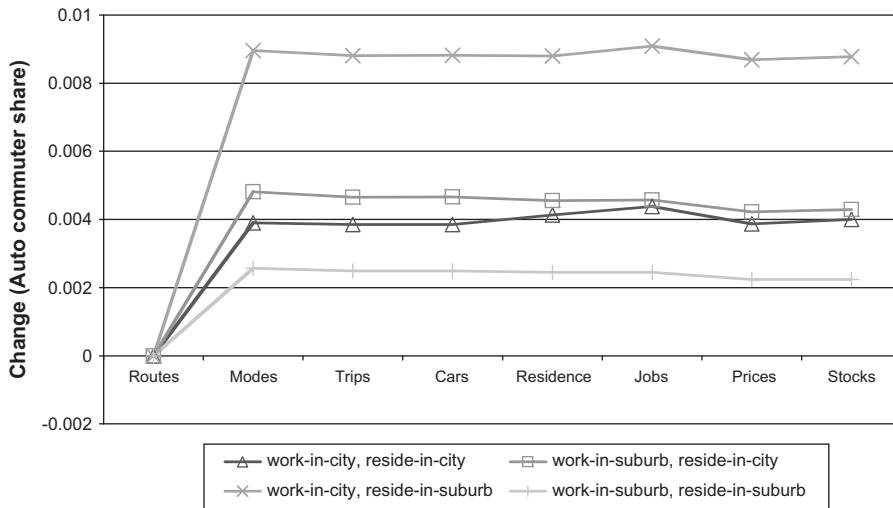


Fig. 7. Auto commuting shares when TFI improves 10%.

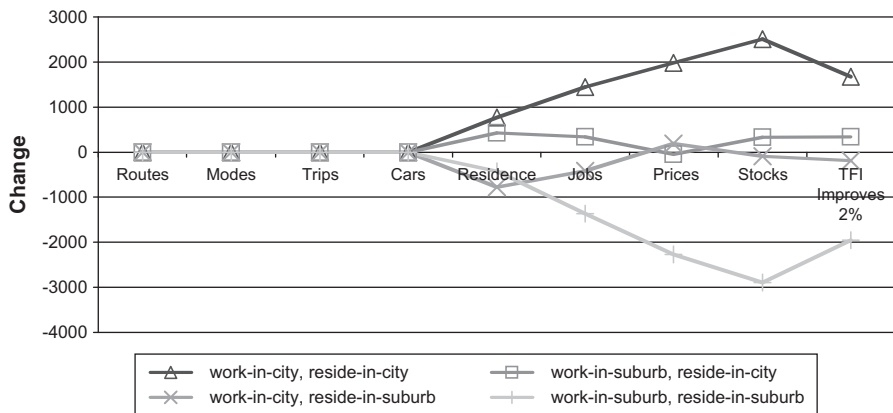


Fig. 8. Number of commuters (sum of all modes) when gasoline price increases 10%.

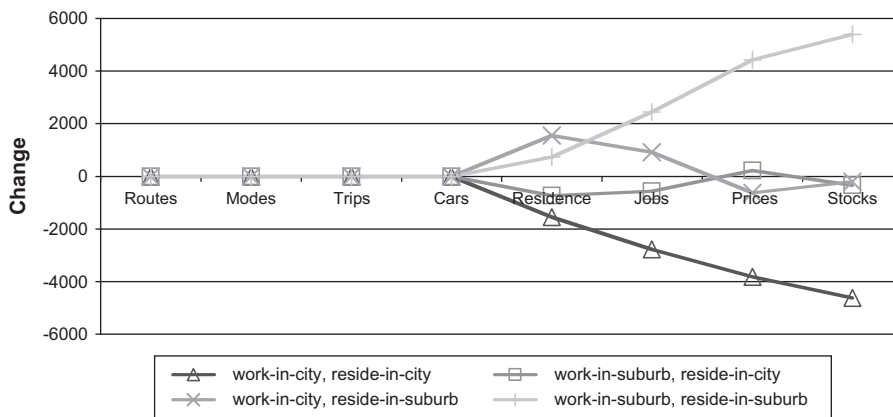


Fig. 9. Number of commuters (sum of all modes) when TFI improves 10%.

also, that the shorter route is more congested and therefore more fuel intensive per mile, but sufficiently shorter so that it is less costly in total monetary cost. Then, an increase in the gas price will cause trips to switch to the shorter route from the longer one if the cost of the longer route increases by more. Hence, VMT and gas use can decrease while MPG can either

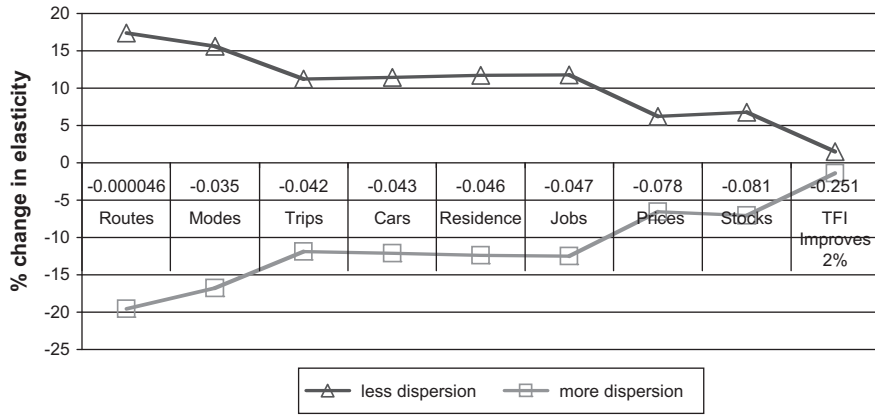


Fig. 10a. Price elasticity of gasoline.

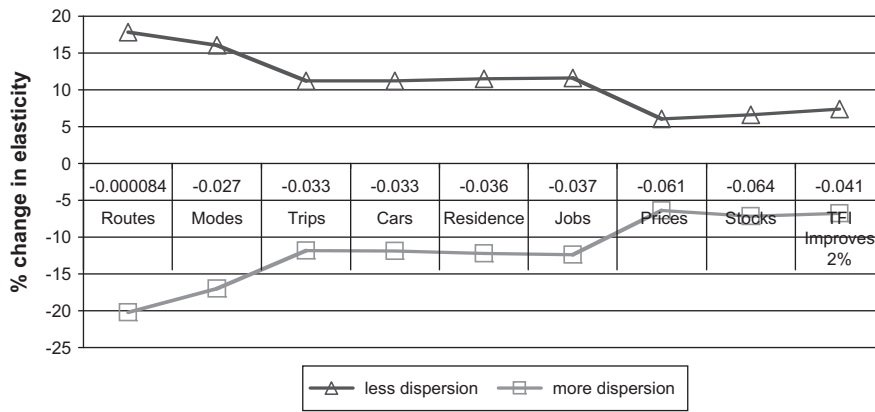


Fig. 10b. Gasoline price elasticity of VMT.

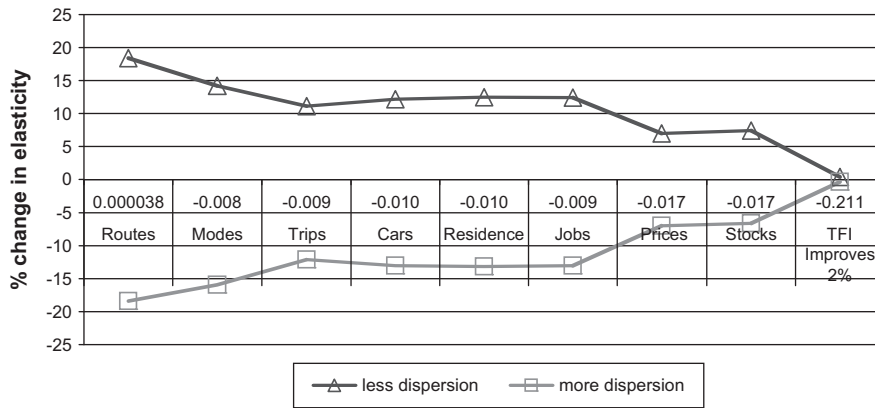


Fig. 10c. Gasoline price elasticity of GPM.

increase or decrease.¹⁰ Once mode choice is allowed (column 2), enough trips switch to transit that aggregate gas use decreases both because there are fewer drivers and because there is less congestion per mile for those still driving. We see from column 2, in this case, that GPM indeed decreases.

¹⁰ A written up rigorous proof is available upon request from the authors.

Second, we see from Table 3 (and Fig. 5) that mode choice enables a big percentage incremental reduction in gas use: the elasticity of gas use when only routes can be adjusted is virtually zero, becoming -0.035 with mode choice. This amounts to about 43% of the long run elasticity. The subsequent steps of trip choices, car type and location adjustments add another 15%. In column 7, rents, wages and retail prices adjust to equilibrium and the elasticity adds another 38% of its long run value. This shows that processes not related to travel and to location choices but to the adjustment of prices make a big difference in how sensitive gasoline consumption is to price. The effect of building stock adjustments accounts for the last 4% of the long-run elasticity (column 8). The long run elasticity including all eight stages and not including trend-line TFI is -0.081 . This elasticity was not targeted by us in calibrating the model, but is an outcome of the model's calibration using the targets and other elasticities discussed in Section 4.

5.2. Exogenous trend-line improvements in fuel intensity

Note from Fig. 1 that CAFE standards stayed constant since 1985 at 27.5 MPG for passenger cars. New passenger cars improved from 24.4 MPG in 1980 to 32.6 MPG in 2009. The average fuel-economy improved from 16 MPG in 1980 to 22.5 MPG in 2007. Fuel economy improvements can be caused by the higher gas price if car producers respond by designing more fuel-efficient cars, or by a tightening of CAFE standards or because of a drop in the relative prices of inputs crucial to better fuel-economy. From 2000 to 2007, new vehicle fuel economy improved by a total of 9.4% but average fuel economy (fleet of new and used cars) improved by a total of 2.7%.¹¹ This corresponds to a 2% reduction in gallons per mile over a 5 year period which we assert we think reasonably, as long enough for all adjustments included in our model.

Column 9 of Table 3 reports the effect of this 2% exogenous trend line improvement in m_1, \dots, m_5 , (shifting down of the curves in Fig. 2) along with the previous adjustments. The column lists the long run percent response of each row variable per 1% increase in the gas price.

Since consumers choose the TFI of their cars, we are able to compare the effect from this demand substitution (column 4 in Table 3) to that from the exogenous fuel economy improvement (column 9 in Table 3). Our results show that the first effect is a lot smaller than the effect from the downward trend line shift of all five curves.¹² Meanwhile, the effect of the 2% trend line improvement is twice as big as that of the long run elasticity of -0.081 (column 8 in Table 3). Thus, the trend line improvement accounts for 2/3rd of the long run response and the endogenous demand reduction for only 1/3rd.

5.3. Rebound effects

From column 8 of Table 3, VMT decreases by 0.64% when all adjustments from a 10% gasoline price increase have occurred. When the 2% exogenous fuel efficiency gain is added, then VMT decreases by only 0.41%. The difference $0.64 - 0.41 = 0.23$ is a 36% rebound due to the reduction in fuel intensity or an 18% rebound per percent reduction in fuel intensity.

In the literature, the rebound effect is sometimes measured in the intensive margin, the fuel cost per mile, something we demonstrated in Section 2.2. Looking at the last row in the top part of Table 3, the fuel cost per mile increases by 9.8% when the price of gasoline increases by 10% and all the lower ranked adjustments have occurred (column 8). This implies a long run rebound of just 2% from a 10% increase in the price of gasoline. From column 9, a 10% increase in the price of gasoline causes a 7.7% increase in the fuel cost per mile when fuel intensity improves exogenously. Thus, the long run rebound from a 10% gas price increase rises from 2% when there is no exogenous improvement in TFI, to 23% or about 12% rebound per percent exogenous improvement in TFI.

5.4. Extensive margin (VMT), fuel intensity and congestion in the intensive margin (GPM)

In the bottom part of Table 3, we report the relative importance of the extensive and intensive margins that contribute to the elasticity in the top part of the table. Note that when all the adjustments but the trend line TFI have occurred (column 8), then 79% of the reduction in aggregate gasoline is from less VMT (extensive margin), and only 21% from a GPM improvement (intensive margin). When the TFI trend is added (column 9), then the shares are drastically reversed: now 84% of the gasoline reduction is from the intensive margin (GPM) and only 16% is from the extensive margin (VMT). The bottom part of the table also shows in column 8 that 16% of the long run GPM reduction comes from substitution in favor of lower-TFI cars and 84% from congestion relief. But once the trend line TFI improvement occurs, then 96% of the GPM reduction comes from lower fuel-intensity and only 4% from congestion relief.

¹¹ Source is Table 4.23 (Average fuel efficiency of US Passenger Cars and Light Trucks), Research and Innovative Technology Administration, Bureau of Transportation Statistics (RITA, 2010).

¹² Car ownership costs (acquisition and maintenance) also change as the TFI curves shift. Our year 2000 annualized marginal cost of car ownership per consumer with respect to TFI is $K'(m_c) = 425.48 \times m_c + 1278.33$. This amounts to a \$ 344 lower annual ownership cost for each MPG improvement in fuel economy.

Table 4
The period 2000–2007.

Inputs to the model		Simulation (2000–2007 change, %)		
		1	2	3
Gasoline price (\$/gallon)		+53.70	+53.70	+53.70
Technological fuel intensity		No change	–2.7	–2.7
Car acquisition costs (\$/year)		No change	No change	–19.2 to –23.0
Outputs of the model		Year 2000 value		
Gasoline (mill.gall./day)	6.17	–4.21	–6.34	–5.20
VMT (mill. miles/day)	132.52	–3.37	–2.99	–2.13
MPG (miles/gallon)	21.48	+0.87	+3.57	+3.24
Speed (miles/h)	21.74	+2.11	+1.87	+1.35
Gas cost/mile (\$/mile)	0.074	+52.37	+48.40	+48.87
Work trips by auto (mill./day)	3.05	–1.58	–1.40	–1.46
Non-work trips by auto (mill./day)	5.73	–3.80	–3.43	–2.06

5.5. Effects by commuting arrangement

The aggregate results of Table 3 and Fig. 5 hide that different commuters are affected quite differently by the gas price or by the TFI improvement. Fig. 6 shows the impact of a 10% gasoline price increase on the shares of car commuters by location pattern. The underlying shares would sum to one only after including mass transit and non-motorized mode shares. Commuters hit hardest by the gas price increase are those residing in the suburbs and working in the city, as they have the longest commutes on average. Most resilient against gasoline price increases are those who work and reside in the suburbs. That is because in suburb-to-suburb commuting, distances and times are shorter and travel is less congested on average, a benefit of job dispersal or housing-jobs balance for those in the suburbs. Fig. 6 also implies that the shares of all commuting arrangements by car are reduced by a gas price increase as switches to mass transit occur. Fig. 7 shows the impact on the same shares for a 10% exogenous improvement in TFI without a change in the gas price. The commuters that benefit most are again those who work in the city but reside in the suburbs. The lower fuel intensity causes more suburbanization of such commuters as it makes longer commutes more affordable. Suburb-to-suburb commuters benefit the least, hence increase the least. In this case, the TFI improvement induces shifts from transit to car and that is why all auto commuter shares in Fig. 7 increase.

Figs. 8 and 9 show how the number of all commuters mass transit and non-motorized included, change by stage of adjustment. Note that in the first four stages (our short run), the number of commuters in each arrangement cannot change, so changes occur only in the long run when locations and prices become flexible. Note from Fig. 8 that an increase in the price of gasoline causes the number of city-to-city commuters to increase and the suburb-to-suburb commuters to decrease. The reason is that by moving to the city where transit is more available, some commuters gain access to mass transit, avoiding the full impact of the gas price. Fig. 9 shows that when TFI improves 10% (no change in gas price), city-to-city commuters decrease while suburb-to-suburb commuters increase as the lower fuel intensity induces some city-to-city mass transit and non-motorized commuters to switch to cars and move out to the suburbs.

5.6. The period 2000–2007

Our last reported simulation is designed to mimic some of the historical changes in the period from the year 2000–2007. The annual average price of gasoline in the Chicago MSA started from a base value of \$ 1.60 per gallon on average in 2000 and climbed steeply to \$ 2.45 per gallon on average in 2007, a +53.7% increase in real terms. At the same time, the TFI of cars changed by a total of –2.7% in the period. Car acquisition costs in real terms changed –19.2% for cars of low TFI and by –23% for cars of high TFI.¹³ Table 4 shows the results of simulations in which these three changes are introduced into the model sequentially while other variables are assumed unchanged at 2000 values. The lower part of the table shows changes in aggregates. In the case of gasoline, the TFI improvement adds about half as much to the reduction in gas demand caused by the price increase but half of this additional demand reduction is taken back by the lower car prices which impart an income effect. The combined effect is a 5.2% total drop in gasoline consumption. VMT drops by only 2.13%, non-work trips by car which are much more discretionary compared to work trips by 2.06% and work trips by car by 1.46%. Meanwhile the consumer substitution of lower TFI cars and the trend line improvement in TFI coupled with lower car prices caused MPG to increase by 3.24% and speed by 1.35%.

¹³ Gas and car prices are from the Bureau of Labor Statistics (consumer price index), <http://www.bls.gov/cpi/>. The TFI trend is from RITA (Research and Innovative Technology Administration) Bureau of Transportation Statistics, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html.

5.7. Sensitivity analysis

Figs. 10a–10c illustrate the effect of changing key parameters on the gasoline price elasticity of gasoline demand, of VMT and of GPM. In RELU-TRAN2 a first multinomial logit model controls route choices, a second mode choices (based on route choice expected generalized costs as the disutility of the car mode) and a third location-housing type and car type choices (based among other things on expected travel times and costs of all modes). The dispersion parameter of each of these logit models is changed up or down 20% from the base calibrated values. Less (more) dispersion in the idiosyncratic tastes of consumers indicates more (less) sensitivity to prices. The same 20% change is also applied to the dispersion of idiosyncratic costs in the developers' model (active in stage 8 only). Figs. 10a–10c indicate how the base elasticities in Fig. 5 (Table 3) are modified by this sensitivity exercise. Note that in the shortest run (stage 1) consumers adjust only route choices. Hence, the elasticity changes a lot (but not more than 20%). But as more margins of adjustment become available in each stage, each elasticity decreases back towards its base value. Thus, the long run elasticity is less sensitive to perturbations in heterogeneity than is the short run elasticity.

6. Conclusions

A spatially disaggregated computable general equilibrium approach is important in understanding how the price of gasoline affects aggregate gas consumption, VMT and on-the-road fuel intensity (GPM) because it determines these effects from basic microeconomic foundations rather than from reduced form regression models. From a methodological standpoint, since this is the first spatially disaggregated CGE model study of gasoline consumption, we believe it serves as a complement to the many econometric studies and points the way to future studies.

Using the RELU-TRAN2 CGE model we were able to quantify how much each stage of adjustment from route choice to full general equilibrium adds to the elasticity of gas consumption (and also to VMT, GPM, etc.). This showed that mode choice and market price adjustments together account for a large part of the elasticity. We were able to achieve three more things. One is to separate the intensive margin (GPM) from the extensive (VMT) in each stage. Second, in each stage, the intensive margin effect was in turn separated into the effect of substitution toward more efficient cars and the effect of congestion reduction. Third, we were able to show that modest trend-line improvements in TFI are responsible for the lion's share of improvements in on-the-road GPM or in aggregate gasoline. In the context of technical progress in fuel-intensity, managing congestion may be relatively less important as it is also politically less tractable. Policies aimed at car fuel intensity improvements are perhaps more important as tools for achieving significant decreases in gasoline use and in emissions.

Acknowledgments

An earlier version was presented at the Kuhmo Nectar Conference on Transport Economics held in Valencia, Spain July 5–9, 2010. We acknowledge 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. Views expressed are solely those of the authors and not of the financial supporters. We thank two anonymous reviewers and co-editor Ken Small for their helpful comments.

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