

**TOWARDS PEAK PRICING IN METROPOLITAN AREAS:
MODELING NETWORK AND ACTIVITY IMPACTS**

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ABSTRACT

Peak-load pricing has long been seen as a way to internalize externalities and, at the same time, as a set of incentives to shift some peak-hour trips to off-peak periods. The policy has also been viewed as a mechanism to generate revenues. But it is an open question how travelers trade off time for money and respond to peak-off-peak pricing differentials. This generates some timely and related questions, including: 1) How can we model the activity location and traffic implications for multiple time-of-day periods in a major metropolitan area? and 2) What are the network level-of-service and urban development effects of implementing peak-load pricing on selected routes? It is seemingly possible to conduct simulations on actual highway networks to treat these questions, but none of the many existing basic urban models is able to examine the issues of simultaneous route choice and time-of-day choice involving millions of travelers, thousands of traffic network zones, and hundreds of thousands of network links in an equilibrium system. This research addresses these questions by extending the Southern California Planning Model (SCPM) so that it can be used to determine the time-of-day, trip distribution, and network traffic effects of various pricing schemes for the greater Los Angeles (five-county) metropolitan area. The model estimates improvements in levels of services throughout the highway network for various toll charges. It examines how drivers trade off route-choice with time-of-day choice against the option of traveling less. Our approach also estimates the implied revenues by local jurisdiction as well as possible land use effects in terms of altered development pressures throughout the region. The effects for two different tolling scenarios are compared and policy implications are discussed.

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I. INTRODUCTION AND BACKGROUND

If price does not ration, something else will. For most U.S. roads and highways, the pricing option has been avoided and rationing by crowding results. The Texas Transportation Institute reports their annual estimates of the resulting costs. Their recent estimate is that losses amount to \$78 billion per year, or about 40 hours per year per urban traveler.¹ Public transit investments have been the preferred policy antidote, but the available evidence shows no negligible effect on road and highway congestion.² The costs of many of these projects can be counted as part of the costs of the policy choice to avoid congestion pricing. The public's reported unhappiness with time spent in slow-moving traffic is apparent in various poll results.³ In addition, recent research has shown that most peak-hour travel is for non-work purposes,⁴ suggesting that pricing could be an incentive for some of these trips to move to off-peak hours, making peak-hour capacity available. Finally, many local governments report that they are facing revenue shortfalls; improved auto energy efficiency will further diminish their revenues from cents-per-gallon revenues. Revenues from road pricing have an obvious attraction for officials in many jurisdictions.

For all of these reasons, transportation economists have long argued for the efficacy of a road pricing policy. But they have with rare exception not been able to persuade policy makers. In the eyes of many, pricing is "inequitable". But things may be changing. Recent research suggests changing public attitudes.⁵ ⁶ And the Federal Highway Administration (FHWA) had in recent years started promoting High Occupancy Toll (HOT) lanes, especially under the previous administration's Value Pricing Program. In 2007, the Federal Transit Administration (FTA) proposed redefining fixed guideways to include dual use

¹ TTI's methodology involves a comparison of reported vehicle-miles traveled with available lane miles. They do this for the major metropolitan areas. http://tti.tamu.edu/research_areas/topic.htm?p_tid=18

² See, for example, Baum-Snow and Kahn (2004) http://www.econ.brown.edu/fac/nathaniel_baum-snow/brook_final.pdf

³ See Zmud and Arce, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_377.pdf

⁴ See Lee et al. Data from the 2009 National Household Travel Survey (NHTS) corroborate these findings. Whereas the 2001 survey showed that 62 percent of all AM-peak (6-9am) person trips were for non-work purposes and 76 percent of the PM-peak (4-7pm) person-trips were for non-work purposes, the corresponding proportions for 2009 were 63 percent and 76 percent. These refer to Monday-Thursday; the Friday patterns are slightly different.

⁵ See http://www.rand.org/pubs/technical_reports/2009/RAND_TR680.pdf

⁶ See, for example, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_377.pdf

HOT/Bus Rapid Transit (BRT) lanes (Poole 2007). The Southern California Association of Governments (SCAG) provides anecdotal evidence that Metropolitan Planning Organizations (MPO) are responding to a seemingly more favorable view by the planning community and placing HOT/BRT projects into regional transportation plans. Actual congestion tolling has been in place in Singapore since 1975 and has more recently been implemented in Norway, Sweden and South Korea, the U.K. as well as on two freeways in California.⁷ Congestion pricing may be an idea whose time has come.

Another auspicious development involves the possibility of what some have called “smart mobility”. GSM-positioning and GPS-tracking technologies vastly expand the possibilities for traffic monitoring, congestion fee determination, and fast feedback to drivers. Whereas “Fastrak”-type toll collection has been available and implemented for some years, the possibilities for the application of modern telecommunications devices are just beginning to be explored. And with these new possibilities, the congestion pricing options are greater than ever. What are the advantages and disadvantages of HOT lanes, cordon pricing, toll roads, pricing on freeways, and their various combinations? Recent experiences in Orange County, for example, suggest many questions remain to be answered. Orange County’s initial response to growth pressures might best be characterized as “don’t build it and they won’t come.” Public authorities maintained a deliberate policy of not increasing road capacity, but growth occurred anyway. Faced with a dramatic decrease in network level of service, policy objectives changed. The Orange County Transportation Authority spearheaded interagency efforts to catch up with the demand for transportation by investing in a variety of toll road facilities, among other strategies. Toll road experience has been mixed and these facilities have not delivered the degree of congestion relief hoped for nor predicted by transportation economists.

The planning challenge is that the abstract systemic representation embedded in the standard economic argument in favor of tolls is replaced by a complex physical network in the real world. It is becoming increasingly evident that, as important as pricing mechanisms are likely to become, their impact on levels of service and the net efficiency of an urban network subject to piecemeal tolling schemes are difficult to predict (Gordon et al., in Richardson and Bae, 2008). In addition, very little is known about how development pressures at various locations throughout a large metropolitan region would be affected.

⁷ Sullivan (2006) discusses these two cases.

This research addressed two timely and related questions. 1) How can we model the traffic and development pressure effects of implementing peak-load pricing on selected routes in a major metropolitan area? and 2) What are the network and development pressure effects of selected pricing choices, as discovered via an application of our model for the Los Angeles metropolitan area?

With respect to possible development effects, consider that some analysts have pinned “excessive urban sprawl” on the absence of road pricing. Indeed, in the simplest monocentric models of cities, low transport costs are linked to lower densities. But even in monocentric models the story becomes more complex when the assumption of a homogeneous population is introduced. Various income groups trade off time for money at distinct rates; how they respond to opportunities to choose between time costs and dollar costs is unique to each. And the availability of these options depends on the peculiarities of the road network in their vicinity – as well as which parts of it are priced and what the prices are. This is why simulations on an actual network are required to address the question. Indeed none of the many extensions of the basic urban model⁸ can possibly identify the net result when a complex population of drivers chooses between a set of paths each made up of a variety of links, some of which are priced and some of which are not. Route-choice and time-of-day choice are compared and system equilibrium is achieved when millions of drivers are indifferent at the margin.

⁸ See Anas (2010) for a summary.

II. THEORETICAL BACKGROUND AND LITERATURE

Economists' interest in road pricing goes back to the early work of Pigou (1932), Walters (1961), and Vickrey (1963). It has been elaborated many times. The simple analysis is clear: absent pricing, traffic can grow to levels that are inefficient, where perceived private marginal benefits are just equal to perceived private marginal costs, but where this volume is inefficiently large because congestion externalities are ignored by each driver. The analysis also points to the user fee (toll) amounts that would internalize the externality. Figure 1 repeats the standard analysis. Drivers equate perceived (private) costs to perceived (private) benefits and the resulting level of traffic is $V(e)$. But at this level, there are external costs that cause the actual cost of each trip to be greater than the perceived private cost. The external costs can be internalized via a toll (user fee). The analysis denotes the toll that would internalize externalities at the efficient level of traffic flow V^* . But the standard analysis illustrates a partial equilibrium result that, while interesting, cannot replicate costs or results on an actual complex network. The latter is analogous to a market general equilibrium.

Consider also that the standard analysis is often used to make the claim that equilibrium shadow prices become available by which possible link expansions within any network can be ranked. The largest toll indicates the link that should be expanded first. But this conclusion may not hold if the links are part of a network. Any particular link expansion can have unique network effects that would have to be considered in a cost-benefit analysis. Gupta et al. (2006) simulated the impacts of road price on transportation and land use as well as economic welfare for Austin, Texas. A travel demand model with joint mode, time of day choice, and destination choice was utilized to examine the effects of different toll scenarios. The model yielded temporal and spatial distributions of traffic, long term changes of location choice, and implications of traveler welfare. Safirova et al. (2006) estimated long term effects of congestion pricing on economic and land use. These models are designed to examine the long term effects of congestion pricing on the transportation system as well as land use. Different from these models, the Southern California Planning Model (SCPM) developed at USC incorporates regional economic input-output analysis and freight traffic, urban location model, and transportation network model to estimate the short-term and midterm effects of congestion pricing (Pan et al. 2011). Our modeling involves comparative statics and we are reluctant to make claims about the long run.

In contrast, Safirova et al (2006) apply the Anas-Xu (1999) model to the Washington DC metropolitan area. They test a cordon pricing policy. Theirs is a general equilibrium model which reports the pricing effects on mode choice as well as long-term land use change

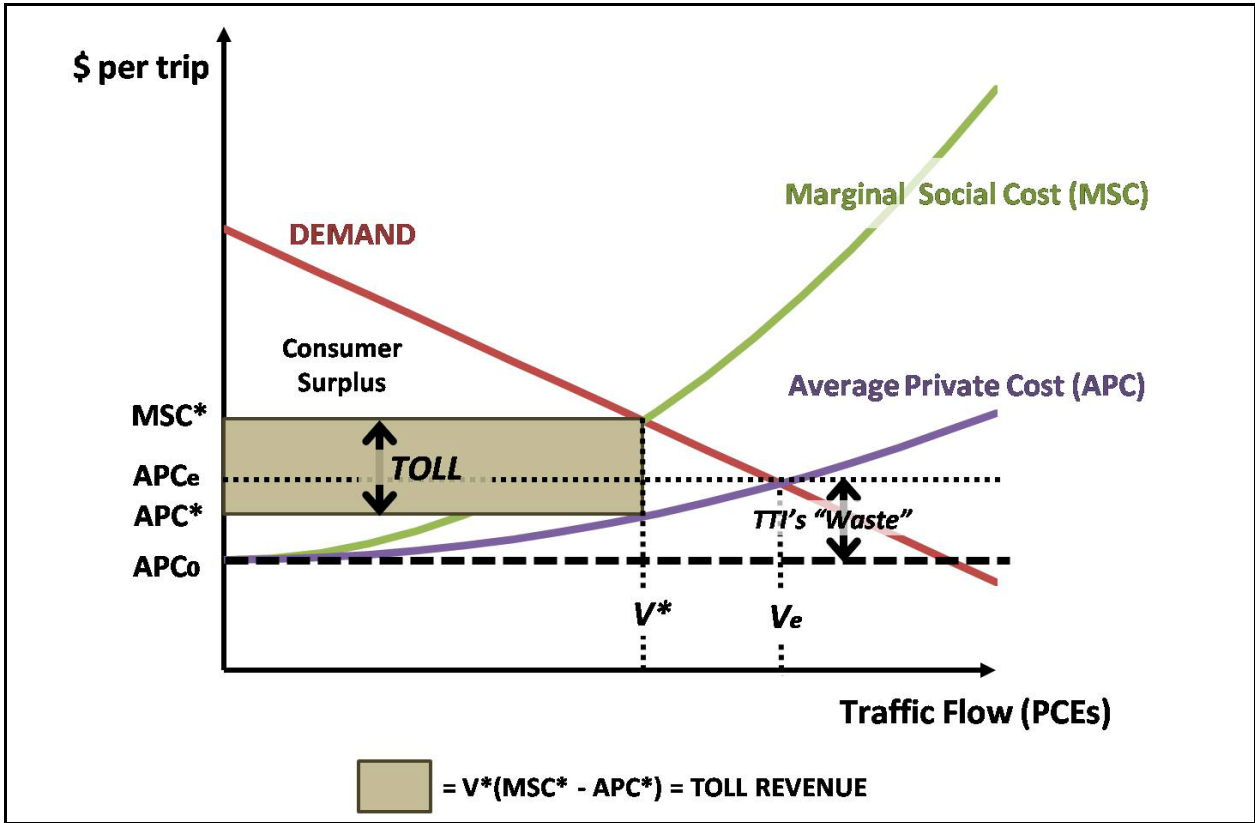


Figure1: Congestion Pricing

III. DATA AND SCENARIOS

3.1 DATA SOURCES AND RECONCILIATION

Data from various sources have been used to develop the Southern California Planning Model (SCPM), which is designed to estimate spatially detailed economic impacts throughout the five-county Los Angeles metropolitan area. Data in the model are for 2001, including a transactions table from a regional input-output model, TAZ-level employment data, passenger OD information, a freight OD database, regional transportation network link files, and political jurisdiction boundaries, etc.

The input-output model component in the current (SCPM 3) model is based on the Minnesota Planning Group's well-known IMPLAN⁹ model (2001). IMPLAN has a high degree of sectoral disaggregation with 509 sectors, which are aggregated to 47 "USC Sectors". The second important model component spatially allocates sectoral impacts including direct, indirect, and induced impacts across 3,191 traffic analysis zones plus 12 "external zones" (entry points that locate shipments to and from the region) throughout region. The TAZs can be aggregated to 282 primarily political jurisdictions. SCPM utilizes network data prepared by SCAG for its 2000 base-year regional transportation model with 3191 traffic analysis zones (TAZs) and 89,356 network links.

Employment data by TAZ by sector are compiled from the Southern California Association of Governments' (SCAG) 2000 job data by business establishment by SIC/NAICs code. We estimated a journey-to-services matrix that includes all the trips classified as SCAG's home-to-shop trips, and a subset of the trips classified as home-to-other and other-to-other trips. The passenger trip matrices by trip purpose are extracted from the SCAG 2000 regional transportation model (SCAG 2003).

SCPM relies on the specification of exogenous direct impacts (final demand changes) at specific TAZs which allocates the indirect effects to TAZs or political jurisdictions using weighted employment or freight flow matrix estimated from a freight model and distributes the induced effects using a journey-to-work matrix. Both of these result from a highway network equilibrium.

⁹ <http://www.implan.com>

This introduces the third basic model component, a freight model that estimates the freight flow OD matrix. The freight model separates regional commodity flows to intra-regional and interregional flows. Intra-regional freight flows are estimated using 2001 I-O transactions table from IMPLAN and 2000 SCAG employment data by sector by TAZ. Interregional freight data such as imports or exports are collected from WISER Trade¹⁰ 2001 dataset, Waterborne Commerce of the United State (WCUS)¹¹ 2000 data, airport import/export data in 2000, Intermodal Transportation Management System (ITMS)¹² 1996 package from California Department of Transportation (Caltrans), and Commodity Flow Survey (CFS)¹³ 1997 data sets. The IMPLAN 2001 data are used as the basis of control total for the freight model that allows adjusting data in different years and maintaining consistency.¹⁴ In order to validate the baseline SCPM freight traffic estimates, we used actual truck count data at eighteen regional screenlines collected by the California Department of Transportation (CalTrans) and SCAG as part of their 2003 Heavy Duty Truck Model study (SCAG/LAMTA 2004).

3.2 SCENARIOS

Our objective was to test the impacts of implementing externality-internalizing tolls using a network model of the Los Angeles metropolitan area. Fortunately, a recent paper by Parry and Small (2009) provides estimates of what such tolls should be for Los Angeles. These authors suggest the efficient congestion as well as pollution and accident externality tolls (less fuel taxes) for peak as well as off-peak hours. Their two estimated congestion charges are \$0.26 per mile and \$0.03 per mile. The associated total charges are \$0.31 and \$0.08, respectively. Our simulations focused on congestion charges only and, rounding the Parry-Small suggestions; we tested scenarios involving \$0.30 per mile and \$0.10 per mile for the two peak periods only. In these tests, we applied the tolls to all freeway links in both peak periods. The dollars per

¹⁰ <http://www.wisertrade.org>

¹¹ <http://www.iwr.usace.army.mil/ndc/wcsc/wcsc.htm>

¹² <http://www.dot.ca.gov/hq/tpp/offices/oasp/itms.html>

¹³ http://www.bts.gov/publications/commodity_flow_survey/

¹⁴ Details on the various freight data sources and reconciliation are in Gordon and Pan (2001), Pan (1996), and Giuliano et al. (2010).

mile congestion toll fees were converted to hours per mile congestion time based on the hourly wage estimated from IMPLAN 2001 data. In the modeling described below, the peak hours are defined as 6-am to 9-am in the morning and 3-pm to 7-pm in the evening for the five weekdays. We realize that a large number of alternate policies can be tested and we plan to study these in future work.

IV. MODEL AND ALGORITHM

Various versions of SCPM have been developed since the 1990s. The early version (SCPM 1; SAS-based) was a regional input-output model to trace all economic impacts, including those of intra- and interregional shipments, usually at a certain level of sectoral and geographical disaggregation. Like most other inter-industrial models based on the transactions flows between intermediate suppliers and end producers. The earlier SCPM 1 was demand driven to account for losses primarily via backward and forward linkages between economic sectors. Different from many other inter-industrial models, however, it allocated regional economic impacts to geographic zones such as political boundaries.

A later version (SCPM 2) was developed using the C programming language in the late 1990s. An obvious enhancement of SCPM 2 was to endogenize traffic flows, which incorporates transportation network model with gravity models to allocate indirect and induced impacts generated by input-output model to the TAZs. When traffic flows are endogenous, any change in economic activity that affects the travel behavior of individuals or the movement of freight will influence how the transportation network is used, and these impacts will work themselves out as change from one network equilibrium to another. This extension allowed use of the freight database in the regional transportation model. Similar to most traditional travel demand model, the transportation network modeling components in SCPM 2 involved consistent, robust, and practical estimates on traveler's route choices. But this version only involved modeling traffic in the three-hour AM-peak period using static user-equilibrium assignment. The model structure is shown in Figure 2. It starts with the design of scenarios for exogenous shocks on the region, e.g. a terrorist attack. The event triggers facility losses or closures, such as the loss of bridges or port closure, which further reduce highway network capacity or trading capacity. There are supply as well as demand impacts on the highway network. The change of final demand due to the direct losses of trading capacity are employed to estimate indirect and induced effects in an I-O model. SCPM's spatial allocation component allocates

direct, indirect, and induced effects to the TAZs or political jurisdictions, which makes the I-O model in SCPM different from a standard I-O model. The economic impacts also change baseline freight flows. The change of network capacity and freight flows has been handled by the transportation network components of SCPM to re-estimate origins and destinations of passenger and freight trips, link and path flows, and link and path travel time at the new network equilibrium.

The current SCPM 3 inherits all the capabilities of previous versions and adds time-of-day functions to model AM-peak, PM-peak, and off-peak traffic. SCPM 3 is developed to facilitate an understanding of the actual effects of peak-load pricing on a complex land use-transportation system, including impacts on transportation network performance at the link level and activity effects at the TAZ level.

4.1. SCPM and Preliminary Peak-Load Pricing Study

The early versions of SCPM employed the traditional user equilibrium algorithm in its travel demand modeling that assumes the trip rates between every origin and destination are fixed for the peak time period. To analyze the effects of congestion tolls, SCPM was extended in this research to incorporate time-of-day factors in its travel demand model. In addition to the AM-peak, traffic in other periods is estimated in the new SCPM model using SCAG's vehicle trips-in-motion factors compiled from its Year 2000 Survey. The fixed-demand assumption for each period was relaxed. Cash tolls are factored into the generalized travel cost function that drivers are thought to respond to. Freight travel may also change routes as reaction to the change of travel costs by cash tolls but it will not shift the time period.

To project the change of demands in response to the change of travel costs, time period share functions are developed for personal trips. The personal trip demand share in time period i for OD pair o, d is calculated using the following logit model,

$$S_{i,o,d} = \frac{R_i \times f(Cost_{i,o,d})}{\sum_{j=1}^n R_j \times f(Cost_{j,o,d})}$$

Where, $f(Cost_{i,o,d})$ is the function of price elasticity of traveling demands for zonal pair o, d in time period i .

R_i are the vehicle trips-in-motion factors (time-of-day factors) from SCAG.

Usually an exponential function is used in the logit model. Therefore, the personal trip demand share is calculated as:

$$S_{i,o,d} = \frac{R_i \times e^{(-Cost_{i,o,d})}}{\sum_{j=1}^n R_j \times e^{(-Cost_{j,o,d})}}$$

and the travel cost is calculated as:

$$Cost_{i,o,d} = \min_{p \in A_{o,d}} \{vt_{i,p} + \tau_{i,p}\}$$

where p is an index of paths, i is an index of time period, $A_{o,d}$ is the set of paths connecting origin o to destination d , $t_{i,p}$ is the travel time on path p in time period i , v is user's value of time, and $\tau_{i,p}$ is the toll charge on path p in time period i .

The updated model follows the general procedures of previous SCPM 2005 model but apply the personal trip demands calculated from the time period share function to re-estimate the personal trip ODs by time period. The model runs iteratively to relocate trips from peak hours to the off-peak in light of relative travel costs at different time periods. Trips are also reallocated by routes within time periods, also in light of travel costs within the same time period. The model structure is shown in Figure 3. It illustrates the modeling framework using the actual functions developed for the model and changes of model structure from the previous SCPM 2005 are highlighted in red. For example, the personal trip O-D matrices are developed for multiple time periods in stead of one peak hour period. The cash tolls are supposed to change the demand of personal travel or shift the time period of personal trips in addition to change the routes of trips. Similarly, the freight trip O-D matrices are estimated for different time periods. In our assumption, freight travel does not change demands or shift time period as a reaction to cash tolls though

freight trips may change routes. Passenger and freight trips are loaded together to regional transportation network for different time periods. The updated travel costs feed back to the model and re-estimate the passenger trips in different time periods.

The model was employed to examine the effects of two scenarios, \$0.30 per mile and \$0.10 per mile tolls. The tolls were applied on all the highway links in the five-county Los Angeles region. As expected, some peak-hour trips are re-allocated to the off-peak and travel times are reduced at the peak-hours and increased at the off-peak hours. More trips from the AM-peak are reallocated to off-peak than those from the PM-peak because the AM-peak has much higher average travel costs than PM-peak and there are many more non-work trips in the PM-peak. In both scenarios, most of the areas (TAZs) with large decreases of trip production in the peak hours are located at the regional boundaries or county boundaries, which have less freeway access. Most of the areas (TAZs) with small increases of trip production are located closer to the center of the region (Pan et al., 2009).

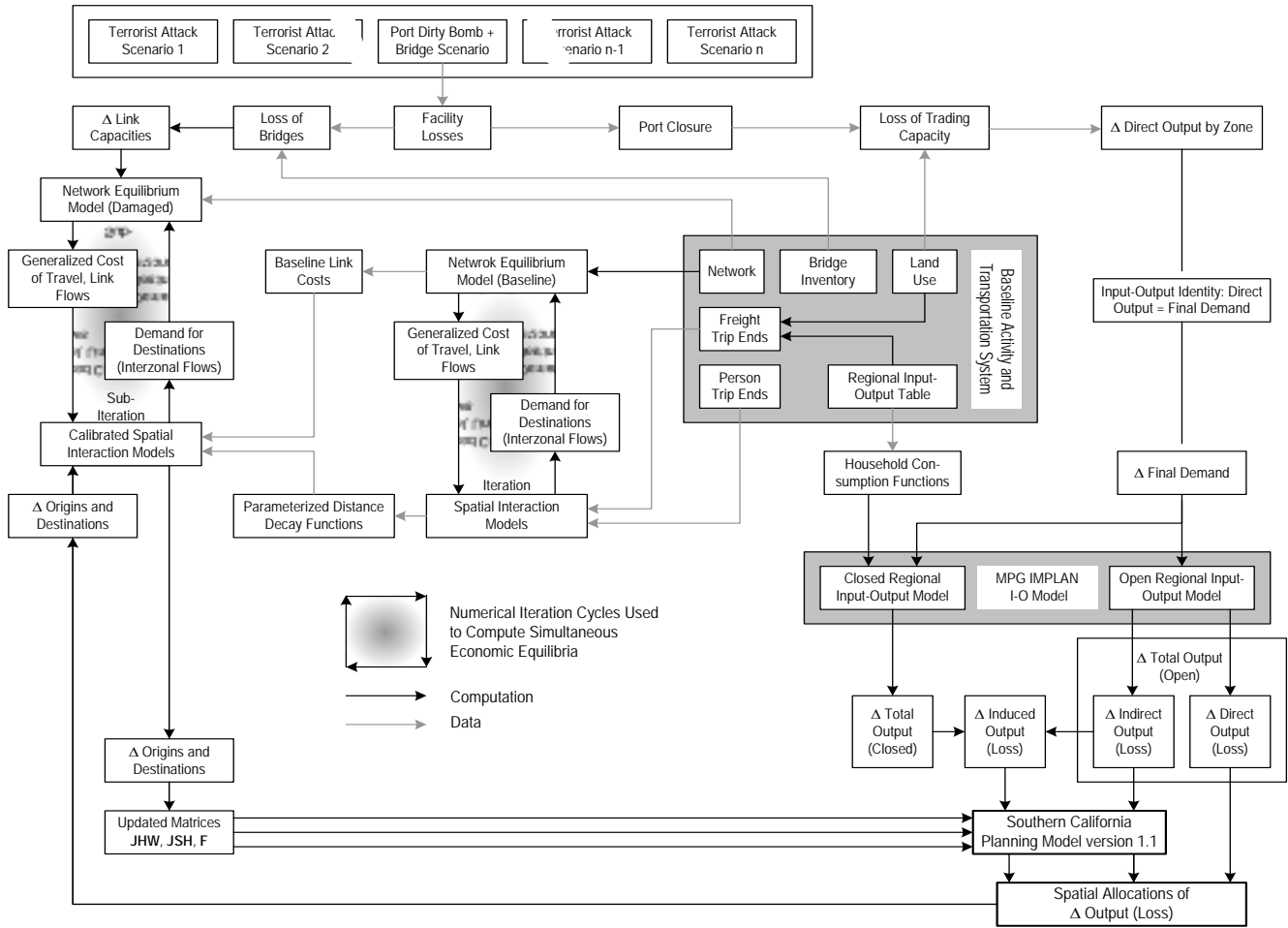
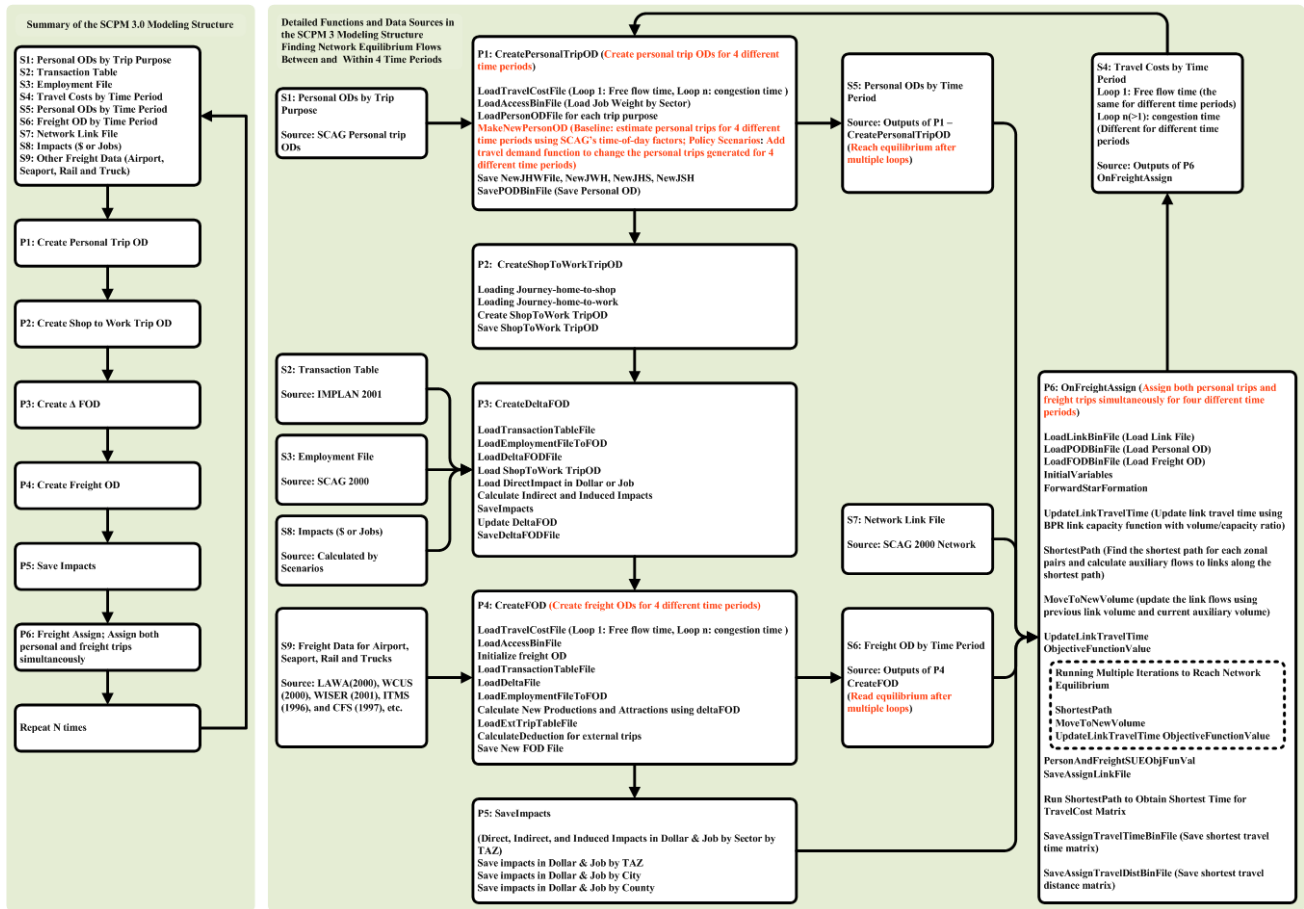


Figure 2. Previous SCPM Data flows and model calculations



4.2. Model Structure and Algorithm Developed for SCPM in Peak-load Pricing Experiments

In the literature, user equilibrium with variable demand (UE-VD) problems have been discussed for scenarios with trip rates influenced by the level of service on the network, i.e. travelers may change the time of travel to get around traffic congestion. Some recent studies (see Verhoef 2002, Zhang and Ge 2004) addressed various second-best tolling issues which are beyond the scope of this paper. In the variable demand scenarios, the fixed trip rate assumption in user equilibrium algorithm developed for traditional travel demand model is dropped. The trip rate is assumed to be determined by the travel time between origin and destination.

Various demand functions have been proposed and different UE-VD algorithms are developed to find the link flows, the link travel times, and the O-D trip rates under the user equilibrium condition. We adopted the appropriate algorithms for the SCPM model to study the time-of-day effects on travel demand and economic activities.

Based on the algorithms described by Shefi (1985), the user equilibrium with variable demand model (UE-VD) for time of the day choice is formulated as follows:

$$\text{Min } \sum_a \int_0^{x_a} t_a(x) dx - \sum_{o,d} \int_0^{T_{o,d}} D_{o,d}^{-1}(x) dx \quad (4.1)$$

$$\text{subject to } x_a = \sum_o \sum_d \sum_p \delta_{a,p}^{od} h_p^{od} \quad \forall a \quad (4.2)$$

$$\sum_p h_p^{od} = T_{od} \quad \forall o, d \quad (4.3)$$

$$h_p^{od} \geq 0 \quad \forall p, o, d \quad (4.4)$$

$$T_{od} \geq 0 \quad \forall o, d \quad (4.5)$$

$$T_{od} \leq \overline{T_{od}} \quad \forall o, d \quad (4.6)$$

where x_a is the total flow on link a .

$t_a(x)$ is the cost-flow function to calculate average travel cost on link a .

$\delta_{a,p}^{od}$ is link-path incidence variable; equal to one if link a belongs to path p connecting OD pair o and d ,

h_p^{od} is flow on path p connecting OD pair o and d ,

T_{od} is peak-hour trip between origin node o and destination node d ,

\bar{T}_{od} is the total trip between origin node o and destination node d ,

p is a network path, o and d are two end nodes on the network,

$D_{o,d}^{-1}(x)$ is the inverse of the demand function for O-D pair (o,d) .

One of the most widely used demand functions is the logit formula that represents the change of demand in terms of congestion time. The peak-hour trips between origin node o and destination node d T_{od} is calculated using a demand function in the logit formula as follows,

$$T_{o,d} = \bar{T}_{o,d} \frac{1}{1 + e^{\theta(t_{o,d} - t'_{o,d})}} \quad (4.7)$$

where, t_{od} is the minimum travel time at peak period between O-D pair o,d ,

t'_{od} is the minimum travel time at free flow (or off-peak period) for O-D pair o,d ,

$\bar{T}_{o,d}$ is the total trips allocated for peak period using trips-in-motion factors between O-D pair o,d ,

θ is a parameter that can be calculated using historical data or determined by local knowledge or experience.

Then, the inverse demand function would be,

$$D_{o,d}^{-1}(\bullet) = t_{o,d}(T_{o,d}) = \frac{1}{\theta} \ln\left(\frac{\bar{T}_{o,d}}{T_{o,d}} - 1\right) + t'_{o,d} \quad \forall o,d \quad (4.8)$$

To solve the variable demand problem with an efficient fixed-demand formulation, an excess demand function is derived by replacing the peak-hour trip $T_{o,d}$ with total trips $\bar{T}_{o,d}$ minus excess demand trips $T'_{o,d}$ in (4.8). The excess demand function is shown as follows,

$$W_{o,d}(T'_{o,d}) = \frac{1}{\theta} \ln\left(\frac{T_{o,d}}{\bar{T}_{o,d} - T'_{o,d}}\right) + t'_{o,d} \quad \forall o,d \quad (4.9)$$

We also know that the variable travel demand can be expressed in terms of excess demand through a network representation. We can derive the following formula

$$-\sum_{o,d} \int_0^{T_{o,d}} D_{o,d}^{-1}(x) dx = -\sum_{o,d} \int_0^{T'_{o,d}} w_{od}(v) dv \quad (4.10)$$

Then, formula (4.1) can be rewritten as follows,

$$\text{Min} \sum_a \int_0^{x_a} t_a(x) dx + \sum_{o,d} \int_0^{T'_{o,d}} w_{od}(v) dv \quad (4.11)$$

The link cost-flow function in the formula (4.1) is shown as follows,

$$t_a = t_a(0) \left[1 + \lambda \left(\frac{x_a}{K_a} \right)^\beta \right] \quad (4.12)$$

where $t_a(x)$ is the cost-flow function to calculate average travel cost on link a, and $t_a(0)$ is the free-flow travel cost on link a,

x_a is the total flow on link a, including both personal trips and freight trips,

K_a is the capacity of link a,

λ and β are parameters, while $1 + \lambda$ is the ratio of travel time per unit distance at practical capacity D_a to that at free flow. Both λ and β are estimated from empirical data. Based on the link capacity function published by Bureau of Public Roads (BPR, 1964), λ is assigned a value of 0.15 and β is assigned a value of 4.

If we plugged in the inverse demand function (4.9) with given parameters and the link cost-flow function (4.12) into formula (4.11), we get the objective function of the user equilibrium with variable demand model (UE-VD).

The solution algorithm is summarized as follows,

- Step 0: **Initialization.** Perform all-or-nothing approach to assign trips using free flow travel costs $t_a = t_a(0)$, for each link a on the empty network. Initial feasible solutions of link flows x_a and O-D trips $T_{o,d}$ in a given peak period are obtained.
- Step 1: **Update.** The travel time on link a is updated as $t_a = t_a(x_a)$ and inverse demand function value $D_{o,d}^{-1}(T_{o,d}) \forall o, d$ is calculated using formula (4.8).
- Step 2: **Find a feasible descent direction.** Use the updated travel time $\{t_a\}$ for an all-or-nothing assignment for the trips.

Given the minimum travel cost of all the paths connecting o and d at the n th iteration is the travel cost in path m , $C_{o,d}^{m,n}$, where $C_{o,d}^m = \min_{\forall k} \{C_{o,d}^k\}$, which is also the peak hour travel time of the O-D trips $T_{o,d}$ between the pair o, d .

- (1) If $C_{o,d}^m < D_{o,d}^{-1}(T_{o,d})$, then all the trips $T_{o,d}$ will be assigned to this minimum cost path and flows to all the other paths would be 0, i.e. path flow $g_{o,d}^m = T_{o,d}$, and $g_{o,d}^k = 0 \forall k \neq m$,
- (2) If $C_{o,d}^m \geq D_{o,d}^{-1}(T_{o,d})$, then flows to all the paths would be 0, i.e. path flow $g_{o,d}^k = 0 \forall k$,

It yields a set of auxiliary link flows $\{u_a\} \{v_{o,d}\}$ with trips in PCEs as follows,

$$u_a = \sum_o \sum_d \sum_k \delta_{a,k}^{od} g_{o,d}^k \quad \forall a$$

$$v_{o,d} = \sum_k g_{o,d}^k, \quad \forall o, d$$

Step 3: **Find optimal parameter.** A linear approximation algorithm (LPA) such as Golden section method described in Sheffi (1985, Chapter 4) is applied to obtain optimal parameter α satisfying the UE-VD equation:

$$\text{Min} \sum_a \int_0^{x_a + \alpha(u_a - x_a)} t_a(x) dx - \sum_{o,d} \int_0^{T_{o,d} + \alpha(v_{o,d} - T_{o,d})} D_{o,d}^{-1}(x) dx \quad (\text{Eq. 4.1})$$

or the derived objective function formula (4.11)

Step 4: **Update link flows.** Link flows x_a is changed to be $x_a + \alpha(u_a - x_a)$, O-D flows $T_{o,d}$ is updated as $T_{o,d} + \alpha(V_{o,d} - T_{o,d})$

Step 5: **Test Convergence.** The process stops when a convergence criterion is satisfied and link flows are the optimal link flows at equilibrium condition. Otherwise, go back to Step 1 and continue the process.

This UE-VD algorithm is applied to three time periods, AM-peak, PM-peak, and off-peak, to examine the time-of-day effects of two toll scenarios, \$0.1 per mile and \$0.3 per mile. The dollars per mile toll fee is converted to hours per mile congestion time based on the hourly wage estimated from IMPLAN 2001. The ‘‘congestion time’’ as transformed from the toll fee is employed to adjust congestion time that will further change the travel demand in different time periods. The \$0.1 per mile toll is converted to 0.0057 hr/mile or 0.3407 min/mile while the \$0.3 per mile toll is converted to 0.0170 hr/mile or 1.0220 min/mile.

The delta trips or the excess demands in both AM- and PM-peak periods, i.e. the difference between the total trips allocated to the peak period using trips-in-motion factors ($\bar{T}_{o,d}$) and the trips estimated by the demand function ($T_{o,d}$), are added to the off-peak period under the assumption that travelers will shift their travel time in response to congestion level in peak hours. The delta trips in the off-peak are removed under the assumption that some travelers will cancel their trips if both peak hour and off-peak travel costs increase beyond their budgets.

The shortest travel time rather than shortest travel distance is applied to finding the shortest path in the traffic assignment function. The traffic assignment model with UE-VD algorithm runs iteratively to reach equilibrium. The change of travel time and the

change of travel distance of trips on both highway and local road are calculated and reported by the model.

V. RESULTS

How would various toll charges improve levels of service on the Los Angeles network?

How do drivers trade off route-choice with time-of-day choice – against the option of traveling less? What are the revenue transfer implications? What are the effects in terms of development pressures around the region? Our simulations of two scenarios suggest some of the answers.

5.1. LEVELS OF SERVICE AND TOLL REVENUES

Table 1 includes a summary of results gleaned from the more detailed findings in Tables 1-2 of the Appendix. Most trips involve freeways (tolled in our scenarios) as well as surface streets (not tolled). We focus on changes for the total trip (average and total trip times) as well as changes for the freeway and surface street components. We find that, depending on the scenario, the extent to which drivers used tolled vs. untolled segments, varied substantially.

Assuming that there are 250 days of the year in which congestion tolling occurs, the lower toll (\$0.10/mile) transfers substantially more revenue to the tolling authority than would the higher toll (\$0.30/mile), \$1,420 million vs. \$550 million. Table 3 in the Appendix shows that revenue estimates are available for the various counties of the metropolitan area. Our model also makes them available for spatial units below the county.¹⁵

Overall (24-hour) trip volumes change very little, with a small decrease at the higher toll (-0.42 percent vs. 0.06 percent). The higher toll moves trip volumes from the peaks to the off-peak periods, but the trip volume effects for the lower toll are very minor – and seemingly in the wrong direction. But substitutions from tolled roads to non-tolled roads are a big part of the story. Both tolls cause improvements in average and total freeway travel times, but at

¹⁵ King, Manville and Shoup (2007) have argued for the usefulness of such information in order to form a political constituency for peak-load pricing. In his analysis, the cities traversed by tolled freeways would share in the revenues.

the cost of increased travel times on non-tolled surface streets. For the lower toll, this adds up to only minor changes in overall travel times. For the higher toll, aggregate travel times increase as riders try to avoid the toll.

Total and average daily travel time is almost unchanged for the lower toll, but increase somewhat at the higher user fee. The significant changes are, as expected, in the shifts from peak to off-peak. And these shifts are revealed by average and total trip time impacts which are much larger for the higher toll. At the same time, for both tolls, there are substantial shifts from tolled to non-tolled roads in each peak period, more so for the larger toll. Off-peak traffic increases for tolled as well as non-tolled roads for the higher toll, but decreases slightly for both at the lower toll. If we accept the Parry-Small findings (the higher toll), internalizing the externalities has high costs.

The trade-off facing policy makers is complex: internalized externalities vs. improved peak-hour levels-of-service vs. greater revenues collected. Notably, improved levels of service on tolled freeways comes at the expense of greatly increased use of surface roads.

5.2. DEVELOPMENT PRESSURE EFFECTS

The application of SCPM generates detailed network effects as well as information on changed trip production for each of the region's TAZs. Regional maps showing the latter effects are shown in Maps 3.1 and 3.2 in the Appendix. Trip production can be thought of as an indicator of land development pressures. In this way, we get a hint of how regional development patterns might eventually change. We resist labeling this as land use change for two reasons. First, land use arrangements are durable and change slowly. Second, the time interval is long enough to include many unpredictable exogenous stimuli. We have already mentioned that most analysts expect that a priced network will bring about higher densities and a less spread out (less "sprawled") metropolitan area. But we have also noted that these suggestions do not reflect the large number of trade-offs that occur in a complex network.

Inspection of the two maps shows that patterns of change are hard to discern or summarize, but one thing does jump out immediately: development pressures shift downward, across-

the-board, for the higher fee but they shift upward, across-the-board, for the lower toll. We wondered whether there is any association between TAZ population density and changes in trips produced. The two plots shown in Figures 4a and 4b show that there is no apparent link. This supports our argument that studying an actual network can yield surprising results that may not be available from discussions involving abstract models.

Table 1. Summary of two pricing scenarios network effects

NETWORK TRAVEL TIME AND REVENUE IMPACTS (ALL CHANGES IN PERCENTAGES)											
\$0.30 per mile toll on all freeways; total revenue transferred from drivers to collecting agent = \$550 million/year						\$0.10 per mile toll on all freeways; total revenue transferred from drivers to collecting agent = \$1,420 million/year					
Period	Trip Volume	Comments	Total Travel Time	Ave. Travel Time	Comments	Period	Trip Volume	Comments	Total Travel Time	Ave. Travel Time	Comments
DAILY						DAILY					
	-0.42%	Pricing has caused some trips to be cancelled	6.50%	6.95%			0.06%	Efficient use of ntwk accounts for small increase in volumes	0.41%	0.34%	
AM-PEAK						AM-PEAK					
Freeways			54.16%	50.15%	Faster travel on less congested freeways	Freeways			13.17%	14.15%	Faster travel on less congested freeways
Local roads			43.08%	55.61%	Slower travel on roads that accommodate more trips	Local roads			12.31%	11.03%	Slower travel on roads that accommodate more trips
Total	-8.05%	Pricing has moved some trips away from peak	2.73%	11.72%		Total	1.15%	Efficient use of network accounts for small increase in peak volume	1.74%	0.58%	
PM-PEAK						PM-PEAK					
Freeways			56.55%	54.18%	Faster travel on less congested freeways	Freeways			15.18%	15.78%	Faster travel on less congested freeways
Local roads			51.28%	59.53%	Slower travel on roads that accommodate more trips	Local roads			12.85%	12.04%	Slower travel on roads that accommodate more trips
Total	-5.17%	Pricing has moved some trips away from peak	7.95%	13.84%		Total	0.72%	Efficient use of network accounts for small increase in peak volume	1.59%	0.86%	
OFF-PEAK						OFF-PEAK					
Freeways			8.29%	2.83%	Slower travel as off-peak accommodates more trips	Freeways			-1.15%	-0.40%	Slightly faster travel due to lower trip volumes
Local roads			7.02%	1.63%	"	Local roads			-1.00%	-0.25%	"
Total	5.30%	Pricing has moved some trips to off-peak	7.53%	2.11%	"	Total	0.75%	Better peak use takes some trips away from off-peak	1.06%	0.31%	"

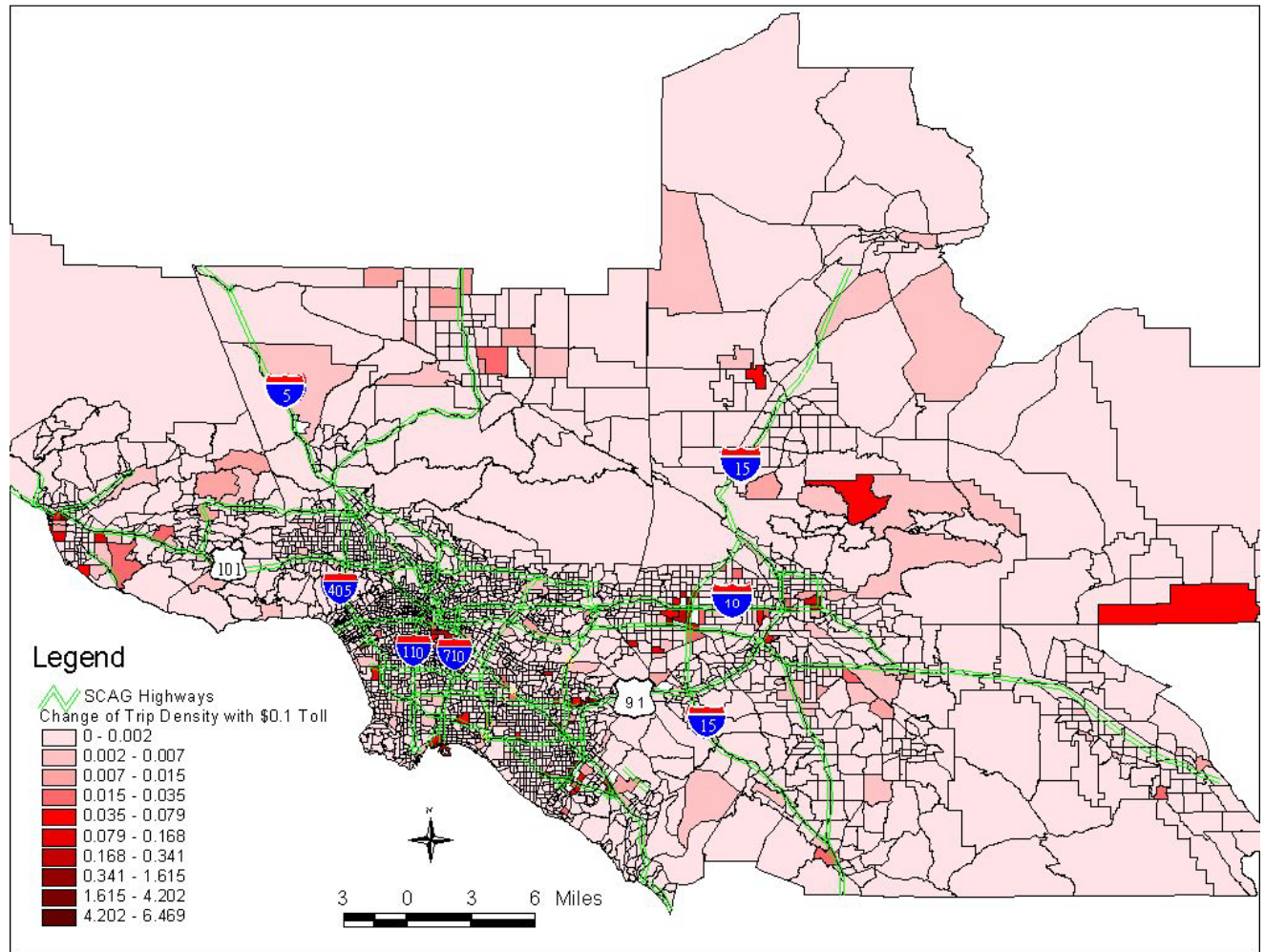


Figure 3.1. The Change of Trip Production Densities, \$0.10 Toll Scenario

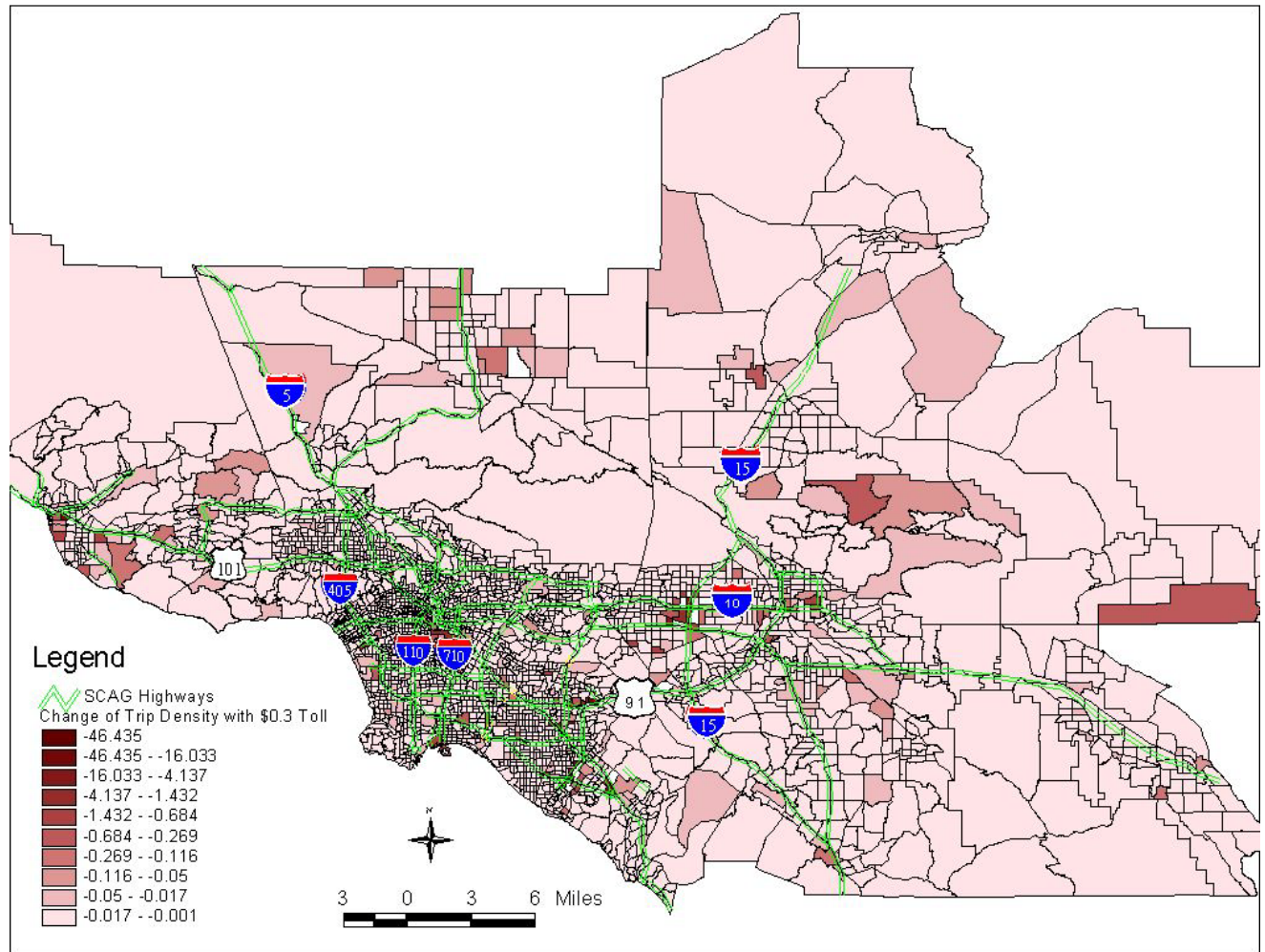


Figure 3.2. The Change of Trip Production Densities, \$0.30 Toll Scenario

Figure 4a. Delta Passenger Trip Production vs. Population density

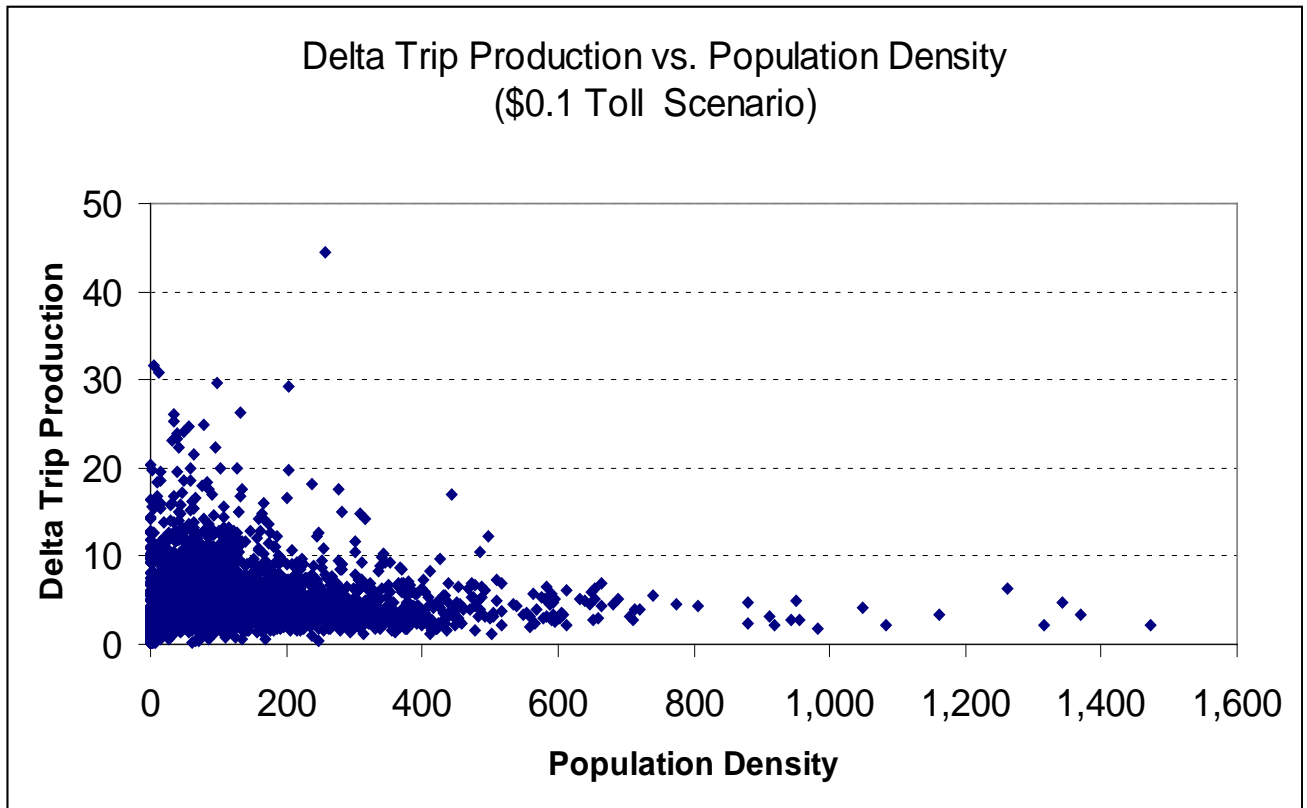
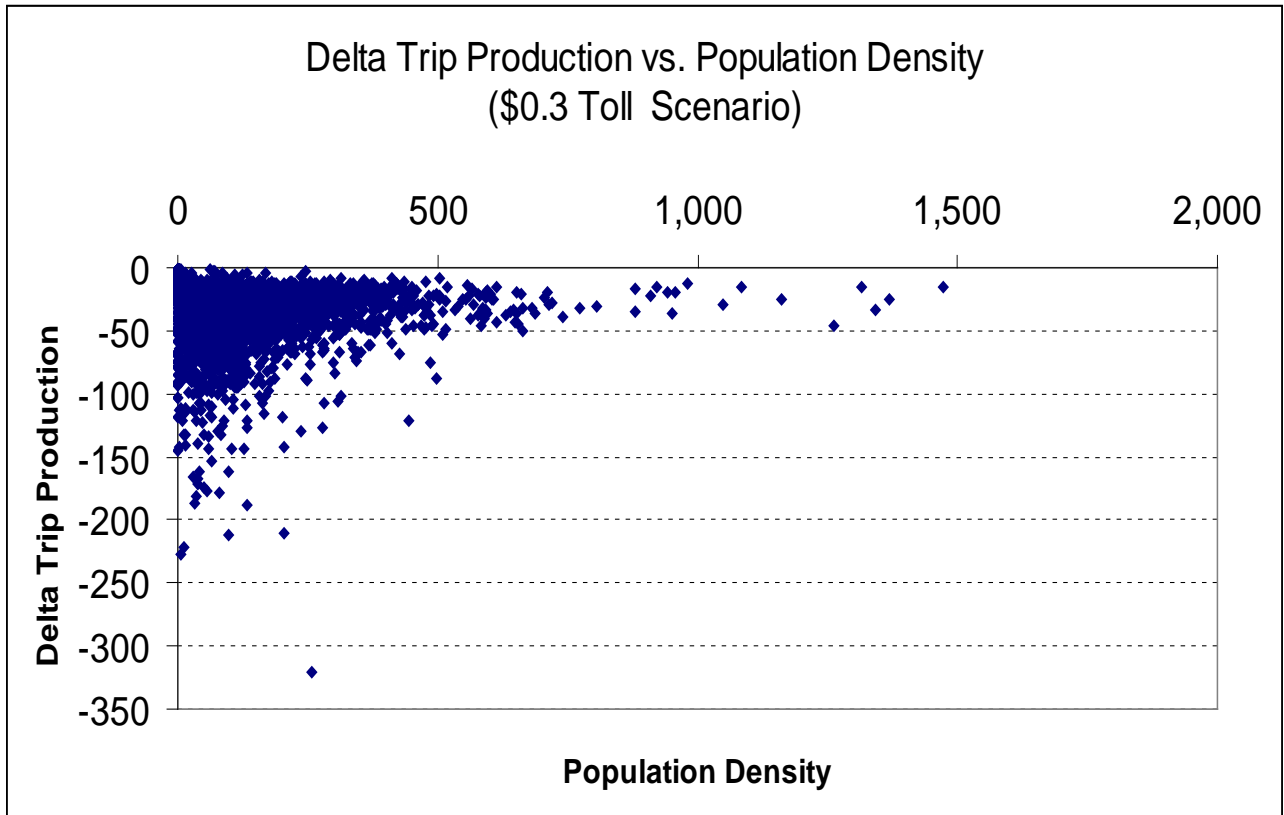


Figure 4b. Delta Trip Production vs. Population Density, the \$0.10 Toll Scenario



VI. CONCLUSIONS

Free access to roads and highways is the dominant approach in most of the world's cities. As more and more people reach a level of affluence to enable them to afford an automobile, road congestion spreads. The various proposals to alleviate the problem (invest in public transit, seek transit-friendly high-density development, narrow roads to discourage auto use, etc.) have their roots in the reluctance to price scarce road space. Our claim is that the political aversion to pricing can be challenged via a better understanding of its consequences. To that end, we have developed a modeling approach to do just that. Tolling all freeways *can* have negative total travel time effects because they prompt increasing use of surface streets. This depends on the level of the tolls set. This raises the issue of whether policy makers may want to consider alternatives to full internalization which involve reconsidering the use of the Parry-Small toll estimates.

Finally, we have not explicitly addressed the discussion of privatization.¹⁶ But if segments of any highway system are to be auctioned off, both buyers and sellers are better off if informed of the time savings expected to be achieved at each level of tolling. Again, these magnitudes are most plausible if estimated from a simulation of traffic and tolls on a network that corresponds to reality and that includes the actual link or links under consideration.

Two significant elaborations of our modeling approach are planned. First, while we do account for freight flows in our model, we have not yet tracked the effect of tolls on truck traffic. Second, we plan to also identify the effect that tolling has on various user income groups.

¹⁶ See Roth (2006) for a discussion of road and highway privatization.

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APPENDIX

Table 1A. Passenger Trips and Travel Time for Baseline and Scenario, AM Peak, PM Peak and Off Peak
(Toll = \$0.30 per mile)

Time Period	Type of Road	Baseline			Scenario			% Change		
		Trips (PCEs)	Total Travel Time (PCE*Mins)	Average Travel Time (Mins)	Trips (PCEs)	Total Travel Time (PCE*Mins) ¹	Average Travel Time (Mins) ¹	Total Trips	Total Travel Time	Average Travel Time
AM Peak	Hwy	4,926,850	28,796,972	5.84	4,530,046	13,200,017	2.91	-8.05%	-54.16%	-
	Local		40,596,044	8.24		58,084,184	12.82		43.08%	50.15%
	Total		69,393,016	14.08		71,284,201	15.74		2.73%	11.72%
PM Peak	Hwy	7,724,865	34,568,832	4.48	7,325,475	15,021,011	2.05	-5.17%	-56.55%	-
	Local		51,464,912	6.66		77,855,680	10.63		51.28%	54.18%
	Total		86,033,744	11.14		92,876,691	12.68		7.95%	59.53%
Off peak	Hwy	12,959,679	52,908,392	4.08	13,647,125	57,292,732	4.20	5.30%	8.29%	2.83%
	Local		79,860,288	6.16		85,469,288	6.26		7.02%	1.63%
	Total		132,768,680	10.24		142,762,020	10.46		7.53%	2.11%
	Sum	25,611,394	288,195,440	11.25	25,502,646	306,922,912	12.03	-0.42%	6.50%	6.95%

Table 1B. Passenger Trips and Travel Distance in Baseline and Scenario, AM Peak, PM Peak and Off Peak (Toll = \$0.30 per mile)

Time Period	Type of Road	Baseline			Scenario			% Change		
		Trips (PCEs)	Total Travel Distance (PCE*Miles)	Average Travel Distance (Miles)	Trips (PCEs)	Total Travel Distance (PCE*Miles)	Ave. Travel Dist. (Miles)	Trips	Travel Dist.	Ave. Travel Dist.
AM Peak	Highway	4,926,850	28,661,390	5.82	4,530,046	13,985,941	3.09	8.05%	-51.20%	-46.93%
	Local		20,088,162	4.08		29,619,714	6.54		47.45%	60.36%
	Total		48,749,552	9.89		43,605,655	9.63		-10.55%	-2.72%
PM Peak	Highway	7,724,865	35,135,996	4.55	7,325,475	16,048,414	2.19	5.17%	-54.32%	-51.83%
	Local		24,858,734	3.22		39,438,316	5.38		58.65%	67.30%
	Total		59,994,730	7.77		55,486,730	7.57		-7.51%	-2.47%
Off peak	Highway	12,959,679	56,544,620	4.36	13,647,125	61,162,608	4.48	5.30%	8.17%	2.72%
	Local		38,537,972	2.97		41,260,804	3.02		7.07%	1.67%
	Total		95,082,592	7.34		102,423,412	7.51		7.72%	2.29%
	Sum	25,611,394	203,826,874	7.96	25,502,646	201,515,797	7.90	0.42%	-1.13%	-0.71%

Table 2A. Passenger Trips and Travel Time in Baseline and Scenario, AM Peak, PM Peak and Off

Peak (Toll = \$0.10 per mile)

Time Period	Type of Road	Baseline			Scenario			% Change		
		Trips (PCEs)	Total Travel Time (PCE*Mins)	Average Travel Time (Mins)	Trips (PCEs)	Total Travel Time (PCE*Mins) ¹	Average Travel Time (Mins) ¹	Total Trips	Total Travel Time	Average Travel Time
AM Peak	Highway	4,926,850	28,796,972	5.84	4,983,433	25,004,728	5.02	1.15%	-13.17%	-14.15%
	Local		40,596,044	8.24		45,592,360	9.15		12.31%	11.03%
	Total		69,393,016	14.08		70,597,088	14.17		1.74%	0.58%
PM Peak	Highway	7,724,865	34,568,832	4.48	7,780,719	29,322,734	3.77	0.72%	-15.18%	-15.78%
	Local		51,464,912	6.66		58,079,104	7.46		12.85%	12.04%
	Total		86,033,744	11.14		87,401,838	11.23		1.59%	0.86%
Off peak	Highway	12,959,679	52,908,392	4.08	12,862,930	52,301,852	4.07	-0.75%	-1.15%	-0.40%
	Local		79,860,288	6.16		79,063,920	6.15		-1.00%	-0.25%
	Total		132,768,680	10.24		131,365,772	10.21		-1.06%	-0.31%
	Sum	25,611,394	288,195,440	11.25	25,627,082	289,364,698	11.29	0.06%	0.41%	0.34%

Table 2B. Passenger Trips and Travel Distance in Baseline and Scenario, AM Peak, PM Peak
and Off Peak (Toll = \$0.10 per mile)

Time Period	Type of Road	Baseline			Scenario			% Change		
		Trips (PCEs)	Total Travel Distance (PCE*Miles)	Average Travel Distance (Miles)	Trips (PCEs)	Total Travel Distance (PCE*Miles)	Average Travel Distance (Miles)	Trips	Travel Distance	Average Travel Distance
AM Peak	Highway	4,926,850	28,661,390	5.82	4,983,433	25,472,128	5.11	1.15%	-11.13%	-12.14%
	Local		20,088,162	4.08		22,923,290	4.60		14.11%	12.82%
	Total		48,749,552	9.89		48,395,418	9.71		-0.73%	-1.85%
PM Peak	Highway	7,724,865	35,135,996	4.55	7,780,719	30,444,014	3.91	0.72%	-13.35%	-13.98%
	Local		24,858,734	3.22		28,832,510	3.71		15.99%	15.15%
	Total		59,994,730	7.77		59,276,524	7.62		-1.20%	-1.91%
Off peak	Highway	12,959,679	56,544,620	4.36	12,862,930	55,893,088	4.35	0.75%	-1.15%	-0.41%
	Local		38,537,972	2.97		38,151,296	2.97		-1.00%	-0.26%
	Total		95,082,592	7.34		94,044,384	7.31		-1.09%	-0.35%
	Sum	25,611,394	203,826,874	7.96	25,627,082	201,716,326	7.87	0.06%	-1.04%	-1.10%

Table 3. Toll Revenues for the Los Angeles Region and its Counties (\$0.30 per mile) and (\$0.10 per mile), AM Peak and PM Peak

County Name	Number of Toll Links	Link Length (Miles)	(Toll = \$0.30 per mile)			(Toll = \$0.10 per mile)		
			AM Peak (\$)	PM Peak (\$)	Total (\$)	AM Peak (\$)	PM Peak (\$)	Total (\$)
LOS ANGELES	3,401	1,428	601,175	707,760	1,308,935	1,488,699	1,752,712	3,241,412
ORANGE	1466	600	213,876	262,046	475,922	468,197	547,097	1,015,294
RIVERSIDE	632	475	83,079	95,832	178,911	336,731	382,716	719,446
SAN BERNARDINO	632	428	87,163	104,330	191,492	250,927	287,885	538,812
VENTURA	355	187	28,964	35,973	64,937	76,879	88,825	165,704
Sum	6,486	3,119	1,014,256	1,205,942	2,220,198	2,621,432	3,059,234	5,680,667

Note: the total revenue is the daily revenue based on the daily AM- and PM-peak passenger vehicle volume and link length of the tolled lanes.