Road Pricing Simulations: Traffic, Land Use and Welfare Impacts for Austin, Texas

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ABSTRACT

This paper explores the traffic, land use and welfare impacts of road pricing in the Austin region, introducing planned toll roads, implementing marginal cost pricing (MCP) on main roads, applying tolls to existing bridges, and instituting a downtown tolled cordon. Different toll scenarios are examined, including fixed versus variable tolling, and tolls based on time of day, traffic, and travel distance. The travel demand model (TDM) incorporates joint mode and time of day choice models and multinomial destination choice models. The resulting travel times and costs are fed back into the TDM in order to obtain converged results. Austin-calibrated DRAM-EMPAL models are used to predict the future residential and work location distribution and the models' outputs are fed into the TDM for modeling future scenarios. The results include traffic redistribution over time and space, location choice changes in the long term, and traveler welfare implications. In summary, the newly proposed toll roads in Austin are revenue generating and travelers' welfare improving. But, the estimated toll road project costs are predicted to exceed the estimated benefits. MCP on main roads reduces the total predicted travel time on these roads, and is estimated to improve welfare for the average Austin resident anywhere in the region, once revenues are redistributed. Bridge tolls are successful in redistributing traffic, while the downtown area appears highly sensitive to cordon tolls.

Keywords: Road Pricing, Toll Roads, Integrated Transportation-Land Use Models

1. INTRODUCTION

Traffic congestion looms large in most cities, as travel demand outpaces infrastructure and operational improvements. [1] report the 2001 cost of congestion in 75 U.S. urban areas to average $517 per person. Supply-side improvements and demand management are the two ways to alleviate the congestion problem. Capacity expansions are usually associated with high construction and land acquisition costs. Traditional funding methods (such as gas tax and user fees) have not been able to cope up with the demand for infrastructural improvements. As a result, new methods of highway financing are being explored [2]. Road tolling serves as a funding mechanism which allows near-term construction of facilities, along with longer-term maintenance, rehabilitation and expansion.[1] However, infrastructure improvements are not always beneficial for congestion mitigation. [4,5] Most economists argue that congestion results from under-pricing of the road network and suggest marginal cost pricing (MCP) to internalize the congestion externality and maximize system efficiency. Cordon pricing, another pricing option, is designed to limit traffic flows into a cordoned area, such as a downtown zone, in order to ameliorate local congestion and pollution levels.

For the last three years, Austin has been rated as the most congested medium-sized city in the U.S. [1]. A number of toll road projects are under consideration for Austin, and several are under construction. While other cities in Texas such as Houston and Dallas offer some toll road options, road pricing will be new to Austin. However, there is presently little consideration of congestion pricing (CP) options for Austin. The Colorado River flows eastward alongside Austin’s downtown, and is crossed by various bridges. These bridges are

[1] For example, SH 130, currently under-construction in Austin, is expected to be built nearly 25 years in advance under the combined effect of toll financing and delivery system [3].

suitable for CP since they are traditional bottlenecks in most urban systems, and also appropriate for revenue tolling[2] since they are much more expensive (per lane mile) to build than roads [7]. The region's popular and densely developed downtown also may benefit from some form of CP. This paper analyzes the impacts of the newly built toll facilities in Austin on the region's traffic, future land use development and residents' welfare. This paper also studies pricing on existing facilities such as roads, bridges and downtown access links as prospective congestion management strategies.

2. LITERATURE REVIEW

There are varied impacts of road pricing on traffic, land use and welfare distributions. Traffic related impacts such as fuel consumption, vehicular emissions, congestion levels, and noise production can be quantified using aggregate level of vehicle travel. While addition of new tolled corridors is expected to reduce congestion on parallel corridors and improve overall level of service, the total system vehicle miles traveled (VMT) may increase due to latent demand. Since they improve overall accessibility, toll roads are expected to be welfare enhancing. In contrast, CP on existing facilities will discourage trip making, thereby reducing VMT. [See, e.g., 4, 5, 8, 9] Due to impact on trip making, CP can generate a set of perceived winners and losers. However, the welfare impacts of CP depend on the design of pricing strategies, user heterogeneity and the way revenue is used to compensate disadvantaged user groups. [See, e.g. 10, 11, 12] Typically, network capacity additions would support suburban development and spread land use in the long term. On the other hand, CP can either encourage urban sprawl or high-density development. The impacts will

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[2] For example, the tolls on two tunnels and four bridges connecting New York and New Jersey were raised in 2001 to generate revenue for construction and maintenance. [6]

vary with the type of pricing, use of revenue and current urban form [8]. In most cases, pricing policies encourage relocation to less costly locations and tend to change the residential and commercial development as well as alter the attractiveness of certain locations and affect the local economy [13].

There are many instances of bridge tolling, road tolling and cordon pricing, in the U.S. and around the world. Currently, there are nearly 5,000 centerline miles of tolled highways (including bridges and tunnels) in the United States. Facing budget constraints, toll financing of roads was introduced as a strategy to meet infrastructure needs. For example, Dallas' George Bush Turnpike (SH 190), a 30-mile four-lane highway, was converted to a tollway due to insufficient funding from fuel taxes. Reduced congestion, improved air quality and enhanced economic development are some of the observed benefits.[14] Some facilities charge differential tolls based on distance, congestion, vehicle type or other characteristics to ensure traveler equity and desired level-of-service on toll lanes. California's Orange County introduced congestion-based tolls on State Route 91's new tolled lanes which vary hourly between $1.00 and $4.75 in 5 cents increments. [15]

The Cape Coral and Midpoint Bridges in Lee County, Florida use differential peak and shoulder period bridge tolls which encourage users to alter their arrival times [16,17]. Similar peak to off-peak shifts were also observed on the bridges connecting New York and New Jersey when off-peak tolls were reduced [6]. Among all the CP projects in the U.S., only Fort Myers Beach, Florida involves cordon pricing [18]. In contrast, many other countries such as Singapore [19], Norway [20] and Italy [21] have opted for such pricing, and have been successful in reducing congestion and generating revenues. While cordon tolls are less optimal than paying as one drives, they are relatively straightforward for drivers and generally easier to implement for administrators. A recent example is London's £5 cordon toll (weekdays between 7:00 am and 6:30 pm) which has been estimated to have reduced zone travel delays by one-third while significantly shifting mode choice (e.g. bus ridership increased by 14%). [See, e.g., 22, 23]

The rest of the paper analyzes various forms of road pricing policies for Austin, Texas to examine the impacts on traffic, welfare and location choices. The following section describes data sources and methodologies in detail. The results for different applications and analyses of impacts are presented in Section 4. Finally, Section 5 highlights the important findings of this paper and identifies limitations of the current approach.

3. METHODOLOGY

3.1 Data Sources and Details

The Austin Capital Area Metropolitan Planning Organization's (CAMPO) planning region covers Travis, Williamson and Hays counties represented as 1074 traffic serial zones (TSZs) and 43 external zone stations. The Austin network data [24] specifies the network from 1997 to 2030. CAMPO data was used to calibrate the travel demand models (TDMs) [25] and land use models [26]. Data used include the 1996 Austin (Household) Travel Survey [27], Austin demographic dataset and level-of-service (LOS) data. The LOS data include the inter-zonal automobile travel times for peak and off-peak times and transit travel times based on service type and transit access. Other data sources include the 1990 and 2000 Census of Population data and the 2000 CAMPO-maintained City of Austin land use data set. Details about the proposed toll plans, amendments to the existing CAMPO's 2025 Mobility plan and 2030 Mobility plan were also provided by CAMPO.

3.2 Tolling Scenarios

The scenarios examined here are revenue tolling on newly built roads and pricing on existing facilities in the form of bridge tolls, downtown cordon tolls and MCP on roads. Different toll types are examined, including fixed versus variable tolling, and tolls based on time-of-day, traffic, and travel distance depending upon different facility types.

Toll Roads

The proposed toll roads are divided into two sets: Toll Road Plan 2007 and Toll Road Plan 2030. The former includes toll roads (SH 130, SH 45, a Mopac/Loop 1 extension, and US 183 A and SE 45) adopted by CAMPO on June 12, 2000, which will all be operational by the year 2007. Tolls were earlier expected to vary between 12¢/mile and 15¢/mile, but now the Central Texas Regional Mobility Authority (CTRMA) may target a system-wide average of 18¢/mile (or less) [28]. For planning purposes, [24] is considering a flat, distance-based toll of 10¢/mile. Tolls ranging between 7¢/mile to 15¢/mile were analyzed in this study. The second set of toll roads analyzed in this study are those operational after 2007. Some of these were adopted by CAMPO on July 12, 2004. Since coded networks are only available for the years 2007, 2017 and 2030, these were used for the TDM runs between 2007 and 2032. The 2030 network was used for the 2027 TDM run assuming that all toll roads are operational by then.

MCP on Roads

The two CP scenarios tested on existing roads are MCP on all roads (MCP- All Roads) and MCP on highways/main roads (MCP- Main Roads). System-wide MCP is the social optimal solution and is also referred to as "first-best solution or first-best CP". In contrast, MCP-

Main Roads (sometimes referred to as "second-best" pricing in literature) is not necessarily the optimal solution since few links are priced; however, MCP-Main Roads is reasonable since main roads operate under higher congestion levels than most other city roads.

Bridge Tolls

The centrally located Austin bridges connect the northern and southern portions of the region. There are ten such bridges, crossing the Colorado River at Redbud Trail, Pleasant Valley Road, Loop 1 (Mopac), Lamar Boulevard, Congress Avenue, South First Street, IH 35, US183, RM 620 and Loop 360 (Capital of Texas Highway). The bridges identified for tolling are those at Redbud Trail, Loop 1, Lamar Boulevard, Congress Avenue, and South First Street, henceforth referred as "Bridge Toll Candidates" as shown in Figure 1. The federally funded IH 35 bridges are also of interest but there are issues with tolling federally financed roads. US183, RM 620 and Loop 360 bridges offer almost no substitute routing, and are distant from the region's center, so they also were not considered for tolling. Pleasant Valley Road is not congested during any time of day, so it is not a candidate for CP. Various fixed-toll combinations and congestion-based tolls (using MCP) were tested, along with differential peak and off-peak tolls, in order to ascertain time of day shifts and traffic congestion levels.

Cordon Pricing

A downtown cordon was constructed around the region's downtown bounded by Martin Luther King (MLK) Boulevard, Lamar Boulevard, IH 35 S frontage road and Cesar Chavez Boulevard, as shown in Figure 1. Fixed tolls ranging from $1 to $5 were applied between 7:15 am and 6:15 pm on all links entering the cordon. This work does not account for the presence of downtown parking costs due to paucity of data.

3.3 Integrated Transportation-Land Use Models (ITLUM) Application

The Austin-calibrated ITLUMs were used to model traffic, land use and welfare impacts of different pricing scenarios. The TDM and land use models are applied sequentially starting with 1997 as the base year. The results from the TDM application are fed into Krishnamurthy and Kockelman's [26] DRAM-EMPAL land use models, which predict future land use demand in time steps of five years.[3] While CP policies on existing facilities are analyzed for the year 2007, the toll road scenarios are analyzed for the period 2007 to 2032.[4]

The Austin TDM models rely on four trip purposes: home-based work (HBW), home-based non-work (HBNW), non-home-based work (NHBW), and non-home-based non-work (NHBNW). Kalmanje and Kockelman's [25] multinomial destination choice models use attraction factors, as well as logsums of travel times, travel costs and choice-specific constants (across modes and times of day, from the joint mode-time of day model). The joint mode-time of day models are calibrated for four modes (drive alone, shared ride, transit and walk/bike) and five times of day (late night and early morning (before 7:15 a.m. and after 8:15 p.m.), morning peak (7:15 to 9:15 a.m.), mid-day (9:15 a.m. to 4:15 p.m.), evening peak (4:15 to 6:15 p.m.), and evening off-peak (6:15 to 8:15 p.m.)).

The production-attraction (PA) matrices were converted to origin-destination (OD) matrices for home-based trips using return trip rates across the five time periods. Vehicle trip matrices were obtained using constant vehicle occupancies by trip purpose. The vehicle trip matrices[5] for the 5 time periods were assigned to the network in TransCAD [29] using the user

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[3] The TDM application and feedback process has been executed using TransCAD [29]. The land use models are applied using GAUSS [30] statistical modeling software.
[4] The VOTT, operating costs and income are kept constant for all years, as an assumption of pure inflation.
[5] Only auto trips were considered in obtaining the vehicle trip matrices since the transit shares were too low.

equilibrium (UE) traffic assignment module. A generalized cost function based on the Bureau of Public Roads' (BPR) volume-delay equation was used in traffic assignment.

$$c_i(x) = k_i + \delta \times L_i + \varphi \times t_i \left[1 + \alpha \left(\frac{x_i}{C_i} \right)^{\beta_i} \right]$$

where $c_i(x)$ = generalized cost for flow x, k_i= fixed toll cost for link i , δ = vehicle operating cost, assumed as 30¢/mile [31], L_i= length of link i, φ = value of travel time (VOTT) (assumed to be $8/hour)[6], C_i = capacity of link i, α_i and β_i are link characteristics (default values of 0.15 and 4 used when data was not provided).

The resulting time and cost skims[7] from traffic assignment were fed back into the destination and mode-time of day choice models until link flows from consecutive feedbacks stabilized. Direct feedback, feedback with method of successive averages (MSA) on link flows, and MSA on both link and OD flows were used wherever appropriate.[8] The TDM feedback process is run separately for each pricing scenario. Work locations for the HBW trips were held constant for all pricing scenarios in 2007, since tolling should not influence the destination choice of work trips in the short term.

The inputs into Krishnamurthy and Kockelman's [26] land use models are base year household distributions by income, employment distributions by job type, household and employment growth rates (3.3% and 3.1% respectively [33]), base year peak and off-peak

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[6] Since the VOTT estimated from the mode-time of day choice models were very low (ranging from $2.35 to $3.36), a higher value was assumed for traffic assignment and for calculating MCP tolls. (For further information on the mode and time-of-day choice model, please refer to [25].)
[7] The transit travel times from one TDM iteration to another are adjusted in the same ratio as the auto travel times. The walk and bike travel times are assumed constant.
[8] The external-external (E-E), internal-external (I-E) and external-internal (E-I) trips were left unchanged from one feedback to another and were added to the larger O-D trip matrix before traffic assignment. The E-E and E-I trips were proportionally increased based on Texas population forecasts [32] and I-E trips were inflated according to Austin population forecasts [33] for future year scenarios.

travel time skims from a TDM application, and zonal household and employment density caps. Wherever applicable, the time skims include tolls translated into units of time (via an $8 VOTT). Based on these inputs, the models compute future zonal household and employment distributions, which are used as inputs to the trip-generation model in the TDM application for the next modeling period (five years into the future).

3.4 Welfare Computations

Estimates of daily travel-related benefits after a pricing policy implementation were estimated as consumer surplus (CS), at the destination choice level for the average person residing in each zone. (Readers may refer to [25] for more information on this approach.) CS is the difference in the maximum expected utility of one's destination choice opportunities before and after a change in the travel environment, as shown in equation 1.

$$\Delta CS_{ip} = \frac{1}{\alpha_p}\left(E(Max(V_{ip}))^n - E(Max(V_{ip}))^o\right) \qquad (1)$$

where α_p is the marginal utility of money (specific to each trip purpose) and is the product of the estimated coefficients on cost (in the mode-departure time model) and generalized cost or logsum (in the destination choice model), n and o denote the new and old scenarios (for e.g., pricing vs. no-pricing, toll roads vs. no-build) and $E(Max(V_{i,p})) = \ln\left(\sum_{j \in C} e^{V_{i,j,p}}\right)$.

$V_{i,j,p}$ denotes the utility of person at origin i choosing destination j for trip purpose p, with C denoting the full choice set of all possible destinations.

In this work, this measure of CS is not applicable for HBW trips since the destination choice is fixed. Instead, equation 2 is used to compute CS for HBW trips. It is the difference in expected maximum utility levels after policy implementation derived across all modes and departure times choices available to a particular destination, and is multiplied by the probability of choosing that destination (*P*(*j*)).

$$\Delta CS_{ip} = \sum_{j \in C} \frac{P(j)}{\beta_c} \left(LOGSUM_{ijp}^{n} - LOGSUM_{ijp}^{o} \right) \tag{2}$$

where $LOGSUM_{ijp}$ is the generalized cost between an origin-destination pair (*i*,*j*) and is defined as the negative of the maximum expected utility derived across all mode and time-of-day combinations for a trip purpose *p*.

$$LOGSUM_{ijp} = -\ln\left(\sum_{m,t} e^{\beta_{t,p} Time_{i,j} + \beta_{c,p} Cost_{i,j} + \beta_{m,t,p}} \right) \tag{3}$$

where β_t, β_c and $\beta_{m,t}$ are the coefficients on time, cost and the alternative-specific constants in the joint mode-departure time choice model.

Average daily CS is calculated for an individual residing in zone *i* by aggregating CS for home-based trips using the average daily number of trips per individual.

4. RESULTS AND DISCUSSION

This section discusses the results of various road pricing simulations. The traffic impacts of introducing the new planned toll roads and pricing the existing facilities (roads, bridges and downtown cordon) were analyzed. For relevant scenarios, the welfare, accessibility and land use impacts were also studied.

4.1 New Toll Facilities

Two sets of toll roads were considered for simulation. The first set includes the toll roads operational by 2007 (Toll Road Plan 2007); and second set includes the toll roads operational after 2007 (Toll Road Plan 2030) which will be built in two phases: operational by 2017 and 2030.

4.1.1 Toll Road Plan 2007 (TR-2007)

Traffic Impacts

Toll road locations and the type and level of tolling have a direct bearing on network traffic patterns. It is expected that the new toll roads will draw traffic from other facilities, thereby improving overall travel conditions. Percentage changes in link-length-weighted average V/C ratios on different facility types were compared for toll road and no-build scenarios as shown in Table I. One finds that there are slight V/C drops on all major roads, including freeways, expressways and arterials, thanks to the new toll roads. IH 35 is predicted to experience just a 2.5% drop during peak hours, which could be largely due to SH-130's construction. If we compare V/C ratios only on freeway segments that have a tolled lane, significant drops are observed on the competing free lanes. The biggest winners appear to be travelers on US 183 and Loop 1, the roads which receive parallel tolled lanes.

For comparison purposes, MCP[9] tolls were tested on all planned toll roads, instead of the expected 10¢/mile toll. Under MCP tolls, tolls are considerably smaller, so greater V/C reductions are observed across most facility types. Moreover, under MCP tolls, the toll roads are expected to carry more traffic than under the planned 10¢/mile tolls. MCP revenues are predicted to be much less (just $1,523/day) than the 10¢/mile alternative ($26,248/day). Other distance-based tolls, ranging from 7¢ to 15¢ per mile, also were tested. And an

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[9] MCP is not quite optimal pricing, since free alternative roads are available to the drivers [34]. MCP is optimal when all relevant "goods" are optimally priced according to their marginal (social) costs.

11¢/mile toll was estimated to be the region's revenue-maximizing distance-based toll. This is surprisingly close to CAMPO's proposed tolls.

Welfare Impacts

Figure 2 illustrates the geographical variation in estimates of CS under the MCP and 10¢/mile toll road scenarios. Clearly, neighborhoods along the toll roads are expected to experience positive welfare changes due to improved accessibility through system expansion (and therefore lowered travel times). The northwest corner of the Austin region also is found to gain due to improved access to those areas. Average welfare gains under 10¢/mile tolls are predicted to be less than under MCP tolls. Under a 10¢/mile toll road policy, less than 1% of the population is predicted to experience a daily gain of more than 10¢, as compared to 12% of the population under MCP. Around 75% of Austin's population is predicted to experience welfare gains of less than 3¢ per day under a toll road policy of 10¢/mile; whereas under MCP, 42% of the population has gains exceeding 3¢/day. These daily gains seem small, of course, but the tolls are applied to a relatively small set of new roads and their effects are averaged across all residents. The yearly traveler benefits are on the order of $18 million. And, depending on travel needs, some persons will benefit much more and others hardly at all. The welfare gains are positive for all zones under MCP; however, distance-based tolls are predicted to impose slight average losses on 14 small central zones. The welfare loss in these 14 zones is estimated to be less than 2¢ per day per individual and the total loss is negligible when compared to the region's overall welfare gain. The drops could be due to travel shifts induced by toll roads that somewhat congest these zones' neighborhoods.

The net benefits of the toll roads over a period of 40 years were calculated for the distance-based toll (10¢/mile) and MCP. Annual benefits were computed for 260 days/year and were discounted at a 5% rate for future years. Population and revenues were inflated by the expected population growth (3.3%) for Austin region, with an assumption of constant welfare benefits per person over the 40-year period. As a result, the present value of net benefits are predicted to be nearly $398 million (welfare benefits of $192 million + $206 million in revenue) and $462 million (welfare benefits of $450 million + $12 million in revenue) under distance-based tolls and MCP, respectively. These estimates are rather small when compared to the estimated project costs of nearly $2,700 million [35].

Land Use Impacts

Toll roads are expected to influence the future land use patterns around the region, through shifts in households and employment. Figure 3 shows percentage household and employment changes as a result of 5 years of toll road operation (under distance-based toll of 10¢/mile), based on DRAM-EMPAL-type model applications. These numbers are obtained from comparing predicted distributions for the year 2012 under the toll road and the no-build scenarios. From Figure 3, one observes that there is a small percentage growth in households located near the proposed toll road corridors, probably due to households moving closer to tolled corridors. Five zones near the toll road corridors are predicted to experience drops (greater than 1%) in number of households; however, the absolute change in households is less than 3 households for three out of these five zones. Most other locations are predicted to experience less than 1% change in household counts. Toll roads are predicted to have very little impact on Austin's employment distribution of the Austin region. Employment is predicted to increase slightly in some areas close to toll roads, but only for one zone is the change (relative to the non-tolled status quo) greater than 1%. Overall, toll roads are not found to significantly impact Austin's land use pattern, but they are predicted to initiate some development in localized areas along the toll corridors.

4.1.2 Toll Road Plan 2030 (TR-2030)

The TDM estimates the total system VHT and VMT to more than double between 2007 and 2032 due to the projected population growth. While the total toll road lane miles would increase 3.5 times (from 379 miles in 2007 to 1,327 miles in 2032), the daily toll road revenue is estimated to grow by a factor of 5.8 (from $26,248/day in 2007 to $151,813/day in 2032). This shows the increased patronage for the toll roads over the years.

Welfare Impacts

Travel welfare impacts of building the post-2007 (TR-2030) toll roads were computed by comparing average changes in region-wide CS for the year 2032 between a TR-2030 toll roads scenario and a no TR-2030 toll roads scenario, as shown in Figure 4. Most locations' residents are predicted to benefit by less than 10¢/day. Those in southwestern portions of the region are expected to gain most, thanks to the development of a radial toll road (US 290) connecting them to central Austin. The net benefits from these toll roads over a 40 year period were estimated to be nearly $3,809 million ($2,619 million of welfare benefits (assuming constant annual welfare gains) + $1,190 million in revenue collection). These estimates are sizable, but still do not cover the estimated project costs of nearly $6,166 million (computed based on the average cost per lane mile for the TR-2007 toll roads).

Land Use Impacts

The welfare gaining area along the US 290 corridor is also predicted to experience high residential and commercial growth. Also, the land use development[10] is estimated to spread to the north-western and south-western parts of the region under development of TR-2030 toll roads, as compared to the no TR-2030 alternative. Some development is also predicted around the toll roads in the south-eastern corner of the region. Some sections of the TR-2030 toll roads will be operational by 2017, while others will be completed by 2030. The land use development estimates appear to be influenced by this two phase development. The toll road sections operational by 2017 appear to attract more households[11]. The areas surrounding RM 620 (operational by 2030) are predicted to experience drops in household counts as compared to no TR-2030 scenario. One of the reasons for this relative loss in counts is probably that the sections of other toll roads (such as US 290) closer to RM 620 will be operational nearly ten years before RM 620. Hence, these toll corridors are expected to attract households from the western regions. These households may not relocate after development of RM 620. Employment levels are expected to slightly decrease (when compared to a no TR-2030 scenario) for a large area between Loop 360 and RM 620.

4.2 Existing Facilities

CP strategies were tested on roads, at bridges and across a cordon in the Austin region. In this section, model estimates of traffic, welfare, and land use changes are discussed for MCP implementation system-wide and main roads only: *MCP-All Roads* and *MCP-Main Roads*. The traffic impacts of tolling many of Austin's bridges are discussed in detail; since other

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[10] Percentage change in land use distributions were ignored when the absolute change was less than 2 in the zonal household/employment values.

[11] Toll roads operational by 2017 are expected to have greater impact on land use distributions in 2032 because they influence household and job allocations over 15 years (equivalent to three runs of DRAM-EMPAL models) as compared to toll roads operational by 2030 which only affect a single run of land use models.

impacts of bridge tolls were estimated to be insignificant, they are not discussed. While the traffic and accessibility impacts of downtown cordon pricing are evaluated, welfare and land use are not (because the welfare measures are origin-based, and the land use models do not recognize drop in number of trips headed downtown; therefore, cordon toll effects will not be adequately captured).

4.2.1 MCP on All Roads and MCP on Main Roads

Traffic Impacts

The total system VHT is predicted to fall by 2.7% under MCP-All Roads and by less than 1% under MCP-Main Roads when compared to a no-pricing scenario. However, the change in VMT is negligible (less than 0.5%) under both scenarios. There is a significant predicted reduction (6%) in VHT on main roads under MCP-Main Roads as compared to considerably small change under MCP-All Roads. A policy of MCP-Main Roads is expected to shift traffic from the priced routes to parallel free routes which can lead to congestion on those parallel routes. In contrast, MCP-All Roads does not lead to addition of congestion on parallel routes. The expected revenue generated from MCP-All Roads ($388,304/day) is more than twice the expected revenues under MCP-Main Roads ($135,580/day). Although MCP-Main Roads is not the optimal solution, it does improve the travel times on the network (particularly on main roads).

Welfare Impacts

The geographical variation of CS changes for an average resident of Austin under MCP-All Roads and MCP-Main Roads is shown in Figure 2. Clearly, most of the areas are expected to experience positive welfare changes due to congestion mitigation under both scenarios.

However, the upper bound of the average change in CS is higher for MCP-Main Roads. The areas in the western parts of Austin are expected to lose under both scenarios. This result can be attributed to the lack of alternative routes connecting western areas to other areas. Under MCP-All Roads, areas near CBD are also predicted to incur welfare losses which can be attributed to larger MCP tolls near the congested CBD area. MCP-All Roads is predicted to produce lower welfare gains since it affects all users and increases system-wide travel costs, rather than main roads only.[12] If the expected revenue generated under MCP-All Roads is equally distributed among the population, the "average" resident is expected to receive nearly 29¢/day. Under MCP-Main Roads, this daily gain is expected to be only 10¢/day per resident. This form of redistribution would change welfare losses to gains for all residents.

Land Use Impacts

The changes in zonal household and job distributions as a result of 5 years of MCP operation are compared to a no-pricing scenario. The eastern parts of Austin region along US 290 E are estimated to experience growth in residential development as shown in Figure 3. Slight reductions in households and employment counts are observed in the western parts of Austin (near Loop 1 and Loop 360) under both scenarios. Jobs are predicted to spread to outer areas of the central Austin region under MCP-All Roads as compared to the no-pricing scenario.

4.2.2 Bridge Tolls

According to our models, most Austin bridges (i.e., IH 35, Loop 360, US 183, Lamar Boulevard, Loop 1 and Redbud Trail) are congested during peak periods. The evening

[12] Under MCP-Main Roads, 2% of the population is predicted to gain more than 4¢ per day which is the maximum predicted gain under MCP-All Roads. Also, MCP-Main Roads policy is predicted to impose *average* losses of no more than 4¢ per day per individual for 3% of Austin's population as compared to 6% of the population under MCP-All Roads.

peak's volume-to-capacity (V/C) ratios are highest, and these effects extend into the evening off-peak period. MCP tolls were applied on all bridge toll candidates throughout the day. But MCP tolls on all bridges and all time periods are difficult to implement in practice. Hence, it should be more effective and practical to find a set of fixed tolls that produce comparable results but require tolling on fewer bridges and/or during fewer time periods. To this end, different combinations of fixed tolls across different time periods and bridges were tested.

The Lamar Boulevard and Redbud Trail bridges operate under hyper-congested traffic conditions during peak periods (with V/C's up to 2.15). The peak-period MCP tolls for these are roughly 10¢ and 40¢ respectively, while tolls on the other bridges were found to be around 5¢. After experimenting with different fixed toll combinations, (varying level of tolls applied across different set of bridges during different times of day) it was determined that the best results would be obtained by levying tolls only on Lamar Boulevard and Redbud Trail bridges during peak and evening off-peak periods. One finds that during the priced periods, the "best" fixed tolls closely replicate the congestion-reducing impacts of a MCP toll. Even small tolls on Lamar Boulevard Bridge cause significant traffic shifts, while the tolls required on Redbud Trail Bridge are somewhat higher (since there are few reasonable substitute crossings for such trips). Figure 5 compares the average V/C ratio estimates for bridge toll candidates to scenarios following imposition of MCP tolls and best fixed tolls.

The best fixed tolls found are 15¢ in both directions on the Lamar Boulevard Bridge during peak periods and 10¢ during the evening off-peak period (and zero cents at other times of day). On the Red Bud Trail Bridge, morning peak tolls are estimated to be 50¢ (northbound (NB)) and 25¢ (southbound (SB)); evening peak tolls are 25¢ (NB) and 75¢ (SB); and evening off-peak tolls are 10¢ (NB) and 20¢ (SB). Proponents of minimum revenue pricing [e.g., 36, 37] argue that it is possible to replicate the impacts of an MCP toll with a minimum revenue toll. Though, the best toll combination in this paper is not calculated by minimizing the revenue, it is interesting to note that the revenue obtained from the best fixed toll combination ($5,466/day) is nearly half of that generated by MCP ($13,733/day).

The V/C ratios on the bridges are observed to change substantially because traffic from the tolled bridges tends to redistribute onto nearby bridges. This is primarily due to toll-induced route shifts because mode and time-of-day shifts are estimated to be negligible (less than 1%). Since downtown bridges are close to IH 35, it can be expected that traffic from these tolled bridges will divert to the non-tolled IH 35 and its frontage roads resulting in increased levels of traffic on a rather congested corridor. Though such traffic impacts are evident under the MCP tolling scenario examined, this issue did not arise under the best fixed toll scenario because the bridges adjacent to IH 35 were left un-tolled. Also, the best fixed tolls examined are not estimated to have any significant negative effect on the traffic on other Austin bridges, as compared to status quo.

Thus, considering the impact on bridges alone, the fixed toll combination offers better results than MCP tolls. However, the best fixed tolls appear to add to congestion levels on some roads connecting downtown bridges, such as Cesar Chavez. Thus, MCP for bridge tolls may be more effective from a system perspective, especially since MCP tolls are applied across most of the competitor bridges. The bridge tolls do not appear to cause any significant land use and welfare changes in the region. Average CS computed in the presence of bridge tolls was found to be insignificant (ranging from 0 to 1¢ per day per individual) since the bridge tolls primarily affect routing choices, rather than mode, departure time and destination choices.

It can be concluded that a combination of fixed tolls on bridge competitors can actually replicate the efficiency-improving impacts of MCP tolls while also providing easy implementation. Some externalities, such as impacts on connecting streets remain, but capacity additions and additional tolling can address those issues.

4.2.3 Cordon Pricing

The downtown cordon tolls examined here are in dollar increments ranging between $1 and $5, from 7:15 am to 6:15 pm on all vehicles entering the downtown area. As expected, the predicted total daily inflow of traffic into the downtown area falls significantly with the introduction of cordon tolls. As shown in Figure 6, total downtown bound traffic decreases by 30% with the application of $1 toll. It further reduces by 20% under another $1 increment in toll. However, the traffic flow drops are insignificant (less than 0.9%) with toll increments beyond the $2 toll. This can be attributed to commuters who are bound to make downtown trips due to fixity of HBW destination. A high percentage of daily traffic enters downtown during the no-toll periods, and shifts to these times of day are evident.

The accessibility of downtown zones is affected by such tolls. Accessibility of a destination zone *i* is calculated using a simple gravity model. For this situation, it is based on the trips produced at other zones *j* (N_j).

$$Accessibility_i = \sum_j N_j \times e^{\beta_p LOGSUM_{ij}} \quad (4)$$

where β_p are assumed to be -0.2884, -0.4681, -0.1181 and -0.3027 for HBW, HBNW, NHBW and NHBNW trip purposes, respectively, based on the corresponding destination choice model coefficients (on the mode-time of day logsums defined in equation 3). As Figure 6 suggests, the accessibility of cordoned zones decreases substantially with toll levels. The non-work trips are affected adversely to a greater extent than work trips because the non-work trips are more sensitive to the generalized cost of accessing a destination zone (as evident from the coefficient on logsum term in corresponding destination choice models). The change in accessibility is significant for the $1 and $2 toll levels; however, the rate of change reduces considerably for toll levels beyond $2. This is consistent with the results of changes in daily traffic inflow with toll levels. A reason for why even a $1 toll is effective in inducing significant shifts could be the low value of travel time implied by coefficients in mode and time-of-day models. Revenues increase with the toll levels up to a $4 cordon toll (thanks to the presence of so many captive users) and later tends to drop (refer to Figure 6) One may expect that captive downtown users will be negatively affected by the cordon pricing policy.

5. CONCLUSIONS AND EXTENSIONS

Roadway tolling is coming to Austin, Texas. This work examines the impacts of new toll roads, as well as possible congestion pricing policies. An integrated transportation-land use model, based on a rather standard TDM process and a DRAM-EMPAL based model for distribution of households and jobs, was applied to the Austin region in order to anticipate the traffic, land use and welfare impacts of various pricing policies. Feedback within the TDM model (from traffic assignment back into trip distribution, mode and time of day choice models) was performed using a method of successive averages on link flows. Results from the TDM were then used in the land use models to predict household and employment locations under various pricing scenarios. Resulting changes in travel demand were evaluated to appreciate the TDM-predicted changes in traffic patterns, destination choices, mode departure time decisions, locational accessibility, network level-of-service, toll revenues, land use patterns, and travel-based measures of welfare.

Different tolling strategies yield distinct results. In order to faster repay bonds for planned toll road additions to the Austin network, distance-based tolls seem to generate the greatest revenues. The construction of new toll roads is estimated to enhance travelers' welfare as compared to a no-build scenario, but the net benefit estimates are far less than the estimated project costs. Also, it catalyzes land development along the corridor; however, these effects are minimal for toll roads operational by 2007, but the toll roads operational by 2030 are predicted to spread land development to the northern and southern corners of the Austin region. From examining results for MCP-All Roads and MCP-Main Roads, we can conclude that these policies improve system VHT without really affecting total VMT. Most zones are predicted to experience welfare gains under both MCP scenarios compared to a no-pricing scenario, with the remaining zones predicted to benefit under uniform revenue redistribution to residents. MCP policies are not expected to significantly impact future land use development in most areas; however, jobs and households are estimated to fall in some central areas.

Model results also suggest it is possible to effectively price only a few of Austin's bridges during select time periods, instead of applying MCP all day on all candidate bridges which are those west of IH-35. Even tolls lesser than a dollar are predicted to result in significant route shifts, since Austin's closely spaced bridges provide easy alternatives to avoid tolls. In contrast, these tolls have no significant impacts on social welfare and land use distributions. Cordon pricing to access the region's downtown was estimated to drastically reduce traffic inbound (and therefore outbound traffic as well). As cordon tolls are raised, downtown traffic flow reduces dramatically; most remaining users being “captive commuters” with fixed downtown job destinations. Cordon revenues are expected to increase with toll levels (up to a toll of $4) and then fall. Downtown accessibility decreases with higher tolls. Overall; it seems that simply a $1 cordon toll may be sufficient for addressing downtown congestion in Austin.

There are a few limitations to this work and some extensions are proposed. For example, trip generation is assumed to be inelastic with respect to travel costs and thus unchanged following the introduction of road pricing policies. The static traffic assignment procedure and the choice models employed deal only with homogenous users limiting predictions of policy impacts to the average user level rather than across user groups. The proposed HOT and HOV lanes could be modeled in the traffic assignment models. The land use models used are gravity-based DRAM-EMPAL models which can be enhanced through recognition of more site specifics (such as topography and natural amenities) and structure characteristics (such as age of improvement). A better procedure is needed to model the growth over time of external-external, internal-external and external-internal trips and their distribution within feedback.

In summary, though Austin toll roads seem to be headed in the right direction, it would be to the region’s benefit to also consider CP policies. Typically, a variety of tolling options are available to the urban region. This study illustrates many ways in which their results may be compared by looking at traffic, land use and social welfare impacts.

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Table I: Percentage change in average V/C ratios by facility type after toll roads are operational (as compared to the no-build alternative)

Facility Type	**Late Night/ Early Morning** (before 7:15 a.m and after 8:15 p.m)		**Morning Peak** (7:15 a.m. to 9:15 a.m.)		**Mid-day** (9:15 a.m. to 4:15 p.m.)		**Evening Peak** (4:15 p.m. to 6:15p.m.)		**Evening Off-Peak** (6:15 p.m. to 8:15 p.m.)	
	MCP	**10¢/mi**	**MCP**	**10¢/mi**	**MCP**	**10¢/mi**	**MCP**	**10¢/mi**	**MCP**	**10¢/mi**
IH 35*	-4.2%	-1.2%	-4.0%	-2.6%	-4.1%	-0.9%	-4.3%	-2.4%	-3.8%	-1.0%
US 183**	-48.0%	-7.0%	-44.7%	-18.7%	-50.2%	-5.5%	-47.8%	-12.6%	-43.4%	0.7%
Loop 1**	-69.6%	-24.1%	-57.3%	-15.1%	-68.5%	-22.3%	-55.8%	-12.5%	-65.0%	-15.0%
Other freeways*	-10.8%	-2.3%	-7.0%	0.1%	-10.9%	-1.5%	-8.0%	1.6%	-11.8%	-1.3%
Expressways	-1.2%	-1.1%	-0.8%	-0.4%	-0.8%	-0.4%	-0.7%	0.2%	-0.2%	0.3%
Principle Arterials	-4.0%	-1.9%	-4.4%	-2.9%	-3.5%	-1.7%	-4.3%	-1.8%	-3.1%	-1.3%
Minor Arterials	-2.2%	-1.7%	-2.0%	-0.6%	-1.8%	-1.5%	-2.2%	-0.5%	-1.8%	-1.3%
Collectors and Locals	0.5%	-0.3%	2.5%	1.7%	1.1%	-0.1%	2.9%	2.3%	2.1%	1.1%

* Including Frontage Roads

** Competing non-tolled lanes

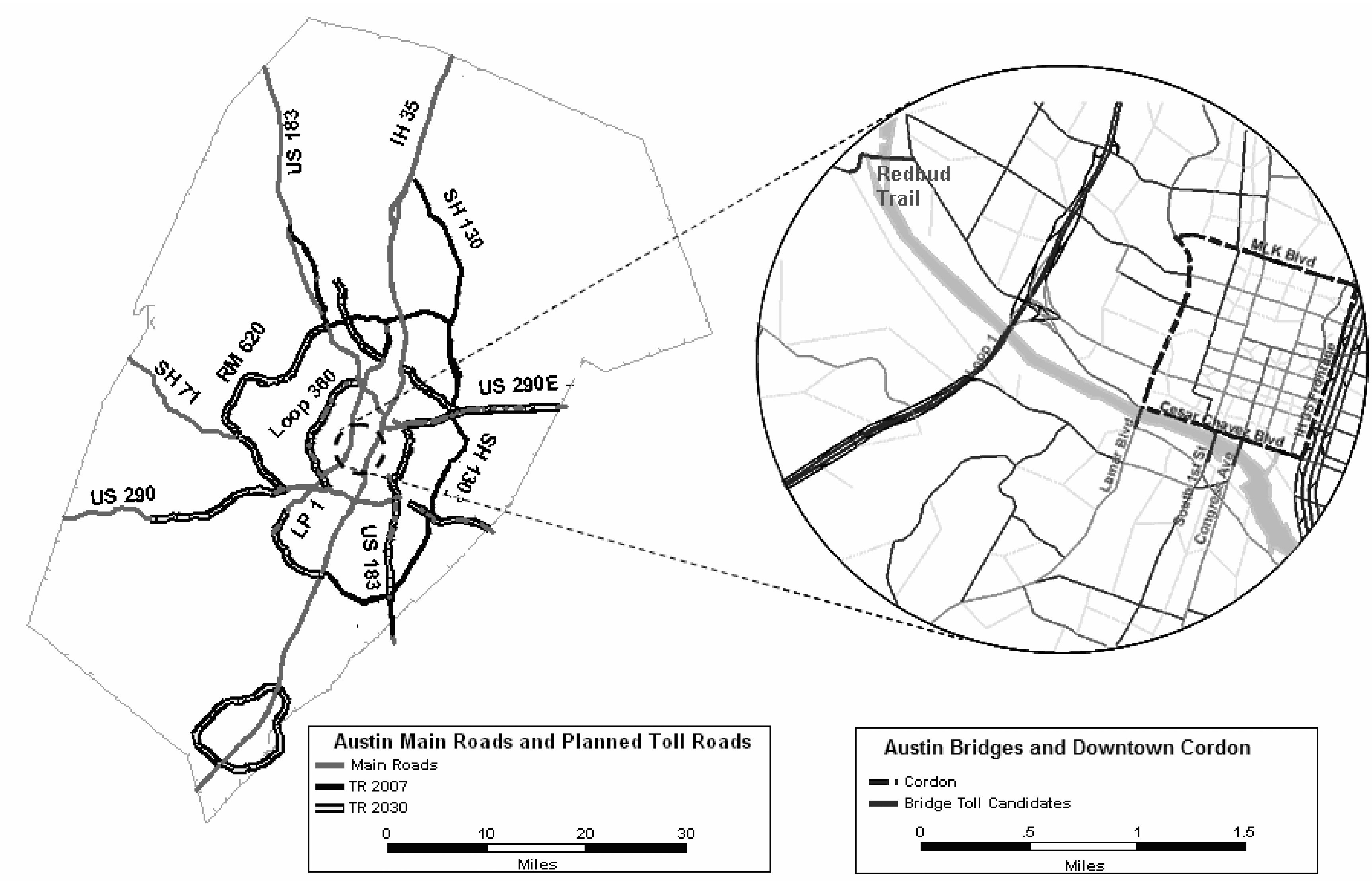

Figure 1: Austin's Planned Toll Roads, Main Roads, Bridges, and Downtown Cordon.

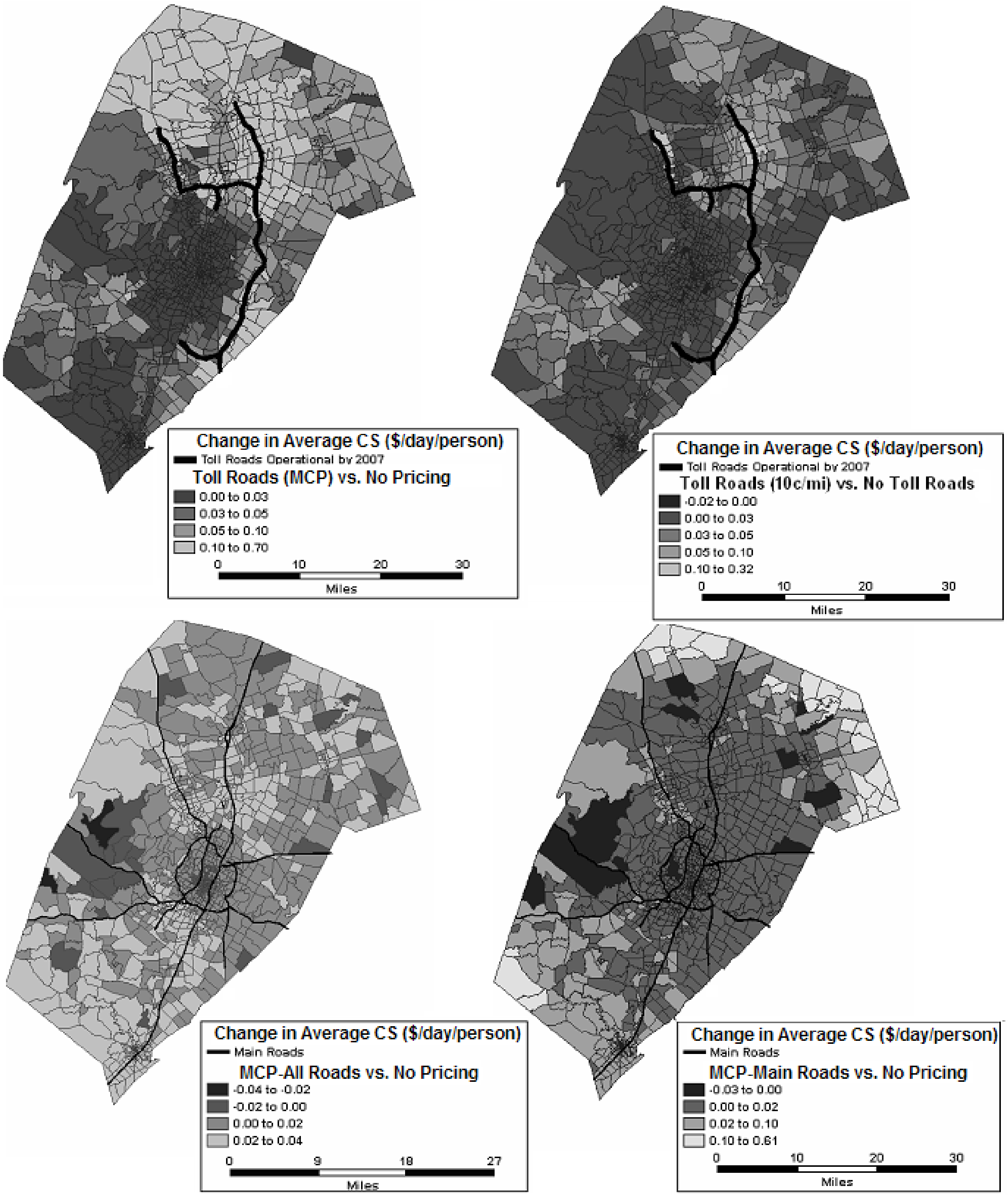

Figure 2: Welfare (by origin) in Year 2007 for an Austin Resident: Toll Roads-MCP vs. No Build (Top Left), Toll Roads-10¢/mile vs. No Build (Top Right), MCP-All Roads vs. No Pricing (Bottom Left) and MCP-Main Roads vs. No Pricing (Bottom Right)

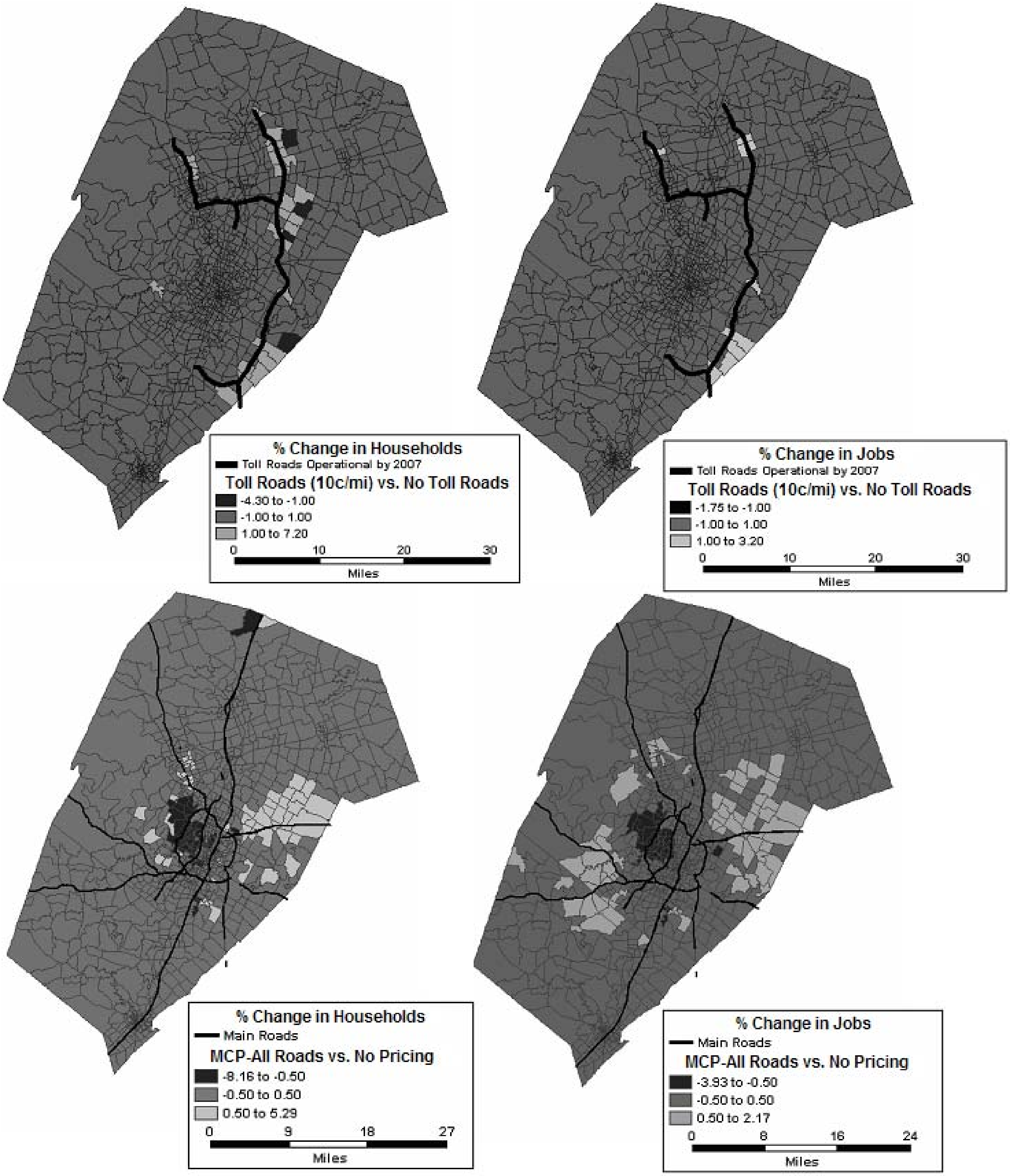

Figure 3: Percentage Change in Zonal Land Use Patterns for the Year 2012: Toll Roads-10¢/mile vs. No Build (Top), and MCP-All Roads vs. No Pricing (Bottom)

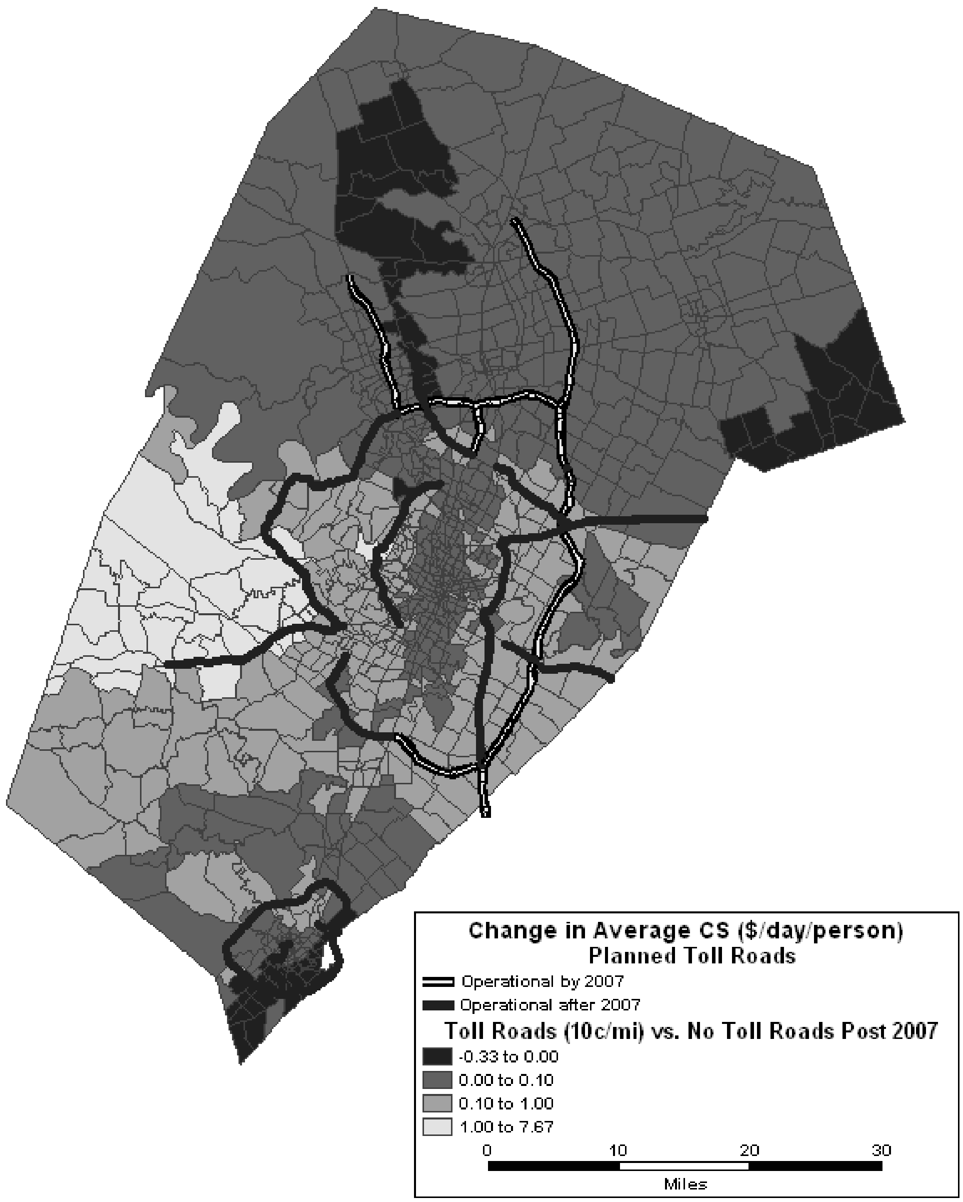

Figure 4: Welfare (by Origin) for an Austin Resident in the year 2027 under Proposed Tolls on TR-2030 Toll Roads, as Compared to the No TR-2030 Toll Roads Alternative

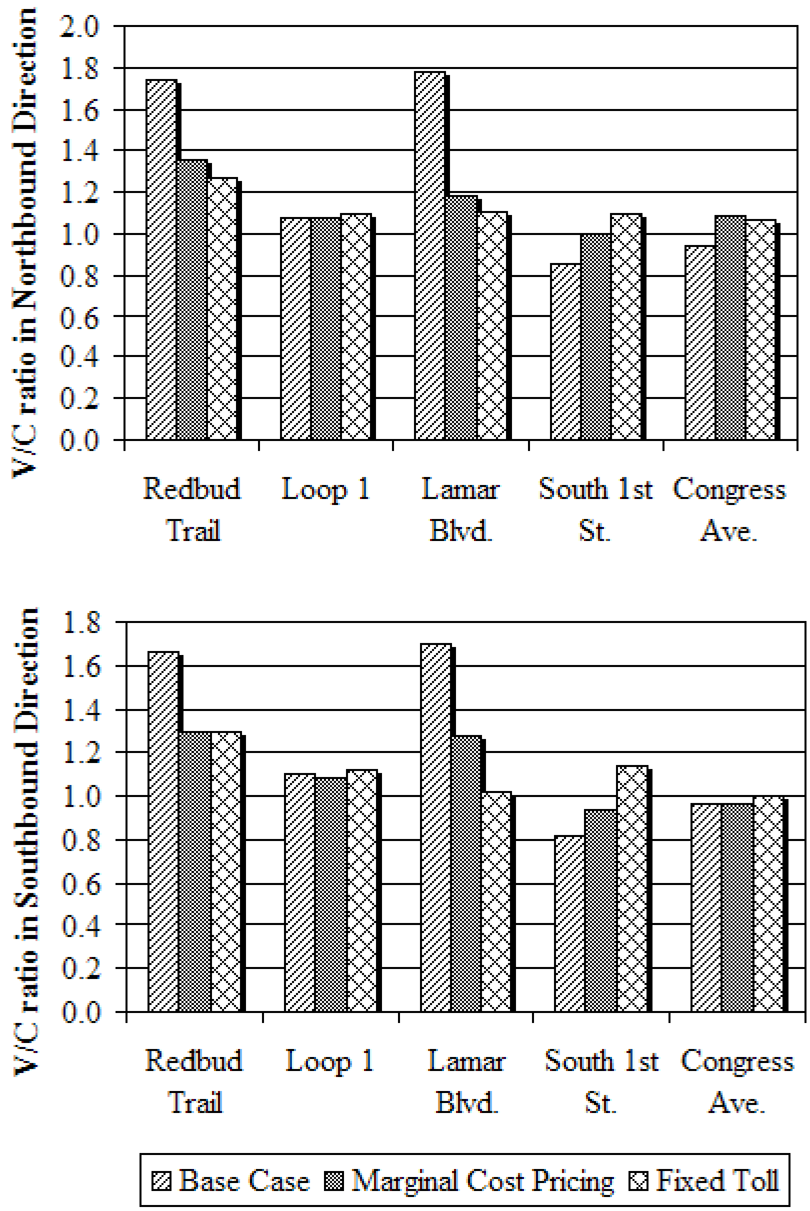

Figure 5: Change in V/C ratios (averaged across toll periods) on toll bridge candidates

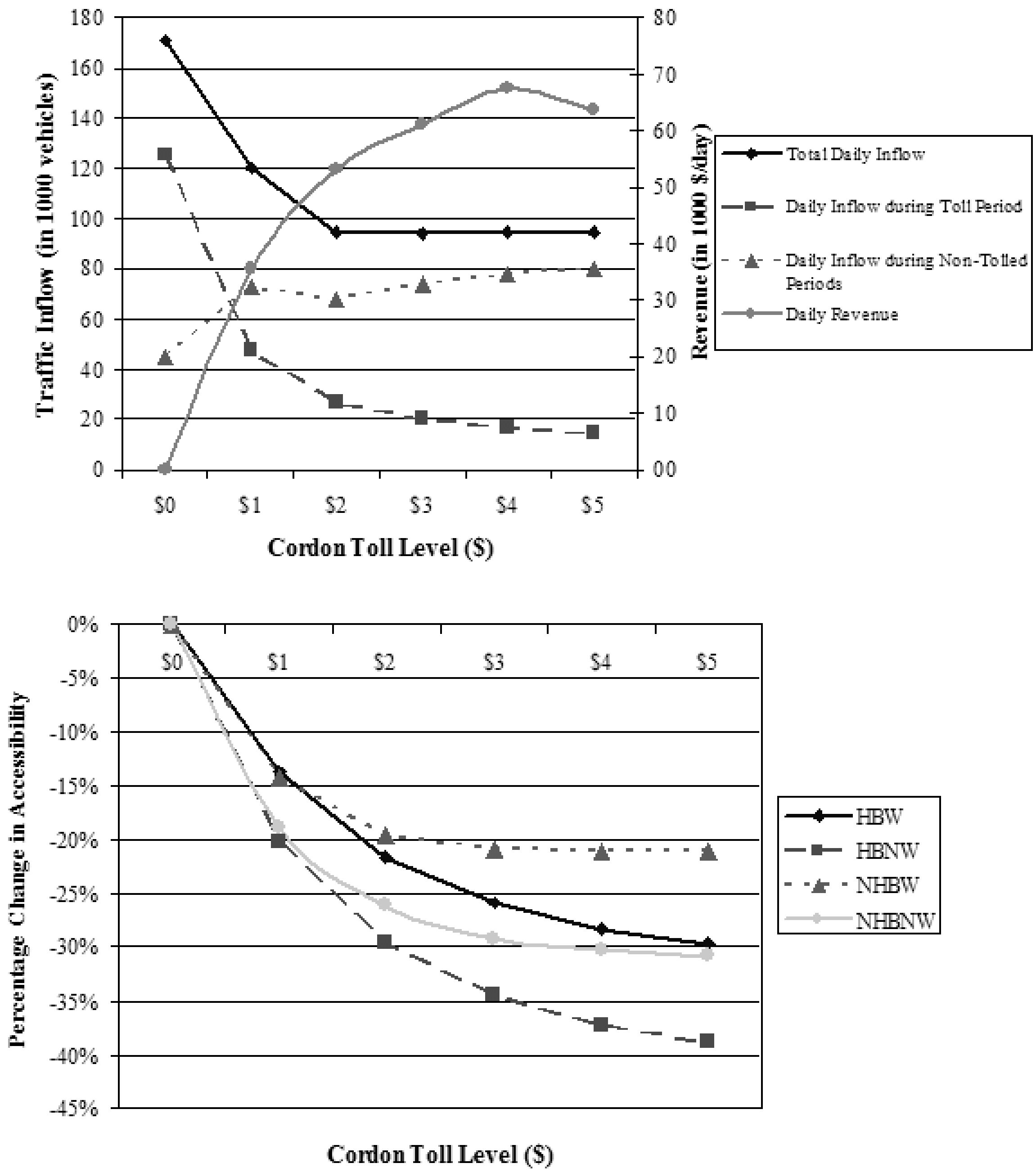

Figure 6: Change in traffic inflow (top), revenue (top) and accessibility (bottom) to downtown with cordon toll level