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CONGESTION PRICING FOR THE TWIN CITIES METROPOLITAN AREA

Herbert Mohring and
David Anderson,
Economics

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FINAL REPORT

Herbert Mohring and David Anderson

Department of Economics
University of Minnesota

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Congestion Pricing for the Twin Cities Metropolitan Area

by Herbert Mohring and David Anderson

Auto travel is growing inexorably in the United States' urban areas. Between 1949-1990, the population of the Twin Cities Metropolitan Area (TCMA) increased 2.3-fold; person trips by all travel modes increased over five-fold. Society appears less and less willing to respond to continued traffic growth with increased road capacity. Increased ratios of traffic volume to road capacity and, with them, increased road congestion are inevitable unless something is done.

"Congestion pricing" is the "something" that many economists favor to solve the urban traffic problem. The conceptual underpinnings of this solution are straightforward: Automobile operators not only experience road congestion, they also contribute to it. The "*marginal costs*" of their trips -- the value of the resources that would be saved if these trips were not made -- include not just the time and vehicle-operating costs they experience directly but also the costs they cause by contributing to the congestion that slows each other down -- a cost that few consider in deciding when, where, and by what mode to travel. Maximizing the value of what society's resources produce in a market economy requires commodity prices to equal their marginal costs. The portion of the marginal cost of a road trip reflecting the cost it imposes on other travelers can be very large. To cite only the two most heavily congested expressway segments, we estimate this imposed cost to be 49 cents *per vehicle mile* during the weekday-morning peak hour for each vehicle northbound on Interstate-35W between its intersections with I-35E and I-494 and each vehicle eastbound on I-94 between its intersections with I-394 and I-35W.

Currently, fuel excises are the major taxes for which total road-user payments are approximately proportional to their road use. These taxes average perhaps 2-3 cents per vehicle mile. Charging anything approaching 49 cents per vehicle mile for auto trips on parts of I-35W and

[*]Department of Economics, University of Minnesota. We are deeply indebted to Mark Filipi of the Metropolitan Council, Jim Kranig of Strgar, Roscoe, Fausch, and Steve Ruegg of Barton Aschman for instruction in the intricacies of Tranplan that has been valuable, patient, and far beyond the call of duty, to Steve Alderson of the Council for going to great lengths to place its data resources at our disposal, and to Guy Peterson of the Council for helpful and understanding administration.

I-94 would, therefore, dramatically change travel behavior. Car pools and the Metropolitan Transit Commission's services would become much more popular than at present. More trips for which peak-period departures or arrivals are not essential would be shifted out of the peak. Over the longer haul, pressures would build to shift business and school opening and closing hours away from the peak. For all of these reasons, present differences between the marginal costs of peak-period trips and those that travelers presently take into account in making peak-period travel decisions greatly exceed the tolls necessary to force them to recognize fully the costs their trips impose on others. Our knowledge of how substantially travel would adjust to congestion tolls is imperfect at best; we presently estimate 15-25 percent reductions in traffic on the most heavily congested portions of the TCMA's Interstate System and, hence, appreciable reductions in the present pressures to expand road capacity.

"Road pricing" in urban areas evokes visions of toll booths at every street corner or expressway interchange -- a collection technology that would be costly in personnel, travel time, and road capacity. Fortunately, distinctly superior alternatives to manual collection are available. Even better techniques are in advanced stages of development. A decade ago, Hong Kong tested a system under which passage of a vehicle over an inductive loop embedded beneath a roadway's surface reliably triggered the vehicle's (US)$60 transponder to transmit an identification code which, when sent to a central computer, would result in a charge appropriate to the time and vehicle location being added to its owner's account. Monthly road-use bills would have been sent to vehicle owners.

Sadly for the progress of congestion pricing, opposition to this system was so intense that the colonial government withdrew its proposal to institute it. Most prominently mentioned of the reasons for public opposition was that the system's ability to identify specific vehicles' locations at specific times would have invaded vehicle operators' privacy -- a concern heightened by the impending takeover of Hong Kong by the Peoples' Republic of China. To overcome this objection, "smart cards" that can store and process on-vehicle information received from a roadside communication device and, hence, could preserve anonymity are in advanced stages of development. Complete success is a few years off, at most.

The world has had little experience with congestion pricing. Passage over a cordon line into Singapore's central business district during the morning and afternoon peak travel periods requires a costly special license. When the predecessor of the current system was instituted in 1975, it radically reduced CBD traffic congestion. In May 1994, Singapore hosts an international conference to celebrate its replacement of technologically primitive windshield stickers with state-of-the-art electronics. The leaders of a country with the sort of civil-rights record that Singapore has might be expected to relish the prospects that a Hong Kong-type system would give it of keeping close tabs on the whereabouts of its citizens. Surprisingly, it has chosen to go with smart-card technology rather than monitoring by a central computer. Norway accounts for all of the world's remaining urban congestion-pricing systems that are in actual operation; even there, whether their systems can accurately be termed "congestion pricing" is open to debate. Its three largest cities all impose cordon-line tolls into their CBDs similar to Singapore's. These tolls are in force for much longer periods than in Singapore and are higher during peak travel hours in only one of the three cities. A few other road-pricing projects are firmly planned or under active consideration in various parts of the world; more were seriously considered in the recent past but ultimately rejected.

Why, despite (or might it be because of?) its popularity with economists, has so little use been made of congestion pricing? Among the world's cities, there are several -- Bangkok, Jakarta, Calcutta, Athens, and Rome as possible examples -- which are so clogged with traffic that instituting congestion pricing could conceivably cut travel time by so much that most travelers would be better off even after paying tolls regardless of how toll revenues are used. Not so in the Twin Cities and most of North America and Europe. Here, congestion tolls would significantly speed traffic flow, but, for most travelers, not by enough to offset the cost of tolls they pay; we calculate that only vehicles with occupants whose aggregate incomes exceed $80,000 a year would gain more in travel-time savings than they would lose in cash from the system of pricing all congested roads that we have studied so far. Thus, the *direct* effect of congestion pricing on most TCMA road users would be to make them worse off. (We concentrate here and throughout this report on congestion as such and not on such environmental benefits as its reduction might yield.)

Naturally, most people oppose government policies that reduce their welfare -- socially desirable though these policies may be. Many of these opponents could be won over by allocating toll revenues in ways that would benefit them sufficiently to offset their direct losses from tolls. *To emphasize, most peak-period travelers in the Twin Cities would support for congestion tolls only if their imposition is coupled with a plan for using toll revenues that would benefit them more than the tolls would cost them.* Such a plan is feasible, at least in principle. That is, tolls would generate enough revenues to compensate losers fully with money left over. In very round numbers, we calculate that optimal tolls -- tolls equaling the costs each traveler imposes on all other travelers by adding to the level of congestion -- would generate roughly $300,000 during the morning peak hour and would generate aggregate travel-time savings of about $100,000. If they could be accurately identified -- no trivial task, that -- compensating all losers would eat up two-thirds of toll revenues. Exact compensation of every loser is an impossibility, of course. A mix of earmarking revenues to make transportation improvements, to reduce fuel and other user taxes, and to compensate people whom tolls would hit particularly hard would be essential parts of a realistic publicly acceptable expenditure package.

Many arguments are made against congestion pricing; one is so common and powerful that a brief counter-argument is worth stating. The argument: congestion pricing would inflict significant harm on the poor. The counter-argument: that they are ill-fed, ill-clothed, ill-housed, and, perhaps, ill-transported is really not the basic problem that poor people have. Their fundamental problem is, rather, that they are poor. If we are genuinely concerned with how road pricing would affect them, we should reimburse them with cash -- or, maybe better, with marketable road scholarships -- for the greater costs tolls impose on them and let them decide whether to maintain their travel patterns unaltered or to spend the cash or proceeds from the sale of the scholarship on other desired commodities while economizing on travel. It would be the height of folly to subsidize road use or any other commodity just on grounds that the poor buy it.

How would charging each vehicle trip an amount equal to the costs it contributes to congestion perform in comparison to our present road-pricing system? We seek answers to this question by using in unconventional ways packages of computer programs, Tranplan and Emme/2, that transportation planners user for a variety of highway and transit forecasting projects. We start with the 1990 Travel Behavior Inventory (TBI), a survey taken in June-November 1990 of 9,746 households in the TCMA which took a total of approximately 98,000 daily trips. Our analysis is limited to automobile trips on the road at some point during the morning or afternoon peak travel hour between any two of the 1,200 Traffic Analysis Zones (TAZs) into which transportation planners divide the TCMA.

Planners have classified the area's road network -- its freeways, expressways, arterials, collectors, and high-occupancy-vehicle lanes -- into approximately 18,800 links. TBI surveys obtain origin and destination addresses and, hence, TAZs for each trip but not the specific route taken. Tranplan, the program on which we have relied most intensively assumes that each traveler selects that route -- a series of links -- for each trip which minimizes the trip's travel time or some other measure of the "impedance" to it. The program "loads" trips onto the road network using a process that finds an equilibrium in which no traveler is able to find a route with lower impedance. Once this equilibrium is found, we can compute the *marginal* cost of each trip -- the cost each vehicle operator directly experiences *plus* the cost that operator imposes on all other travelers by adding to congestion. As an example, here is the distribution of road links during the morning peak hour by what we term the "gap," *i.e.*, the difference between the *marginal* cost per mile of a vehicle trip and the cost that the vehicle's occupants experience directly if travel time worth $10 per *vehicle* hour is the only travel cost that congestion affects:

"Gap"/Mile Range	*Road Miles*	*Vehicle Miles (100s)*	*Aggregate "Gap"*
$0.00-0.02	7,718	18,011	$7,514
$0.02-0.20	1,214	17,581	$156,652
$0.20-0.50	414	9,198	$300,848
$0.50-4.00	253	5,808	$490,805
>$4.00	7	101	$93,680
Total	9,667	50,700	$1,049,508

In the morning, the average gap between marginal and directly experienced costs is 20.7 cents per vehicle mile. However, the 79.8 percent (7,718 miles) of all links that currently have "gaps" less than two cents a vehicle mile account for 28.6 percent of all vehicle miles traveled but only 0.7 percent of the aggregate gap between marginal and directly experienced costs.

To get a partial impression of what a congestion-pricing might look like on the Twin Cities road network, let us restrict attention to its interstate-expressway portion. Figure 4 is a schematic diagram of it which gives the lengths in miles of the individual expressway segments that we analyze. Figure 5a shows the present state of the network at the time the 1990 Travel Behavior Inventory was undertaken during the morning peak travel hour. In the triplet associated with a line segment, the first number is the time in minutes required to traverse the segment, the second number is the cost in cents for the entire segment that each vehicle imposes on other vehicles by adding to the level of congestion *if* the occupants of each vehicle value their travel time at $10 an hour, while the third number is this cost *per mile*. The side of the road on which a triplet is placed indicates direction of travel. Thus, on east-west segments, bottom triplets refer to eastbound travel and on north-south segments, right-side triplets refer to northbound travel. During the morning peak, the five most heavily congested segments of the TCMA Interstate system are: I-35W northbound from I-35E to I-494 (49 cents per vehicle mile), I-94 eastbound from I-394 to I-35W (also 49 cents), I-35E southbound from I-694 to I-94 (48 cents), I-35W northbound from I-494 to I-94 (43 cents), and I-394 eastbound from I-494 to I-94 (41 cents).

Again, were tolls of this magnitude to be imposed, radical changes in travel behavior could be expected. Suppose for a moment, though, that this is not the case, that all morning peak travelers would continue to take exactly the same trips as before imposition of tolls. A marginal-cost toll system would still cause some shifts in impedance-minimizing routes to occur. Figure 5b what equilibrium tolls would be under these circumstances. By "equilibrium tolls," we mean the set of tolls which simultaneously equal the congestion costs each traveler imposes *and* induce travelers to take those routes which minimize aggregate travel time. It

Figure 4

TCMA Interstate Network--Segment Mileages

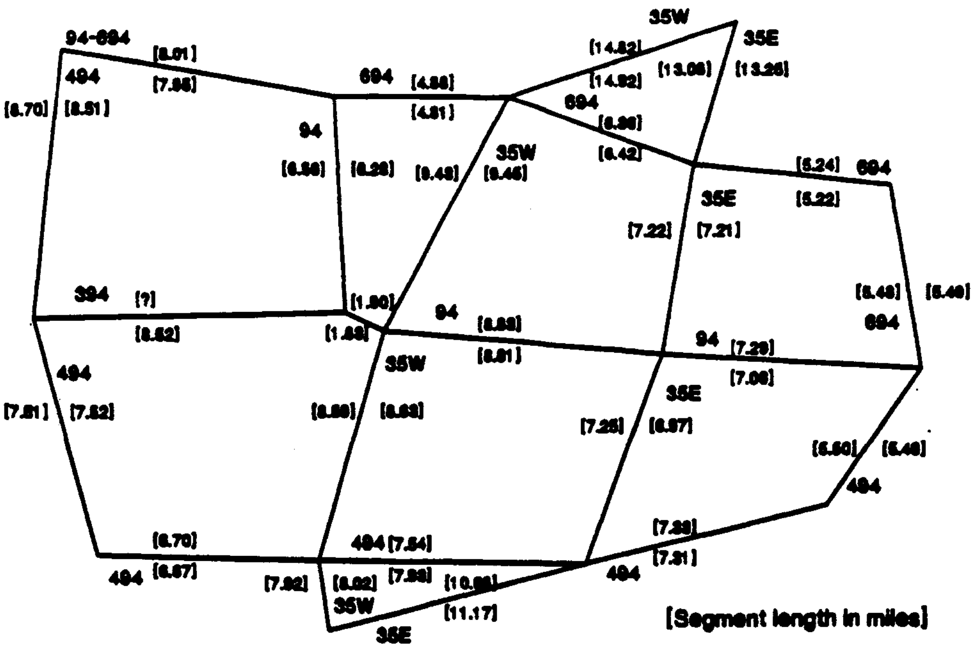
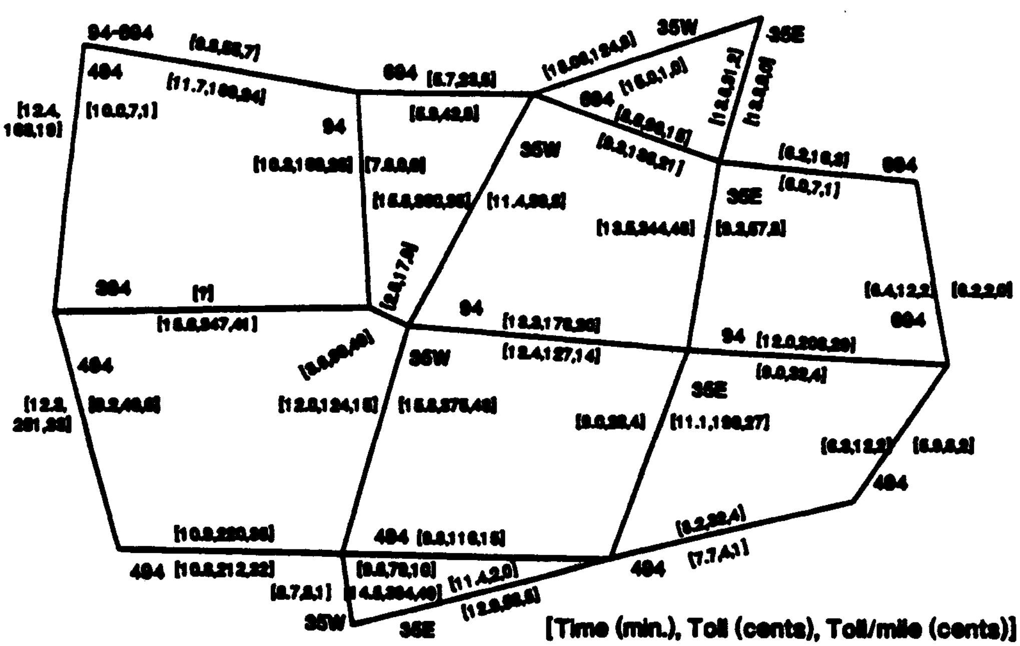


Figure 5a

TCMA Interstate Network Morning Peak Travel Times and "Gaps": No Tolls



turns out that, without changing the menu of trip origins and destinations, marginal-cost pricing would increase miles traveled by about two percent but would reduce aggregate travel time by about 2.4 percent -- not as much as we expected.

Our final piece of equilibrium analysis rests on the same assumptions as the second except that we recognize the effects tolls will have on the number of trips taken. Specifically, for reasons detailed in the appendix to this report, we suppose alternative "full-price" elasticities of demand for auto-vehicle trips of -0.5 and -1.0. That is, we suppose that a one-percent increase in the time *plus* money costs of a particular trip results in either an 0.5 or a 1.0 percent reduction in the rate at which that trip is taken. Limitations of Tranplan permit us to perform these calculations only for morning travel. Figure 5d indicate respective equilibrium tolls for AN elasticities of 1.0. Note that the most congested segments -- those for which the "gap" is 49 cents without tolls, the equilibrium toll is 17-18 cents with a 1.0 elasticity. For the system as a whole, the average toll would be almost exactly 7 cents a vehicle mile. With an 0.5 elasticity, the corresponding numbers are tolls on the most congested links of 20 cents a mile and average toll of 8.2 cents a mile (See Figure 5c, p. 53).

What effects would congestion pricing with tolls of this magnitude have on development patterns in the TCMA? Generally speaking, people value both living space and proximity of their residences to work places, recreational activities, stores, schools, and the like. As with so many other desires, those for space and proximity are in conflict. The more proximate is a residence to desired trip destinations, the more expensive is its site and the more intensively that site is utilized. Reductions in the "full price of trips" -- the dollar outlay they require *plus* the amounts trip takers would be willing to pay to save the time they require -- can be interpreted as increasing the "supply of proximity" -- the number of places that can be reached at a given money *plus* time cost. Increasing the supply of a commodity generally lowers its price and allows people to enjoy more of it, of other commodities, or both without increased expenditure.

Particularly in relatively uncongested areas such as the Twin Cities, congestion pricing

Figure 5b

TCMA Interstate Morning Peak Travel Times and Tolls: Zero Elasticity

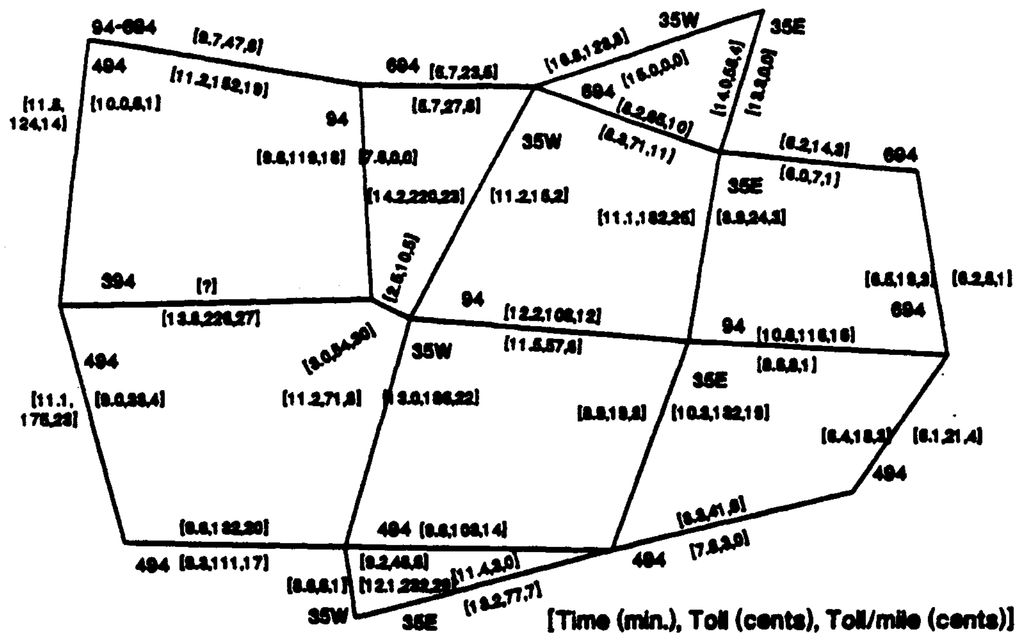
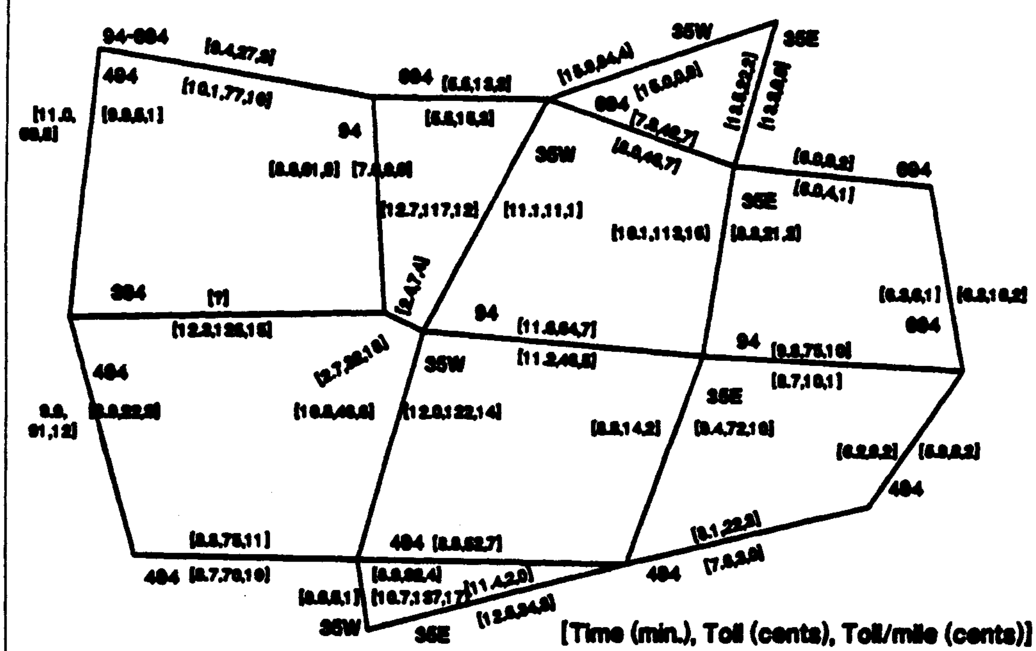


Figure 5d

TCMA Interstate Morning Peak Travel Times and Tolls: Elasticity = -1.0



will, if instituted, increase transport costs for most people. These cost increases will set adjustment processes into motion. While some households and business firms will find that some trips must be made regardless of cost, more will be able to mitigate the adverse effects of transport cost increases by using less congested or unpriced routes, by switching modes, by traveling at less congested times, or by changing destinations or even their own locations.

These adjustments will ultimately result in less transport-intensive business operations and household behavior. Households will, on average, live closer to their work places. The market areas of retail establishments will diminish and their numbers will increase somewhat. The rate at which residential decentralization is taking place will diminish and could even reverse itself; higher transport costs will inevitably make tradeoffs between space and proximity less advantageous. Not all residential decentralization will cease, however. Firms that have, for whatever the reasons, chosen to locate at the periphery of the metropolitan area will find their employees relocating near them at a more rapid rate than would otherwise have been experienced.

To repeat, congestion pricing will increase the travel costs of most Twin Cities residents -- *most*, but not all: for affluent residents of the TCMA, the full cost of travel will have declined; the value of the time they save will more than offset the added cost of the tolls they will pay. Particularly prominent in this group are the lawyers, corporate executives, bank officers, and others for whom frequently required face-to-face negotiations make central-business-district locations very valuable. For them, the speedier drives from Wayzata and Woodbury in which congestion pricing will result will make downtown a more rather than less attractive place in which to do business.

Just how substantial are the shifts in travel patterns to which congestion tolls would lead cannot be predicted with great certainty; assuming a full-price demand elasticity of -1.0, here is a summary of our results for the five most heavily traveled expressway segments noted above *if* tolls are charged that equate each remaining trip's marginal cost with its directly experienced *plus* toll costs:

	No-Toll Time Cost	With-Toll Time Cost	Toll	Full Price	Percent Travel Decline	Critical Time Value
I-35W: I-35E to I-494	$2.41	$1.78	$1.37	$3.15	23.4	$21.41
I-94: I-394 to I-35W	$0.60	$0.45	$0.32	$0.77	22.1	$22.59
I-35E: I-694 to I-94	$2.25	$1.68	$1.13	$2.81	20.0	$19.77
I-35W: I-494 to I-94	$2.63	$2.00	$1.22	$3.22	18.2	$19.26
I-394: I-494 to I-94	$2.60	$2.05	$1.25	$3.30	21.2	$23.08

To explain, the top line indicates that, at $10 per *vehicle* hour, the 14.5 minutes currently required in the absence of a toll to cover the stretch of I-35W from I-35E to I-494 is valued at $2.41. Imposing a $1.37 toll would result in an equilibrium full price for the trip equal to its $3.15 marginal cost and a 23.4 percent reduction in the hourly number of trips. Reducing traffic would reduce travel time for the trip to 10.7 minutes. If a vehicle's occupants value their collective time at more than $21.41 per hour rather than $10 per hour, the toll would be less than the value to them of the time it saves.

In round numbers, then, if the peak-hour elasticity of demand for private-passenger-vehicle travel is about -1.0, imposing marginal-cost congestion tolls would result in approximately a 15-20 percent reduction in peak-hour vehicle flow, a 20-30 percent increase in the full price of a trip for the average vehicle, and a 10-15 percent reduction in travel time per trip. The corresponding numbers for a demand elasticity of -0.5 are a 10-15 percent reduction in flow, a 30-40 percent increase in full price, and an 8-12 percent reduction in travel time.

I Introduction

Auto travel is growing inexorably in the United States' urban areas. Between 1949 and 1990, the population of the Twin Cities Metropolitan Area increased 2.3-fold, from 0.94 to 2.2 million, about 23 percent a decade. This was a period during which person trips by all travel modes increased over five-fold -- just over 50 percent a decade -- from 1.7 to 8.9 million, while person trips per capita more than doubled, from 1.8 to 4.0. A diminishing fraction of trips in vehicles with more than one occupant has heightened the effects of this travel growth. Average passengers per automobile trip declined from 1.51 in 1970 to 1.30 in 1982 to 1.28 in 1990 while the fraction of person trips taken by bus declined from 26 percent in 1949 to 18 percent in 1958 to 3.2 percent in 1970, a level around which it has hovered since.[1]

Society appears less and less willing to respond to this continued growth in auto traffic with corresponding increases in road capacity. Increasing ratios of traffic volumes to urban road capacities and, with them, increasing road congestion are inevitable unless something is done. "Congestion pricing" is the "something" favored by many economists to solve the urban traffic problem. The conceptual underpinnings of this solution are straightforward: Road travelers not only experience road congestion, they also contribute to it. The costs of their road trips do not include just the congestion they experience -- a trip attribute they normally take into account in deciding whether to travel. Their trips also impose costs on other travelers by adding to the level of congestion -- a cost that only the most altruistic of them consider in deciding when, where, and by what mode to travel.

As a quite general proposition, economic efficiency -- maximizing the value of the commodities that the resources at society's disposal can produce -- requires that commodity prices be set equal to their marginal production costs. The portion of the marginal cost of a road trip that reflects the cost it imposes on other travelers can be very large. To cite only the most extreme case, our estimates (see p. 54 below) for northbound travel on the eight-mile

[1]Data from Metropolitan Council of the Twin Cities Area [1984], *1982 Travel Behavior Inventory*, (St. Paul) and — [1992], *Home Interview Survey Methodology and Results*, (St. Paul).

stretch of Interstate-35W between I-35E to I-494 during the weekday-morning peak hour give 49 cents *per vehicle mile* as the monetary equivalent of the congestion costs each vehicle imposes on the occupants of all other vehicles once it enters the expressway. Added to this cost of movement are the delays travelers impose on those behind them in the queues at metered access ramps -- costs that are certainly large although we have not yet been able to quantify them.

Currently, fuel taxes are the closest things we have to charges on road-users for the congestion costs their vehicles impose on each other. These taxes average perhaps 2-3 cents per vehicle mile. Charging anything approaching 49 cents a mile for morning peak trips on I-35W between I-35E and I-494 would, therefore, almost certainly dramatically change travel behavior. Car pools and the Metropolitan Transit Commission's services would become much more popular than at present. More trips for which peak-period departures or arrivals are not essential would be shifted out of the peak. Over the longer haul, pressures would build to shift business opening and closing hours away from the peak. For all of these reasons, the present gaps between the full costs of peak-period trips and the costs that travelers recognize in making peak-period travel decisions greatly exceed the tolls necessary to force unaltruistic travelers to recognize fully the costs their trips impose on others. Our knowledge of how substantially travel would adjust to congestion tolls is imperfect at best; we presently estimate (see Section V) 15-25 percent reductions in traffic on the most heavily congested portions of the TCMA's Interstate system and, hence, appreciable reductions in the present pressures to expand road capacity. We further estimate that, in equilibrium -- a state in which travel has adjusted so that all travelers remaining on the road value their trips by at least their full social costs and pay congestion tolls equal to the costs their trips impose on other travelers -- the morning peak toll on I-35W between I-35E and I-494 would fall from 49 cents to 17-20 cents a vehicle mile.

Section II of this report briefly develops the economic theory of congestion pricing. Section III describes -- also briefly -- the rapidly evolving electronic technology that could be employed to replace human-operated toll booths in putting congestion pricing into effect and the successes and failures of the something-less-than-a-dozen attempts to employ congestion pricing that have taken place worldwide during the last 20 or so years.

The value of what is today termed "congestion pricing" was first recognized in the economics literature 70 years ago.[2] Serious, extended discussion of the subject in this literature began in the late 1950s.[3] The British Ministry of Transport undertook an extended study of the subject during the early 1960s resulting in the seminal "Smeed Report"[4] which has had a profound effect on thinking about the subject by economists and engineers. It is safe to assert that most professional economists regard congestion pricing as a concept whose time has long since arrived. Yet the world possesses only two operating urban congestion-pricing schemes, the more prominent of which the Republic of Singapore introduced in 1975. Clearly, economists have not been overwhelmingly successful in communicating the virtues of congestion pricing. Section IV evaluates the major objections that have been raised to congestion pricing by planners, politicians, and others. Section V reports on our preliminary attempts to quantify optimal congestion pricing in the Twin Cities Metropolitan Area. We deal with two hypothetical scenarios in both of which we are forced to suppose that the occupants of all vehicles attach the same value to their travel time: In one, we suppose that *all* peak-period travel is subjected to congestion pricing.[5] In the other, we suppose that only expressways are tolled. Section VI concludes with a discussion of the benefits and costs of congestion pricing and of the income and geographical distributions of the gains and losses from it.

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[2]Introduced in the frequently cited "Pigou-Knight two-roads controversy." See Frank H. Knight [1924], "Some Fallacies in the Interpretation of Social Costs," *Quarterly Journal of Economics*, **38**, 582-606.

[3]See, in particular, Martin Beckmann, C. B. McGuire, and Christopher B. Winsten [1956], *Studies in the Economics of Transportation* (New Haven: Yale University Press) and Alan Walters [1961], "Theory and Measurement of Private and Social Cost of Highway Congestion," *Econometrica*, **29**, 676-699.

[4]United Kingdom, Ministry of Transport [1964], *Road Pricing -- The Technical and Economic Possibilities* (London: Her Majesty's Stationery Office).

[5]Treating each mile of a two-way road as two miles of one-way road, the Twin Cities Metropolitan Area has 9,667 miles of one-way expressways, freeways, arterials, collectors and high-occupancy-vehicle (HOV) lanes. Of these, 82 percent would morning peak tolls of 2 cents per vehicle mile or less if tolls were imposed on all roads and the demand elasticity is -1.0. Thus, tolling "all" roads would not be as overwhelming a task as might at first blush appear to be the case.

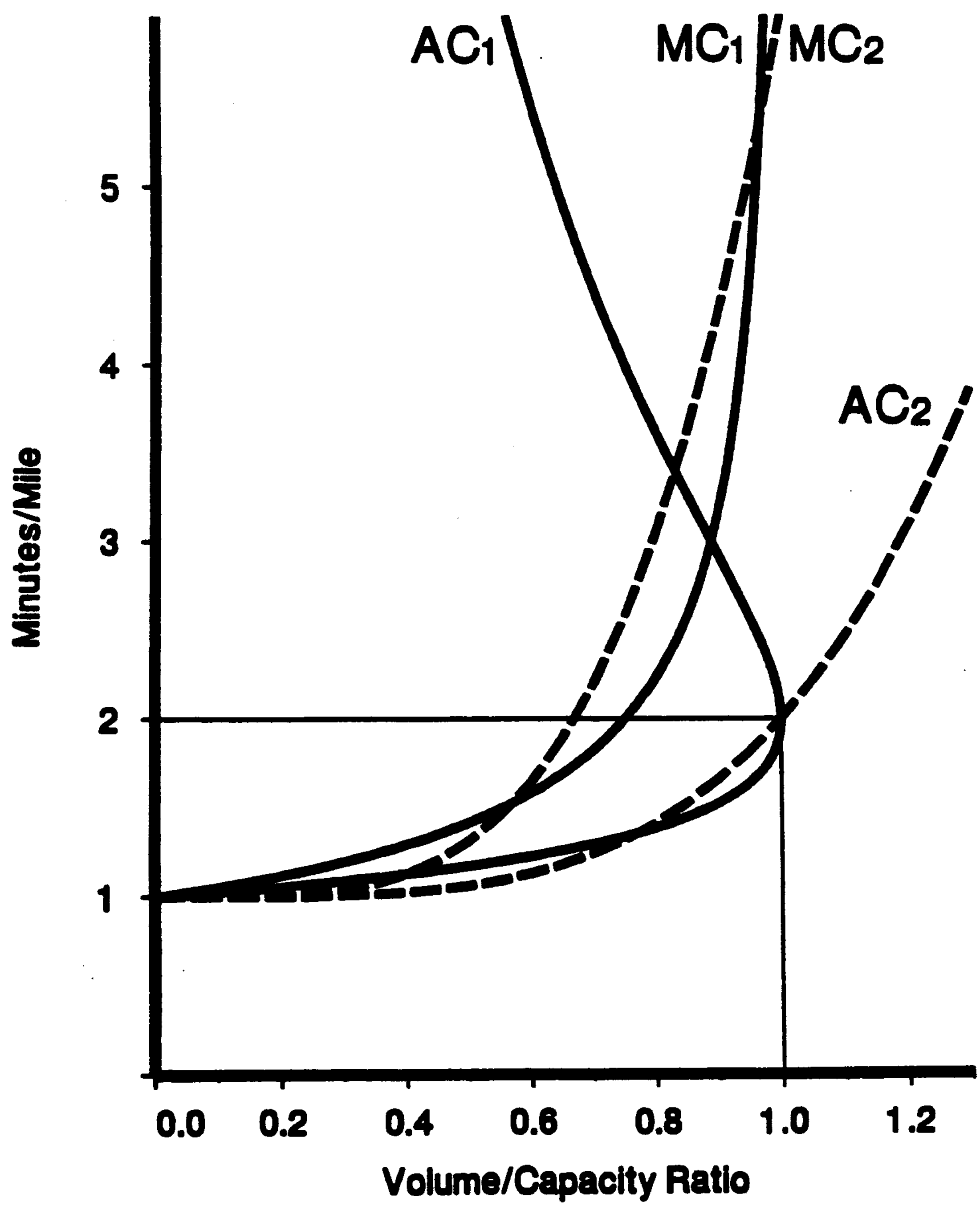
II The Theoretical Foundations of Congestion Pricing

Urban travelers both experience congestion and contribute to it. Inducing the operator of a vehicle -- any vehicle -- to remove it from a traffic stream would save not just its occupants' own time but also the time cost they would otherwise impose on other travelers by adding to the road's congestion level. This time cost is the change in time per trip the departed vehicle would have produced *times* the number of vehicles that change would have affected.

A commonly invoked rule of safe road behavior is that drivers should stay one car length behind the vehicles they follow for each ten miles an hour of travel speed. If all travelers follow this rule and all would travel at 60 miles per hour (*i.e.*, would take one minute to travel a mile) on an otherwise unused expressway, there would result the relationships between the instantaneous ratio of actual traffic volumes to "ideal" capacity (about 2,000 vehicles per lane-hour on an expressway) and the average (AC_1) and marginal (MC_1) travel times per mile that are given by the solid curves in Figure 1. Curve AC_1 depicts the travel-time costs that individual travelers directly experience; curve MC_1 includes these costs plus those that each vehicle operator imposes on others by adding to congestion. Curve AC_1 illustrates a commonly observed phenomenon of urban-expressway travel: maximum traffic flow occurs at about 30 mph. Above 30 mph, lower speeds result in increased traffic flows. In the top, backward-bending portion of AC_1 where it takes more than two minutes a mile, however, further speed reductions lower traffic flows.

Peak-period travel does not take place at a constant rate but, rather, gradually increases to a peak then decreases. Someone traveling at the peak of the peak period is more likely to experience the backward-bending portion of curve AC_1 than is someone who travels at the beginning or end of the peak. Still, both peak-of-the-peak and fringe-of-the-peak travelers do almost always get where they are going; a peak-of-the-peak trip just takes longer. We have, therefore, used marginal and average travel-time relationships similar to those given by the dashed curves, AC_2 and MC_2 in Figure 1 in deriving the toll estimates that are reported in

Figure 1
Relationships between Volume/Capacity Ratios and Travel Time



Section V.[6]

In developed countries, travel time is by far the most costly variable input to trip production. Several subsequent studies support the results of Lisco's early, excellent analysis of travel behavior.[7] Converting its results into current prices yields the conclusion that travelers with annual incomes of more than $35,000 tend to value their travel time at half their hourly earnings rates. That is, they are willing to pay up to half of what they earn working an hour to save an hour of travel time. For travelers with lower incomes, the *ratio* of travel-time value to income is proportional to income. This proportion increases linearly from zero for someone with no income to 50 percent for someone with an annual income of $35,000. Applying these proportions to household- and family-income data for the Twin Cities Metropolitan Area from the 1990 US Census of Population yields respective hourly averages for the whole area of $9.98 per household and $11.86 per family. We use $10 per *vehicle* hour in all of the following calculations.

A claim often made by opponents of congestion pricing is that it would only push travelers around among roads and force them to pay additional taxes but would not actually save any travel resources. It will prove useful for the discussion of later sections to examine these claims carefully here by using as illustration a simple example that leads to a surprising conclusion: carelessly chosen road "improvements" can actually worsen travel flows.[8]

In the hypothetical road network illustrated in Figure 2, travelers wish to go only from point *A* to point *D*. Five one-way roads connect these two points. Travel on three of them -- *AC*, *CB*, and *BD* -- is subject to congestion; the greater is the rate at which trips are made on them, the slower traffic flows. Specifically, if *N* trips per hour are taken on *AC* or *BD*, travel

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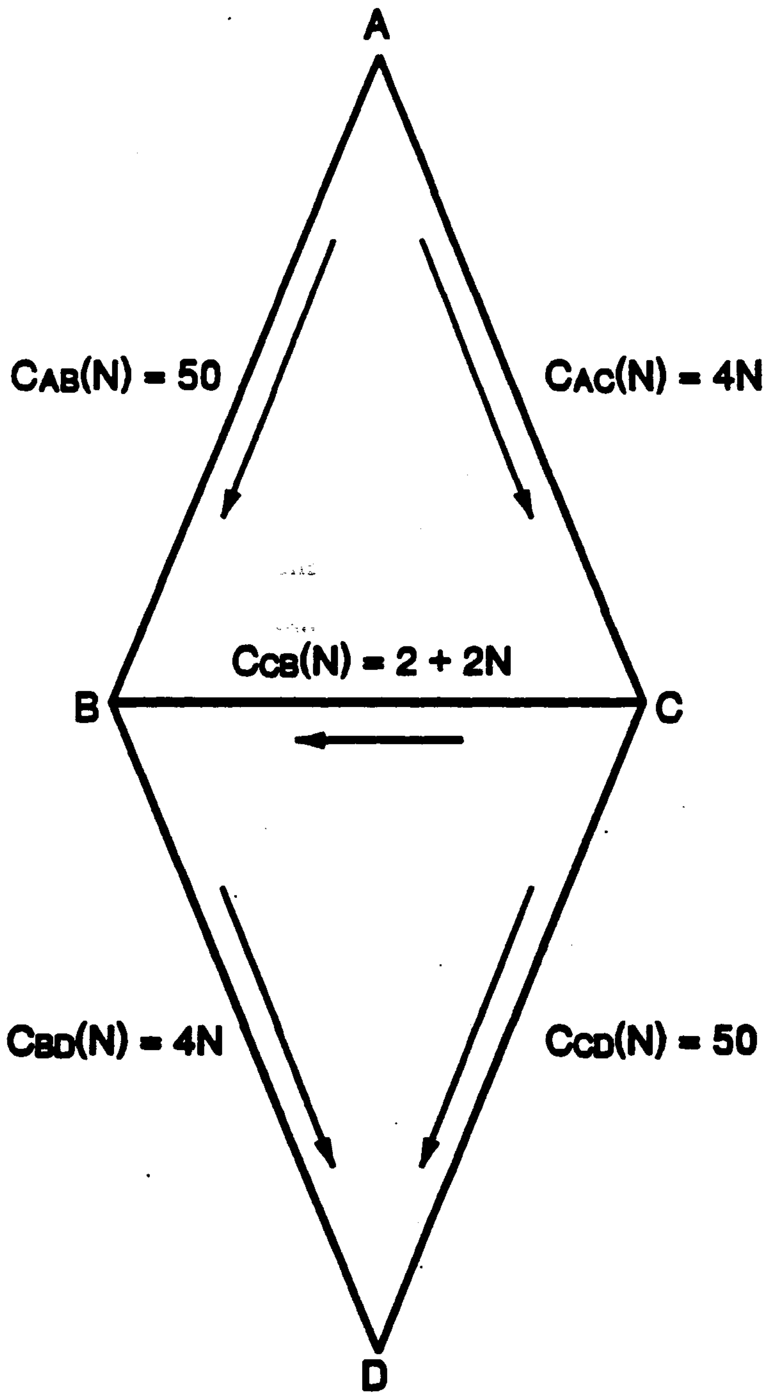
[6]The formulae for the solid and dashed average cost curves are, respectively, $N/K = 4(1 - t^*/t)t^*/t$ and $t = 1 + (N/K)^4$ where N/K denotes the ratio of vehicle volume to ideal capacity and t and t^* are respectively actual travel time per mile and travel time per mile at a zero N/K ratio.

[7]Thomas E. Lisco [1967], *The Value of Commuters' Travel Time: A Study in Urban Transportation*, PhD Dissertation, University of Chicago.

[8]D. Braess [1968], "Ueber ein Paradoxen der Verkehrplanung," *Uenternehmensforschung* 12, 258-268.

Figure 2

Hypothetical One-Way Road Network



time on each is $4N$ minutes while, if N per hour travel on CB, travel time on it is $2 + 2N$ minutes. Although circuitous, the remaining two roads, *AB* and *CD*, are so wide that travel time on each of them is 50 minutes, regardless of traffic flow.

Suppose that 16 trips an hour are made between *A* and *D*. Trial and error reveals that *total* travel time will be minimized if eight of them travel from *A* to *B* to *D* -- an *ABD* trip, call it -- and the remaining eight take *ACD* trips. With these routings, travel time per trip is 82 minutes. However, adopting the usual assumption in traffic-assignment analyses that travelers select routes to minimize their own travel times, this allocation would not be an equilibrium. Starting from this assignment, a single *ACD* traveler could reduce his or her travel time from 82 to 76 minutes by shifting to an *ACBD* trip. It turns out that no traveler will individually be able to reduce trip time only if four *ACBD* trips are made an hour together with six *ABC* and six *ACD* trips. In this equilibrium, travel time is 90 minutes per trip. Paradoxically, closing the *CB* road would force travelers into the cost-minimizing traffic allocation; more generally, in the absence of congestion pricing, it is possible that all travelers could be made better off by eliminating part of a transportation network.

To extend these conclusions, imposing congestion tolls on urban roads would do much more than just enhance government revenues and reduce vehicular travel. Imposing tolls would increase the efficiency with which urban travel takes place. At present, if travelers can take more than one route between two points, they tend to adjust their travel patterns so as to equalize travel time -- the *average* time cost of a trip -- among the routes they use. Equalizing *average* costs does not, in general, equalize *marginal* costs, a necessary condition for minimizing total costs. Suitably chosen congestion tolls would achieve this objective. Imposing them would, in general, both reduce user-borne costs of travel and increase tax revenues to highway authorities or state or federal governments. The relative and absolute sizes of government and user benefits depend on a number of factors. Two are particularly important: the greater is the current level of road congestion and the more sensitive are changes in travel behavior to price changes, the greater will be both total benefits and the users' share of them.

III The Technology of Road Pricing and the World's Experience with It[9]

"Road pricing" evokes visions of toll booths at every street corner or expressway interchange. Particularly for the short trips that predominate in urban areas, manual toll collection absorbs a large fraction of toll revenues and slows travel appreciably. It is fortunate that both low- and moderate-tech alternatives to manual collection are already available and that more advanced techniques are in fairly advanced stages of development.

Any system of road-user charges requires three broad elements:

(1) An in-vehicle unit (IVU) which can respond to external interrogation and may include a display for the use of drivers or enforcement staff coupled with an external or internal device for recording road use thereby enabling charges to be levied,

(2) An external device to communicate with the IVU,

(3) A means of detecting and uniquely identifying non-complying vehicles.

Singapore's "Area Licensing Scheme" (ALS), the pricing system that it introduced in 1975, performed these tasks very simply and very effectively.[10] The "IVU" required of a private passenger vehicle crossing a cordon line into the "Central Area" -- Singapore's central business district -- during the weekday-morning peak period was either containing more than three people or displaying on its windshield a license that cost (S)$3 per day or S$60 per month. ((S)$3 was the equivalent at the then current exchange rate of about (US)$1; henceforth, all price and related data will be converted into US dollars at contemporary exchange rates.) Human monitors stationed at each of the 21 entry points to the Central Area recorded the license numbers of non-complying vehicles; their owners received in the mail a few days later traffic tickets imposing (US)$18 fines for first offenses.

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[9]We rely heavily here on three unpublished papers: Timothy D. Hau [1992], "Congestion Charging Mechanisms for Roads: An Evaluation of Current Practice," World Bank Policy Research Working Paper 1071, A. D. May [1993], "Potential of Next-Generation Technology," University of Leeds (UK), and Michael Pietrzyk [1993], "State of the Art in Electronic Toll Collection," University of South Florida.

[10]Edward P. Holland and Peter L. Watson [1978], "The Design of Traffic Pricing Schemes," *Transportation Engineering*, 48(2), 32-38 contains an extended description of the development and early accomplishments of the Singapore scheme.

Singapore's ALS satisfies several of the road-pricing desiderata that the Smeed report and subsequent writers have identified: The system is simple and understandable. Prices are stable and easily ascertainable before a journey. Payment in advance is possible. The "equipment" -- paper licenses and human observers -- is reliable and -- at least in Singapore -- reasonably free from the possibility of fraud and evasion. Occasional users and visitors can be equipped easily and at low cost.

But the ALS does have shortcomings: Charges are not closely related to the use a traveler makes of road services; what matters for charging is whether a vehicle crosses the cordon line during the morning (and, since 1989, afternoon) peak, not how far or in what level of congestion it traveled to reach the Central Area or within it. Only limited temporal and spatial variations in charges are possible; colors, shapes, and sizes of licenses could be varied to identify different time periods and areas, but reliability of monitor identifications dictates using only a few combinations. Singapore's use of just one time period and one cordon line resulted in substantial congestion both before and after the restricted period and on roads just outside it during that entire period.

Had it been put into operation, the system that Hong Kong tested during the early 1980s promised to improve upon a number of the Singapore ALS's limitations -- those on spatial and temporal price variations, in particular. In the trial system, passage of vehicles over inductive loops embedded beneath the pavement surfaces of roadways reliably triggered the vehicle's US$60 transponder to transmit an identification code which would have been sent to a central computer where a charge appropriate to the time and location of the code's transmission would have been added to the vehicle owner's account. Monthly road-use bills would have been sent to vehicle owners.

Sadly for the progress of congestion pricing, then newly instituted, popularly elected district councils objected so vigorously to the congestion-pricing proposals that the colonial government effectively withdrew them. The councils' reasons for opposition were not entirely clear. Most prominent among those mentioned, however, was that the system's ability to identify specific vehicles' locations at specific times would have invaded vehicle operators' privacy -- a concern heightened by the impending takeover of Hong Kong by the Peoples' Republic of China.

Stickers (as in Singapore) and read-only tags (as in Hong Kong's transponders but also including bar-code identification panels) are already widely used for enforcement and automatic toll collection. The simplicity and low cost of read-only tags would make it easy to provide for visitors and occasional users but also opens them to fraud. More complex and costly are read-write units that store and process information received from a roadside communication device on-vehicle. This on-vehicle processing could range from keeping an independent record of recent transactions that a Hong Kong-type computer has processed to deducting distance-based congestion-related charges from a prepaid account balance. Although more complex units would decline in cost with volume production even without further development, their inevitably higher production and installation costs would limit their use for visitors and occasional users particularly if they require odometer links. Policing compliance also presents serious problems.

Vehicle detection and identification are the least advanced of the technologies that would be required for a functioning road-pricing system. Inductive-loop/axle sensor systems, pulse-mode microwave systems, infrared light-beam systems, and video-image processing systems have all been the subject of experimentation in the detection and classification of vehicle types. All have deficiencies in one or another of accuracy, ability to operate with high-speed vehicles or in multi-lane environments, obscuring of small vehicles by large vehicles, installation costs, ability to distinguish simultaneous signals, and recording accurately where lane changes are not prohibited. Development efforts aimed at overcoming these difficulties continue. Success is, at most, a few years off.

By way of summary and example, using as entry points bridges over the Mississippi and Interstate Highways 94 and 35W, and judiciously restricted streets between the Mississippi and I-94 on its north side, a Singapore-like congestion pricing system could be instituted in

Minneapolis in very short order. Singapore itself has invited proposals for making its system electronic at, roughly, a Hong Kong level of complexity and extending it to cover multiple sectors and charges which vary with time of day. Unlike Hong Kong, sensitivity about the privacy of vehicle operators will not deter the Singapore government; it will install the winning system in the near future.

Turning to the present state of congestion pricing, Singapore's Area Licensing Scheme was and remains incredibly successful. Its planners aimed at a 25 percent reduction in Central Area morning traffic; they achieved a 75 percent reduction in private-passenger vehicle travel and a 50 percent reduction in all travel into the Central Area. Indeed, the Central Area was so free of traffic that congestion delays there were trivial. If anything, Singapore had overdone it: Congestion just outside the Central Area's periphery was so great that, despite free flow within it, no reduction occurred in travel times per bus or auto trip to Central Area destinations.

At first blush, the extreme effectiveness of Singapore's traffic restraints is puzzling. The country's living standards are and were high; Gross Domestic Product per capita was about a third of that in the United States in 1975. Taxes on auto ownership were and are among the world's highest; only the most affluent of Singaporeans owned private passenger vehicles. It seems unlikely that one US dollar could induce 75 percent of high-income Singaporeans to shift to bus from commuting by autos with less than four occupants. That would imply that a very large group of travelers had travel-time values just slightly over the effective price of saving travel time by auto commuting -- the difference between auto and bus cash costs divided by the difference between their travel times. Unfortunately for the prospects of using Singapore data to estimate the distribution of these time values, the ALS was accompanied by a doubling on average of parking charges in the Central Area and a shift from uniform hourly charges to rates varying with location and duration of stay. The effect of these changes on the full price of auto commuting is imperfectly known.

Apart from that of Singapore, we are aware of only four systems in actual operation that might reasonably be labeled "congestion pricing." Several more are in various stages of planning and development while still others have joined Hong Kong in being seriously proposed but ultimately rejected.

As for operating systems, the three largest cities in Norway -- Oslo, Bergen, and Trondheim with respective populations of about 500,000, 200,000, and 140,000 -- all impose cordon-line tolls into their central business districts. Whether they belong in a discussion of congestion pricing is unclear. Revenue was clearly important in establishing these tolls; each municipal government states its purpose to be raising funds for transport improvements. According to one story, however, congestion control is the *ultimate* objective of the tolls; raising revenue is a function of governments that Norwegians dislike but accept as necessary (2/3 of a sample of Oslo residents opposed the imposition of tolls there) while they deem using taxes to control behavior as an unconscionable infringement on human liberty. As of late 1991, only Trondheim varied its toll diurnally; there, charges of about US$1.50 and US$1.15 during peak and off-peak periods are collected between 6 *a.m.*-5 *p.m.* on weekdays. 85-90 percent of Trondheim users are equipped with transponders; they are leased to users at no charge and an appreciable discount for their use is offered from the manual toll-collection rate.

The only other congestion-pricing scheme of which we are aware that is actually in operation involves a toll road that connects Paris with the English Channel. The road was heavily congested southbound late on summer Sunday afternoons by recreational travelers returning to Paris. In cooperation with traveler groups, the toll road authority changed the Sunday toll from the approximate equivalent of US$6 per trip regardless of time of day to approximately US$8 during the peak travel period and US$4 during the remainder of the day. The change spread the flow of traffic much more uniformly through the day and greatly reduced peak period congestion without appreciably affecting toll-authority revenues.

A small sample follows of other road-pricing projects that are firmly planned, under active consideration, or were seriously considered but ultimately rejected in the recent past. California's Department of Transportation has granted the California Private Transportation

Company (CPTC) the right to plan, construct, and operate for 35 years four tolled lanes in ten miles of the median of State Route 91, the primary link between Orange and Riverside Counties. These lanes will, in part, function as a high-occupancy-vehicle facility in that vehicles with more than two occupants will travel free at first and at a discount later should their use jeopardize the economic viability of the project. Unlike a high-occupancy-vehicle (HOV) facility, however, vehicles carrying fewer than three occupants that are equipped with smart cards costing about $30 may pay to use the facility. An assumed $13 an hour value of travel time entered into the design of the toll structure; during peak periods, the toll for the ten-mile facility is initially expected to be about $2.50 but will be adjusted to prevent congestion in the restricted lanes. CPTC estimates that tolls will cover its operating costs and yield a 17-20 percent return on its $88-million investment.

Reversible HOV lanes have occupied the median strip of Interstate Highway 15 in San Diego since 1988. These lanes currently carry about 1,600 vehicles -- less than half of their capacity -- and each carries a somewhat smaller fraction of person trips in the peak direction of the morning peak hour than do each of the expressway's four general purpose lanes. The San Diego Association of Governments (SANDAG) is seeking approval of the California Legislature to sell some of this excess capacity to single-occupancy-vehicle (SOV) operators who are willing to pay for premium service. Although at an early stage, the legislative approval process has experienced no appreciable opposition at either the state or the local level. If approved, a low-tech subscription license fee will be charged. Subsequently, SOV access to the HOV lanes will be controlled electronically through real-time monitoring of available capacity and real-time specification of tolls designed to maximize HOV-lane use subject to maintaining "Level-of-service-A speeds."

In England, the Cambridgeshire County Council is contemplating a pricing scheme based on experienced rather than expected congestion for Cambridge. Under it, when a vehicle equipped with a county-provided smart card enters the city during the peak traffic period, the card would be triggered on by a roadside beacon and would remain on as long as the vehicle's engine is running. "Congestion units" would be debited against the card's stored value when the time required for a rolling half kilometer exceeds a threshold level.

Alas, congestion pricing proposals are more often vanquished than victorious. Thus, for a decade or more, California highway authorities have recognized that, at its current effective toll of $1 per round-trip, the San Francisco-Oakland Bay Bridge is heavily congested. Stop-and-go driving at entry points to the bridge contributes significantly to air pollution and wastes enormous amounts of travel time. Bay Area residents consistently rank transportation as their most important problem. The area's five counties have each voted one percent sales taxes to fund transportation improvements. The California legislature passed a measure in 1988 for an area-wide vote on whether to (1) raise tolls on all area bridges by $1 to finance a variety of bridge and approach improvements and (2) devote 90 percent of bridge tolls to transit improvements. 73 percent of the voters endorsed this proposal. Despite this concern, the Bay Bridge toll remains at $1 per round trip. An increase is not in prospect in the near future. Several concrete proposals have been made during the last five years for specific packages of toll increases *and* allocations of toll revenues. Each has met with outraged opposition by groups who feel themselves discriminated against by the tolls, by the proposed use of toll revenues, or both. The opposition has always triumphed.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 provides for grants to communities to conduct congestion-pricing demonstrations. So far, only one such grant has been approved. It is to the Bay Area's Metropolitan Transportation Commission and the California Department of Transportation which plan to devote the grant's first-year funds to a study demonstrating what is probably impossible to demonstrate (see Section IV): that, apparently without reference to what will be done with toll revenues, pricing will benefit *all* bridge users.

In response to a 1988 policy decision by the Netherlands' government to institute a comprehensive road-pricing scheme for the entire country in 1992-96, its Ministry of Transport established a task forcorce on road pricing to investigate the feasibility of a comprehensive experiment in 1992 which would lead to instituting road pricing by 1995 in the entire Ranstad Area which comprises the cities of Amsterdam, Rotterdam, the Hague, and Utrecht with a total of six million residents -- 40 percent of the country's population. Objectives of the proposal were to reduce by 14 and 30 percent respectively the projected 72 percent growth of both auto and peak-period travel between 1986-2010 and to reduce waiting time by 19 percent. Revenues were to be used to finance roads and tunnels with left-over receipts to be rebated to motorists somehow -- perhaps through reduced auto ownership taxes.

These broad proposals floundered badly. The Dutch auto lobby apparently suspected that revenues would be used not as proposed but, rather, simply to enhance government revenue. The government drastically scaled back the first phase of the project simply to employing electronic toll collection at tunnels. In 1992, the Ministry of Transport announced institution of Singapore-type licensing for peak-period use of the main road network with seasonal passes priced sufficiently attractively that 80 percent of current users would purchase them thereby equating to zero the short-run marginal cost of commuting by auto.

IV Why Isn't the Public as Enthusiastic as Economists about Congestion Pricing?

Shortly after the Clean Air Act of 1970 was passed, Boston attempted to institute a comprehensive package of transportation control measures. It succeeded with some. Others proved much more difficult, particularly those dealing with area licensing and parking charges. In writing about the opposition such proposals face from the public, politicians, and the many institutions involved in implementing them, Howitt found public response to be

> more sensitive to the *distribution* and *visibility* of the impact of the policies than to the net benefits or costs.... What prevents the emergence of more active support for auto restraint policies is the almost total absence of individuals or firms that might receive immediate, direct, 'selective' benefits. The few such beneficiaries -- private taxi or transit firms, residents eager to exclude commuter parking and through traffic from their neighborhoods -- are not the base of a broad political coalition.[11]

Modifying Figure 1 provides a good beginning basis for understanding why.

The real-world relationship between travel time per mile and the volume/capacity ratio on a road -- the line labeled *AC* in Figure -- has a backward-bending portion. At low levels, traffic flows at about the maximum allowable speed for any given road type. As the number of vehicle operators seeking to travel increases, speeds slow somewhat but more trips are completed per hour. However, when the rate at which trips are begun approaches and then comes to exceed the capacity of the road, speed slows sharply and the trip-completion rate actually declines.

On an expressway, for example, traffic flows at 60-70 mph at low volume/capacity ratios. As traffic builds, speed decreases slowly at first and then more rapidly as it falls to the 30-35-mph range which characterizes capacity flow. An accident or sudden influx of vehicles at an above-capacity rate can suddenly reduce speeds to less than 30 mph. There results the bumper-to-bumper flow with which all urban drivers are familiar; expressways draw closer and closer to becoming parking lots. It is for this reason that metered access ramps can greatly improve traffic flow on an expressway by keeping the rate at which vehicles enter below its

[11] Arnold M. Howitt [1980], "Adopting and Implementing Urban Transport Innovations," *Journal of Transport Economics and Policy*, 14(2), 157-8.

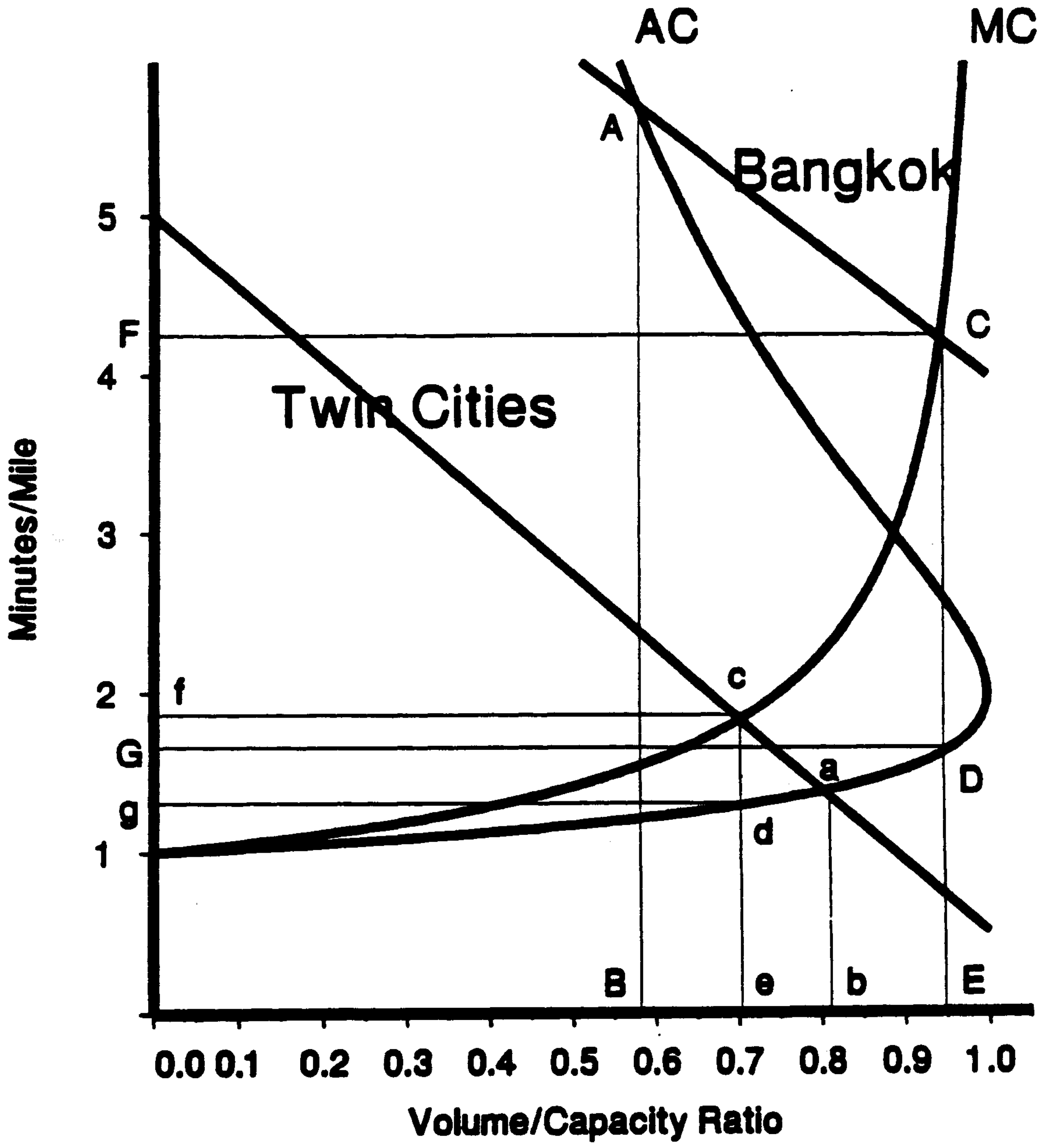
capacity.

Two types of urban traffic situations can usefully be distinguished. First is the state of affairs in Bangkok (or Jakarta or Calcutta or Athens or Rome): Traffic conditions are in the backward-bending portion of the travel-time/flow relationship for a large part of the day. Suppose for sake of illustration that all Bangkok travelers attach the same value to their travel time. Multiplying by this value, the vertical axis is converted from minutes per mile to dollars per mile. A line like that connecting points *A* and *C* in Figure 3 can then be thought of as the demand schedule for trips in Bangkok -- the number of them that would be taken at alternative full prices. In the absence of tolls, equilibrium would be reached at a point like *A* where supply intersects demand with line *AB* being both the price and the resource cost of traveling a mile. Under such circumstances, imposing a toll of *CD* per mile would, after a period of adjustment, lead to an equilibrium at a point like *C* with a price of *CE* per trip. Not only is *CE* smaller than *AB* but also only part of it, *DE*, reflects resources used up in traveling. The remainder, *CD*, represents a transfer of control over resources from travelers to toll collectors, not the using up of resources. Thus, if all Bangkok travelers were to place the same value on their travel time, the results of imposing congestion tolls would please everyone involved in highway provision and use regardless of how toll revenues are used. The price of a trip falls and its resource cost falls even further. The toll collector receives revenues of *CD* per trip or *FCDG* in the aggregate.

This felicitous outcome of congestion pricing would not occur in the much less congested conditions of the Twin Cities. Assuming all travelers to have the same travel-time value with the demand schedule which connects points *c* and *a* in effect, equilibrium in the absence of tolls would occur at *a* with a trip price (equals resource cost) of *ab*. With a toll, the resource cost of a trip would fall to *de*, but its price would rise to *ce*. While aggregate toll revenues, *fcdg*, would more than suffice to compensate travelers for their losses, the *direct* effect of imposing tolls on them is to make them worse off.

Contrary to the assumptions on which the discussion of Figure 3 was based, travelers

Figure 3
Direct Benefits of Congestion Pricing: Twin Cities v. Bangkok



do, of course, differ in the values they attach to travel time; a hotshot attorney on her way to sue the socks off of a miscreant would be willing to pay more to save an hour of travel than would an unemployed ditch digger on his way to pick up an unemployment-compensation check. Recognizing that travelers differ in travel-time values complicates analysis further in both the Bangkok and the Twin Cities cases. Two sorts of complications are of particular importance in this discussion. The first is related to the income distribution of the benefits and costs of congestion pricing and the second to the optimal design of road networks.

In converting to dollars the minutes per mile that each traveler imposes on all other travelers by adding to the level of congestion, the average travel-time value of all travelers is the appropriate number to use. The higher are travelers' incomes and, with them, travel-time values, the smaller is the resulting toll as a fraction of their full price of a trip. Indeed, in the Twin Cities, although a direct effect of congestion tolls would be to make the *average* traveler worse off, the reduction in travel time per mile that tolls yield would benefit some high-income travelers more than the additional toll payments would cost them. Similarly, even though tolls would lower the *average* full price of a Bangkok trip, they would make some low-income Bangkok residents worse off.

In brief, the *direct* effect of congestion pricing on some low-income Bangkok residents and all but the highest-income Twin Cities residents would be to make them worse off. Most people naturally respond with opposition to government actions that reduce their welfare -- socially desirable though these actions may be. Many of these opponents could be won over by allocating toll revenues in ways that would benefit them sufficiently to offset their direct losses from tolls. *To emphasize, gaining the support of most Twin Cities peak-period travelers for congestion tolls would require coupling the tolls with a plan for using the resulting revenues that would benefit them more than the tolls would cost them.* Using some of these revenues for road or, perhaps, other transportation improvements is one possibility. Using some of them to reduce fuel and other user taxes is a second. Using some to make direct cash grants to low-income households is a third. Using some to reduce real-estate taxes is yet a fourth.

Turning to road-design issues, optimal capacity for a road can be defined as requiring the last unit of capacity added to it to generate benefits in the form of future congestion-cost savings with a present value equal to that of the unit of capacity. Since the present value of minutes of congestion cost saved depends on the value of travel time assigned to them, so, too, does the optimal volume/capacity ratio of a road. A road designed for low-time-value travelers would have a high optimal volume/capacity ratio. Each vehicle mile traveled would impose many minutes of congestion delay on other users. However, the effect of the low time value more than offsets that of the high volume/capacity ratio; holding construction costs fixed, the lower is the value of time associated with a road, the higher is its optimal volume/capacity ratio but the lower is the associated marginal-cost congestion toll. Similarly, an optimal road for users with high time values would have a low volume/capacity ratio and few minutes of congestion delay imposed by each vehicle mile of travel. The congestion toll would be large, however; delay minutes per vehicle mile would be multiplied by high values of delay time.

Justifying a specialized real-world road would require so large a homogeneous group of users that building one would rarely be economically feasible. Still, opportunities do arise in which it is possible to provide differentiated services to groups with different travel-time values -- opportunities that would make both groups better off than they would be if forced to use the same undifferentiated road. Important cases in point are the plans in Southern California to sell the right to use HOV lanes to operators of single-occupancy vehicles at prices sufficiently high that the number of buyers will not reduce attainable speeds appreciably. Although a similar proposal for the HOV lanes on I-394 and those planned for I-35W would likely generate much egalitarian ire, it would still be worth serious consideration for congestion pricing in the Twin Cities. Similarly, imposing tolls on urban expressways would be considerably easier technologically than imposing them on urban arterials and collectors. Preliminary analysis suggests that imposing tolls only on Twin Cities expressways would save almost as many minutes of congestion delay as would imposing them on the area's entire road network even if all travelers attach the same values to their time. Offering travelers an expressway/non-expressway choice at an appropriate difference in price would undoubtedly increase aggregate traveler benefits and mollify somewhat the lower-income travelers whose ire over congestion pricing would likely be particularly severe. Expressway-only pricing could, though, significantly increase congestion on residential collectors -- a price that some would undoubtedly regard as unacceptable.

Congestion pricing has been much more widely discussed in Britain than in North America. Here are brief economist-type arguments that respond to six reservations that, Jones reports,[12] are particularly prominent there followed by two arguments that he does not mention but that have been heard in North America:

1. *Congestion pricing will not work; people will still drive:* People *do* respond to changes in transportation prices with changes in travel behavior. Here are just a few examples of responses to changes in these prices; many more can be cited. In 1988, the Massachusetts Port Authority (MassPort) briefly changed its landing fee structure at Logan International from $1.31 per thousand pounds of aircraft weight with a minimum fee of $25 to $88 *plus* $0.47 per thousand pounds. Several organizations and states successfully sued MassPort claiming that the new formula discriminated against small aircraft and was contrary to federal statute. The US Department of Transportation made it clear that, as long as MassPort continued in its "discriminatory" ways, it would receive no federal funds for airport capital improvements. Still, during the brief period during which the new price schedule was in effect, the number of commuter-aircraft flights to Logan from Burlington, VT declined from 22 to 12.

Several transit systems in the United States have experimented with surcharges and discounts during peak- and off-peak periods respectively. The results have varied from system to system and with characteristics of travelers and trips -- age, income, e.g., and trip length and purpose -- but, Cevero reports,[13] the overall fare elasticity of demand -- the

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[12]Peter Jones [1991], "Gaining Public Support for Road Pricing through a Package Approach," *Traffic Engineering and Control*, 32(4), 194-196.

[13]R. Cevero, "Transit Pricing Research: A Review and Synthesis," *Transportation*, 17(2), 117-141.

percentage change in demand resulting from a one percent fare change -- ranges between -0.22 and -0.33.

Finally, we have the example of Singapore where a modest peak-period fee to enter its Central Area together with significant increases in parking charges dramatically reduced peak-period traffic congestion.

2. *The technology is not reliable:* Hong Kong's tests of an inductive-loop/transponder combination achieved accuracies in the 99.9-100 percent range a decade ago. Since then, rapid strides have been -- and are being -- made in a variety of technologies that could be used in sophisticated road-pricing applications. Automatic vehicle-identification (AVI) procedures are particularly advanced but smart-card technology that would permit in-vehicle record keeping for prepaid road-use accounts is not far behind. Except for paper licenses, fraudulent use of road pricing technologies is no more easy than fraudulent use of magnetically coded credit cards. Fraud resistance is being developed rapidly for both credit cards and AVI systems.

3. *Congestion pricing will invade privacy; it can provide information that would make it possible to trace unpopular individuals' vehicles continuously:* AVI technology is somewhat -- but only somewhat -- further developed and lower cost than are technologies that would allow in-vehicle accounting for road use. Using AVI technology is not necessarily inconsistent with privacy; Swiss banks are quite successful in keeping secret the identities of privacy-desiring account holders. It ought not to be too difficult a task to provide account numbers whose owners are known only to themselves but whose vehicles could be identified if used when account balances are negative.

4. *Congestion pricing would inflict significant harm on the poor:* That they are ill-fed, ill-clothed, ill-housed, and, perhaps, ill-transported is really not the basic problem that poor people have. Their fundamental problem is, rather, that they are poor. If we are genuinely concerned with how road pricing would affect their welfare, we should give them cash or marketable road scholarships. It would be the height of folly, however, to subsidize all of our private-passenger-vehicle road use in the supposed interests of helping them.

5. *There are boundary problems in dealing with congestion pricing; when does the peak begin and end?* In a manually policed system like that of Singapore which uses paper licenses, human monitors are seriously limited in the number of combinations of license size, shape and color that they can distinguish reliably and speedily. The combination of this limitation and cordon-line pricing can lead to appreciable temporal and spatial boundary congestion; again, congestion around the periphery of Singapore's Central Area was so severe that its Area License Scheme left travel times to Central Area destinations unchanged despite free-flowing traffic in the Central Area itself. With electronic technology, however, charges can be graduated as finely in time or space as travelers are capable of comprehending. With narrower gradations, boundary congestion will become a smaller problem.

6. *No matter what "they" say, congestion pricing is just another way to collect taxes:* The services that government provide tend to be labor intensive. With increases in living standards, the relative costs of these services have increased. If living standards continue to improve, therefore, government revenue requirements will continue their secular increase. If only for this reason, the suspicion that congestion pricing is just another tax gimmick will be difficult to dispel. *It is, therefore, essential that a detailed proposal for using the revenues congestion tolls will generate accompany any serious proposal to institute them. The greater is the number of auto travelers who feel that proposed reductions in road-user taxes and other give-backs will make them better off, the more likely it is that a congestion-pricing proposal will be accepted.*

Turning to objections to congestion pricing that have appeared in the North American literature and have not already been touched upon, consider:

7. *We have already paid for roads through fuel and other user taxes. Why should we have to pay for them again?* It is by no means certain that user fees cover road costs. Consider the following:

> Contrary to popular belief, drivers do not pay their own way through user fees. In the United States, gasoline taxes and other user fees account for roughly 60 percent of federal, state, and local spending on highways and roads. The remainder, $29 billion in 1989, comes from general funds, property taxes, and other sources. Another cost,

"free" parking, has an estimated value of $85 billion per year. Additional expenses not covered by drivers such as for police and emergency services, traffic management, and routine street maintenance represent some $68 billion annually. When harder-to-quantify costs such as air pollution, traffic congestion, and road accidents are figured in, the total subsidy to drivers in the United States soars to an estimated $300 billion a year.[14]

Even those who would cast these views aside as the rantings of hard core environmentalists cannot dispute that those who gain most from urban road expenditures -- peak-period travelers in the main direction of traffic flow -- have paid through user taxes only a small fraction of the costs of providing the benefits they have received. With important qualifications, road expansion makes sense as long as the present value of aggregate benefits to users exceed the costs of expansion. Peak-period users benefit much more from road expansion than do off-peak users but pay about the same in user taxes per vehicle mile for these benefits.

8. *We impose congestion on each other; why should we pay someone else for the harm we do to ourselves?* It is true that travelers pay for the congestion costs they experience. They do not, however, pay for the congestion costs they impose on others by adding to it. Congestion tolls would force them to recognize the external costs they impose by making them pay their cash equivalent. The logical recipients of these payments is not the users affected by congestion but, rather, the public at large whose expenditures on roads reduce the congestion costs that all drivers experience.

Thus far in this section, we have emphasized the concerns with "efficiency" -- roughly speaking, cost minimization -- that dominate the thinking of economists in discussing such policies as congestion pricing. Economists tend to ignore the income redistribution to which changes in social policy can give rise on grounds that altering the income distribution is a "normative" issue -- an issue that economists are not professionally qualified to decide but, rather, that they must leave to politicians and "decision makers."

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[14]From James J. MacKenzie, *et al.* [1992], *The Going Rate: What It Really Costs to Drive* (Washington, DC: World Resources Institute) as quoted by Marcia D. Lowe, "Rediscovering Rail," in Lester R. Brown, *et al.* [1993], *State of the World 1993: A Worldwatch Institute Report on Progress Toward a Sustainable Society* (New York: W. W. Norton), 135.

Economists' discussions of efficiency have a way of leaving the general public glassy eyed; to them, it is the income distribution -- often, "What's in it for me?" -- that really matters. Distributional issues are particularly important in dealing with congestion pricing where the immediate effect of road pricing, if instituted, will be to make most travelers worse off. In addressing similar serious concerns, economists are inclined to point out that increased efficiency would provide the wherewithal to make everyone better off (or, at least, to make someone or group better off without harming anyone else) but then to leave it to politicians to decide just how to accomplish "making everyone better off."

Often, accomplishing the income redistribution that would make everyone better off would require so much information as to be a practical impossibility. With road pricing, however, the potential gains are so vast that careful analysis of available information -- *available*, note, not *ideally* available -- should make it possible to come up with one or -- better still -- more schemes for allocating the gains from congestion pricing so that everyone would made better off. Meeting this objective must be high on the list of tasks to be accomplished if congestion pricing is not to be rejected out of hand by the public at large.

V Quantifying Congestion Pricing in The Twin Cities Metropolitan Area

Metering vehicle entry at access ramps limits the frequency in the Twin Cities Metropolitan Area with which peak-period expressway travel enters the backward bending portion of the travel time-volume/capacity relationship pictured in Figures 1 and 3. Time spent there in long queues discourages expressway use, particularly for short trips. Use of high-occupancy vehicles (HOVs) is encouraged by allowing them to bypass these queues of single-occupancy vehicles (SOVs) at a few entry ramps and by providing them with reserved "diamond lanes" and heavily subsidized parking at the Minneapolis CBD end of one expressway.

How would a system that collects from each vehicle -- HOV or SOV -- an amount equal to the costs it imposes on all other vehicles by adding to the level of congestion perform in comparison to the present system? We seek to answer this question by using in unconventional ways a package of computer programs, Tranplan, that is produced by the Urban Analysis Group of Danville, CA and used locally by transportation planners at the Minnesota Highway Department, the Metropolitan Council, and several consulting firms for a variety of highway and transit forecasting projects. We should make it clear at the outset of this report that we have only scratched the surface of Tranplan's abilities to serve our purposes. Two shortcomings are particularly serious: First, we have been able only partially to take into account the way in which real-world travel behavior would respond to changes in trip prices. Second, we have been forced to assume that all road users place the same value on their travel time. For this reason, we cannot yet estimate the responses of travelers who differ in travel-time values to routes connecting their origins and destinations that offer different combinations of tolls and travel times. Our inability to analyze these differential responses limits our ability to deal realistically with the effects of imposing tolls only on limited access portions of the road network, the road-pricing option that would be easiest to implement technologically. For all of these reasons, our estimates of the equilibrium toll structure that would arise given plausible responses to increased travel costs are still quite rough. Fortunately, computer packages are available that allow more complete specifications of traveler characteristics. We will work with them in our future pricing studies.

Our analysis starts with the 1990 Travel Behavior Inventory (TBI), a survey taken in June-November 1990 of 9,746 households which took a total of approximately 98,000 daily trips. These trips were carefully expanded through use of cordon-line counts and other data to reflect private-passenger-vehicle travel in the entire metropolitan area on an average 1990 weekday. The current study is limited to those private-passenger-vehicle trips that were on the road at some point during the morning or afternoon peak travel hour. Each trip studied originated in one of the 1,200 traffic-analysis zones (TAZs) into which the metropolitan area is divided and terminated in one of the remaining 1,199 TAZs; congestion is generally not significant for intra-zonal trips.

The metropolitan area's road network is broken into approximately 18,800 links. Examples of links include several-block stretches of an arterial or collector street and an expressway access ramp, HOV lane, or one-way segment between two interchanges. TBI surveys obtain origin and destination addresses and, hence, TAZs for each trip but not the route taken. The section of Tranplan on which we have relied most intensively is based on the assumption that each traveler selects that route -- a series of links -- for each trip which minimizes the trip's "impedance." Tranplan "loads" trips onto the network using a process that finds an equilibrium in which no traveler is able to find a route with less impedance. Travel time is Tranplan's default measure of impedance, but distance, a combination of time and distance, *marginal* travel time, or a variety of other measures could be used.

We assume that travel time is the only cost of travel that is affected by the level of congestion. Tranplan's default measure of travel time for link i is what its manual terms "the historic standard Bureau of Public Roads capacity restraint formula." Using it, the time required to traverse link i, T_i, is

$$T_i = = T_{io}\{1 + 0.15[N_i/K_i]^4\} \tag{1}$$

where N_i is the rate at which vehicles travel on link i, K_i is what we term its "practical" capacity, and T_{io} is the time required to traverse link i when no other trips are being taken on it.

Note that it is *practical* capacity that enters into equation (1), not the *ideal* capacity assumed in drawing Figures 1 and 3. A volume/*ideal* capacity ratio of one is approximately equivalent to a volume/*practical* capacity ratio of 1.6.

Equation (1) implies that any number of trips per hour can be squeezed through a link provided only that enough time is spent on each. Road links do, of course, have definite upper bounds on the rates at which vehicles can traverse them (see Figures 1 and 3). Nevertheless, equation (1) provides a plausible summary relationship. As traffic increases to a peak and then ebbs during the morning and afternoon rush hours, most vehicles do ultimately arrive at their destinations. Trips at the peak of the peak just take longer.

If travel time per trip on link i is given by equation (1), the total travel time, τ_i, expended by the N_i trips per hour taken on it can be found by multiplying (1) through by N_i:

$$\tau_i = N_i T_i = N_i T_{io}\{1 + 0.15[N_i/K_i]^4\} \qquad (2)$$

Marginal travel time -- the change in total travel time when an additional traveler is added to the traffic stream -- can then be written

$$\Delta\tau_i/\Delta N_i = T_{io}\{1 + 0.75[N_i/K_i]^4\} \qquad (3)$$

The difference between equations (3) and (1) -- marginal travel time *minus* average travel time on link i -- multiplied by the average value of travel time (the reasoning described on page 13 leads us to value it at \$10 per private-passenger-*vehicle* hour) is the cost an additional traveler imposes on all other travelers by adding to congestion on the link.

If travel activity were independent of the price charged for it, \$10 *times* the difference between equations (3) and (2) would be the appropriate congestion toll for link i. But imposing tolls would affect travel activity; imposing a toll of \$10 *times* the difference between equations (3) and (2) on a previously untolled road would lead to reduced travel. For this reason, we use the word "*toll*" to refer to \$10 *times* the difference between equations (3) and (2) only on road networks (a) where travelers have fully adjusted to the existence of a tolling system and (b) where \$10 *times* the difference between equations (3) and (2) is the actual cost a traveler imposes on other link-i travelers by adding to the level of congestion. We use the word "*gap*"

Table 1

Distance, Travel Time, and "Gap" between Average and Marginal Travel Time for 1990 Morning Peak Trip from I-494 to I-94 (TAZ 484 to TAZ 404)

Links Traversed	*Link Description*	*Distance (Miles)*	*Time (Min.)*	*Direct Time Cost*	*Gap between Marginal and Direct Cost*	
					Minutes	*Dollars*
2104-2099	I-494 to I-35W entry ramp	0.12	0.15	$0.03	0.10	$0.02
2099-2097	I-494 to 76th St.	0.22	0.29	$0.05	0.20	$0.03
2097-2086	76th to 66th St.	0.97	1.38	$0.23	1.27	$0.21
2086-2004	66th St. thru 62d St. merge strip	1.69	2.46	$0.41	2.31	$0.39
2004-1994	62d cross town to Diamond Lake Rd.	0.42	1.16	$0.19	1.71	$0.29
1994-1984	Diamond Lake Rd. to 36th St.	2.47	5.14	$0.86	7.63	$1.27
1984-1946	36th St. to I-35W exit to I-94 East	2.72	5.23	$0.87	7.85	$1.31

Source: Authors' computations -- see text.

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to refer to $10 *times* the difference between equations (3) and (2) on road networks on which congestion tolls are not imposed. To emphasize, the *gap* on link *i* is the cost a link-*i* traveler imposes on other link-*i* travelers *when congestion tolls are not charged on link* i.

As an example, consider a trip beginning at 8 *a.m.* in Traffic Analysis Zone 484 on the entry ramp to northbound I-35W from westbound I-494 and ending in TAZ 410 on the exit ramp from northbound I-35W to eastbound I-94 just south of downtown Minneapolis. Travel time for this trip is, of course, minimized by taking I-35W. Table 1 lists the freeway links (identified by beginning and ending nodes) which the trip traverses, their lengths in miles, actual travel times in minutes, and the gap in minutes and dollars between the directly borne and marginal costs of a trip on each link. In 1990, the trip took 15.81 minutes -- an average speed of 32.7 *mph* over its 8.61 miles. The *direct* time cost of the trip at $10 per vehicle hour was \$2.64 while its marginal cost was \$6.15. The difference, \$3.51 or 41 cents a vehicle mile, is the cost the trip imposed on other travelers by adding to the expressway's congestion level.

We analyze three types of equilibria for the morning and afternoon peak hours. We first run Tranplan's "equilibrium highway load program" in its default configuration. That is, we suppose that each traveler chooses that route for a trip which minimizes the time it takes, *i.e.*, the sum of equation (1) over all of the road links incorporated in a trip. Knowing each link's length, required travel time at a zero volume/capacity ratio, and, from data on the loaded network, the actual volume/capacity ratio permits evaluating equations (1)-(3) and, from them, determining all of the items in the first column of Table 2.

Our second equilibrium analysis rests on three assumptions: First, equation (3), the marginal cost of a trip, rather than equation (1), its average cost, governs each traveler's route choice. Second, whatever tolls are charged for uses of a network's links affect only the route taken for a trip, not whether it is taken. Third, the occupants of each vehicle are willing to pay the same total amount -- \$10 an hour -- to save travel time so that all travelers have the same rank ordering of routes for any origin/destination pair. This analysis produced the second column in Table 2.

Our final piece of equilibrium analysis rests on the same assumptions as the second except that we recognize the effects tolls will have on the number of trips taken. Specifically, for reasons detailed in the appendix to this report, we suppose alternative "full-price" elasticities of demand for auto-vehicle trips of -0.5 and -1.0. That is, we suppose that a one-percent increase in the time *plus* money costs of a particular trip results in either an 0.5 or a 1.0 percent reduction in the rate at which that trip is taken. Tranplan does not permit trips to disappear. For the morning peak, we can simulate the effect of having them do so by providing each origin-destination pair with a dummy link to which we give just enough capacity to attract the required number of trips. We cannot do this for the afternoon peak because the number of dummy links that depart from zones with heavy concentrations of employment would violate

Table 2

Travel Times, Costs, Distances, Tolls, and Gaps between Price and Marginal Cost with No Tolls and with Tolls on All Links and Zero, -0.5, and -1.0 Demand Elasticities: Travel Data from the Twin Cities Metropolitan Area 1990 Travel-Behavior-Inventory Trip Table

	No Toll Charged	With Equilibrium Tolls Charged on All Links when Demand Elasticity is: 0	-0.5	-1.0
Morning Peak Hour				
Total				
Trips Taken	518,106	518,106	470,075	454,486
Travel Time (hours)	152,541	148,826	124,874	118,094
Travel Miles	5,071,615	5,171,843	4,576,653	4,387,590
Marginal Time Cost*	$2,574,905	$2,184,233	$1,625,625	$1,490,081
MC - Full Price ("Gap")	$1,049,497			
Tolls		$695,975	$376,888	$309,144
Consumer Surplus Loss		$658,825	$309,185	$201,298
Tolls and (Gaps) per mile				
All Links (cents)	(20.7)	13.5	8.2	7.0
Expressways (cents)	(23.6)	15.9	9.4	8.0
Other Links (cents)	(17.7)	10.5	6.9	6.0
Afternoon Peak Hour				
Total				
Trips Taken	678,143	678,143		
Travel Time (hours)	164,721	160,999		
Travel Miles	5,590,161	5,680,647		
Marginal Time Cost*	$2,596,860	$2,223,238		
MC - Full Price ("Gap")	$949,648			
Tolls		$613,251		
Consumer Surplus Loss		$576,031		
Tolls and (Gaps) per mile				
All Links (cents)	(17.0)	10.8		
Expressways (cents)	(20.1)	12.7		
Other Links (cents)	(13.6)	8.4		

*Travel time valued at $10 per vehicle hour.

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limits that Tranplan imposes on the number of links that can exit from any given Traffic Analysis Zone. Calculations for non-zero elasticities are possible, therefore, only for morning travel.

The most surprising implication of Table 2 is how costly congestion is. The average gap between marginal and average travel-time costs on *all* road links -- not just those that are heavily traveled -- is 20.7 and 17.0 cents per vehicle mile respectively during the morning and afternoon peaks; the numbers are even greater on expressways -- 23.6 and 20.1 cents respectively.

Also surprising is that congestion per mile traveled (although not in total) is heavier during the morning than during the afternoon peak hour -- this despite there being a third more trips and ten percent more miles driven during the afternoon than during the morning peak hour. The average gap between average and marginal travel times per trip is 22 percent greater on all links and 17 percent greater on expressways in the morning than in the afternoon. Apparently, the stops at the grocery store, gas station, and dry cleaner on the way home from work, which largely account for the greater number of afternoon than of morning trips, spread travel out more evenly across the road network than do the morning's more direct trips.

If it were true that imposing congestion tolls would affect only the routing of trips but not their timing, mode, or, indeed, whether they are taken, tolls would still have a measurable effect on the resource costs of peak-period travel. With all links tolled, total travel time would drop by 2.5 and 2.3 percent respectively in the morning and afternoon peaks. Theoretical analyses of abstract cities with central business districts that dominate non-residential activity suggest that congestion tolls would tend to make travel more circuitous.[15] To put this prediction in a Twin Cities context, a trip originating at the University of Minnesota, two miles east of the Minneapolis CBD, that is destined for the Guthrie Theater, two miles to its west, would likely go through the CBD in the absence of tolls; tolls would induce that traveler to skirt around it. The results in Table 2 correspond to this prediction albeit not to the extent that theory would lead one to expect. When tolls are imposed and the demand elasticity is zero, total miles traveled are about two percent greater in both the morning and the afternoon peaks

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[15]See, for example, Marvin Kraus [1974], "Land Use in a Circular City," *Journal of Economic Theory* 8(4), 440-457 and ... [1976], "Land Use in a Circular City: Some Numerical Results," *Regional Science and Urban Economics* 6(4), 399-418.

than when no tolls are imposed. Although imposing tolls in the zero-elasticity case has only a small effect on both aggregate travel time and aggregate distance, doing so has a major effect on the difference between marginal and average travel-time costs. In both the morning and afternoon peak hours, this difference declines by about a third on expressways as well as on other links in the road network.

If the full-price elasticity of demand for peak-period travel is in the range of -0.5 to -1.0, imposing tolls would have an appreciable effect on the amount of travel undertaken. Within this range of elasticities, both trips taken and miles traveled would decline in the morning by 9-14 percent while total travel time would fall by 18-23 percent. Depending on elasticity, the difference between the average and the marginal time costs of travel would decline by 60-67 percent. Toll collections would amount to about $380,000 if the full-price elasticity of demand is -0.5 and to about $310,000 if it is -1.0. These increased outlays are only partly offset by the improvements in travel speed to which tolls give rise. The net "consumer surplus loss" -- a concept described in the appendix to this report -- would be about $310,000 and $200,000 if the full-price elasticities are -0.5 and -1.0 respectively. Put differently, only about 18 percent of toll payments are offset by travel-time benefits if the elasticity is -0.5 and about 35 percent if the elasticity is -1.0.

Tables 3 and 4 respectively show for the morning and afternoon peaks the distributions of link miles, vehicle-miles traveled, and aggregate differences between average and marginal travel-time costs among toll-per-vehicle-mile categories. In the morning, the 79.8 percent of all links that currently have "gaps" -- differences between marginal and average travel-time costs per mile -- of less than two cents account for 35.5 percent of vehicle miles traveled but only 0.7 percent of the aggregate gap between marginal and average costs. Imposing tolls on *all* road links rather than on all *expressway* links with appreciable gaps between marginal and average travel times would not be as large a task as might, at first blush, be supposed; for both morning and afternoon together, on the order of 2,000 miles of *all* road links as opposed to about 400 miles of *expressway* links currently have gaps in excess of five cent a vehicle mile.

Table 3

Distributions of Miles of Road, Miles Traveled, and "Tolls"* Collected within "Toll"-Per-Mile* Groups: Morning Peak-Hour Travel in Twin Cities Metropolitan Area with 1990 Travel-Behavior-Inventory Trip Table

	All Road Links			Expressway Links Only		
"Toll"/Mi. Range*	*Road Miles*	*Vehicle Miles (100s)*	*Aggregate "Tolls"**	*Road Miles*	*Vehicle Miles (100s)*	*Aggregate "Tolls"**
			No Tolls Charged			
$0.00-	7,718	18,011	$7,514	305	4,514	$2,747
$0.02-	487	5,051	$16,318	67	2,171	$6,907
$0.05-	396	5,748	$42,319	67	2,948	$21,847
$0.10-	239	3,975	$49,152	44	2,177	$26,730
$0.15-	152	2,807	$48,863	30	1,520	$26,566
$0.20-	188	3,853	$92,854	37	2,062	$49,068
$0.30-	133	3,125	$109,362	32	1,848	$65,102
$0.40-	93	2,220	$98,641	19	1,217	$53,556
$0.50-	184	4,637	$304,270	39	2,510	$162,940
$1.00-	57	983	$135,320	3	144	$21,080
$2.00-	12	188	$51,215	0	3	$656
>$4.00-	7	101	$93,680	0	0	$0
Total-	9,667	50,700	$1,049,508	642	21,114	$437,198
			All Links Tolled -- Zero Demand Elasticity			
$0.00-	7,352	18,895	$8,706	307	4,700	$3,108
$0.02-	659	6,950	$23,361	88	3,061	$10,446
$0.05-	552	7,033	$51,421	79	3,300	$24,371
$0.10-	299	4,740	$57,939	52	2,498	$30,490
$0.15-	206	3,488	$60,279	35	1,760	$30,289
$0.20-	251	4,564	$112,230	42	2,262	$54,940
$0.30-	140	2,593	$89,524	21	1,174	$40,317
$0.40-	72	1,439	$65,001	12	720	$32,733
$0.50-	102	1,529	$102,011	6	314	$19,220
$1.00-	25	354	$46,556	0	14	$1,740
$2.00-	5	70	$19,297	0	0	$0
>$4.0-	4	46	$59,656	0	0	$0
TOTAL-	9,667	51,702	$695,980	642	19,803	$247,655

(Continued)

*As used here, "Toll" and "Tolls" denote the difference between the marginal and the average time cost of a trip regardless of whether a toll is charged.

Table 3 (Continued)

"Toll"*/Mi. Range	All Road Links: Road Miles	Vehicle Miles (100s)	Aggregate "Tolls"*	Expressway Links Only: Road Miles	Vehicle Miles (100s)	Aggregate "Tolls"*
All Links Tolled -- Demand Elasticity = -0.5						
$0.00-	7,759	19,517	$9,159	342	5,321	$3,669
$0.02-	682	7,285	$24,322	95	3,341	$11,119
$0.05-	507	7,350	$53,892	95	4,017	$29,712
$0.10-	236	3,669	$45,759	40	1,857	$23,414
$0.15-	171	2,908	$50,088	32	1,481	$25,411
$0.20-	165	2,985	$72,151	29	1,487	$36,154
$0.30-	59	970	$33,484	7	353	$12,288
$0.40-	30	354	$15,670	1	35	$1,705
$0.50-	45	568	$36,963	2	57	$3,381
$1.00-	8	111	$15,081	0	0	$0
$2.00-	3	32	$7,765	0	0	$0
>$4.00	2	18	$12,555	0	0	$0
TOTAL	9,667	45,766	$376,888	642	17,951	$146,852
All Links Tolled -- Demand Elasticity = -1.0						
$0.00-	7,921	19,955	$9,570	360	5,648	$3,954
$0.02-	668	7,151	$23,833	93	3,308	$11,095
$0.05-	469	6,890	$48,878	90	3,725	$26,092
$0.10-	232	3,879	$48,678	48	2,183	$27,630
$0.15-	144	2,501	$43,635	27	1,273	$22,450
$0.20-	122	2,057	$49,268	19	956	$23,197
$0.30-	46	651	$22,093	3	150	$4,902
$0.40-	24	284	$12,849	1	61	$2,766
$0.50-	31	390	$24,904	1	29	$1,682
$1.00-	7	89	$12,477	0	0	$0
$2.00-	2	20	$5,550	0	0	$0
>$4.00	1	10	$7,410	0	0	$0
TOTAL	9,667	43,876	$309,144	642	17,332	$123,770

*As used here, "Toll" and "Tolls" denote the difference between the marginal and the average time cost of a trip regardless of whether a toll is charged.

Table 4

Distributions of Miles of Road, Miles Traveled, and "Tolls"* Collected within "Toll"-Per-Mile* Groups: Afternoon Peak-Hour Travel in Twin Cities Metropolitan Area with 1990 Travel-Behavior-Inventory Trip Table

	All Road Links			Expressway Links Only		
"Toll" /Mi. Range*	*Road Miles*	*Vehicle Miles (100s)*	*Aggregate "Tolls"**	*Road Miles*	*Vehicle Miles (100s)*	*Aggregate "Tolls"**
			No Tolls Charged			
$0.00-	7,408	20,439	$9,200	265	4,922	$3,360
$0.02-	650	7,127	$24,545	96	3,112	$10,881
$0.05-	471	7,178	$51,876	88	3,897	$28,035
$0.10-	262	4,090	$50,587	45	1,985	$24,052
$0.15-	174	3,101	$53,772	30	1,500	$25,985
$0.20-	231	4,638	$114,271	47	2,586	$63,813
$0.30-	139	3,058	$105,969	31	1,814	$63,293
$0.40-	91	1,737	$77,311	13	825	$36,748
$0.50-	167	3,387	$224,606	23	1,389	$87,747
$1.00-	54	845	$112,956		114	$14,191
$2.00-	14	217	$54,239	1	29	$6,339
>$4.00	5	75	$70,325	0	0	$0
TOTAL	9,667	55,893	$949,657	642	22,173	$364,445
			All Links Tolled -- Zero Demand Elasticity			
$0.00-	7,022	21,260	$10,508	267	5,038	$3,742
$0.02-	863	9,292	$31,865	119	4,077	$14,328
$0.05-	624	8,580	$62,204	107	4,357	$31,413
$0.10-	367	5,092	$62,902	48	2,214	$27,472
$0.15-	232	3,666	$63,154	35	1,747	$30,105
$0.20-	253	4,486	$108,708	44	2,282	$55,197
$0.30-	112	1,648	$57,394	10	551	$19,324
$0.40-	64	1,021	45,420	6	360	$15,980
$0.50-	102	1,385	$90,826	6	257	$15,686
$1.00-	20	266	$34,483	0	16	$2,102
$2.00-	5	58	$15,899	0	0	$0
>$4.00	3	43	$29,893	0	0	$0
TOTAL	9,667	56,798	$613,256	642	20,899	$215,349

*As used here, "Toll" and "Tolls" denote the difference between the marginal and the average time cost of a trip regardless of whether a toll is charged.

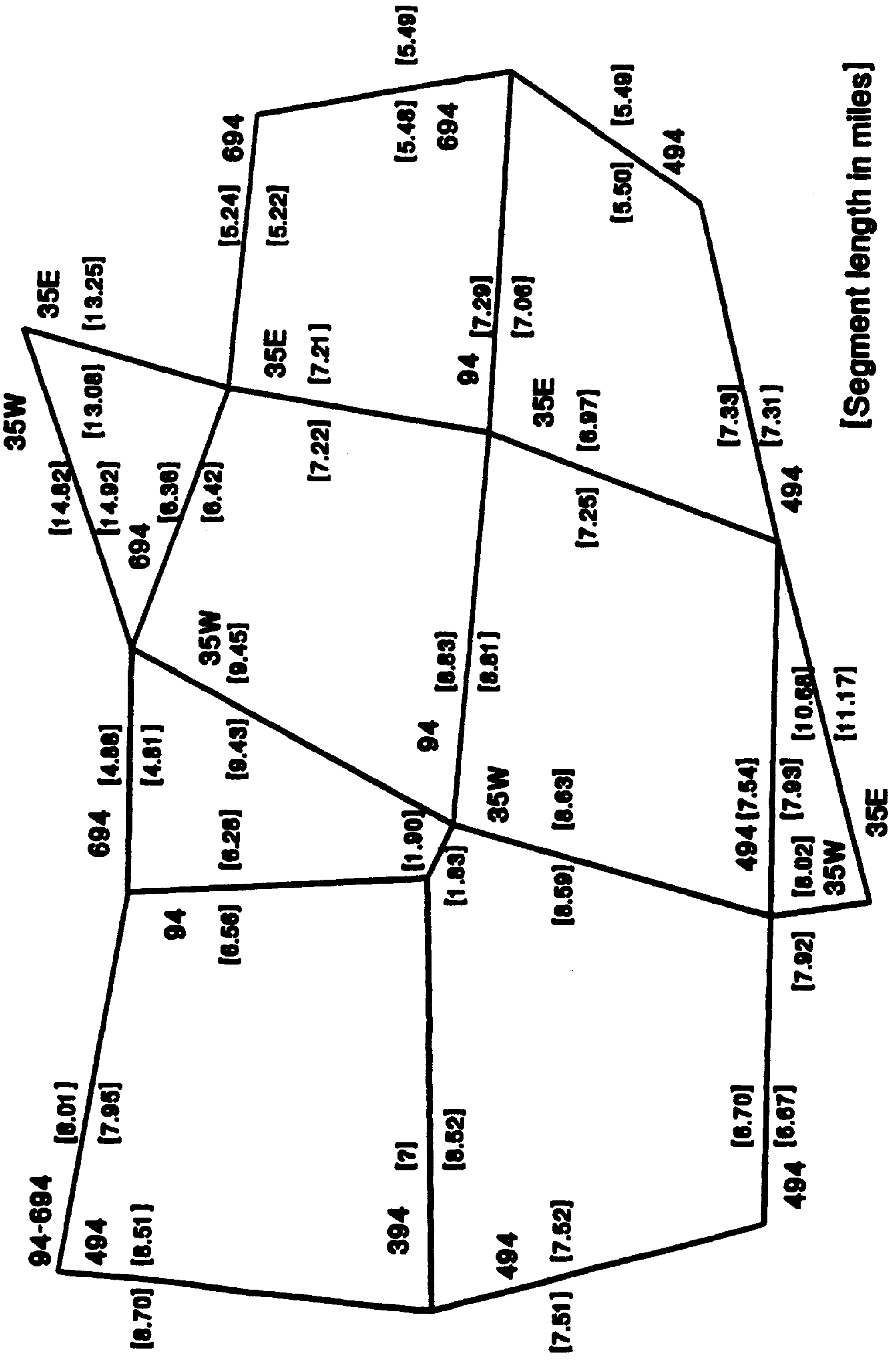
The average gap on all links is 20.7 cents per vehicle mile while the average gap for links with gaps greater than two cents is 31.9 cents. At the opposite extreme, the 260 miles of road links -- 2.7 percent of the total -- with gaps of 50 cents per vehicle mile or more account for 11.7 percent of total travel.

The 47.5 percent of *expressway* links that have gaps of less than two cents during the morning peak account for 21.4 percent of expressway miles traveled and 0.6 percent of the aggregate gap between average and marginal costs on expressways. The expressways' average gap in the morning for all links and for links with gaps of more than two cents per vehicle mile are respectively 20.7 and 26.2 cents. At the opposite extreme, the 42 miles of expressway links with gaps of 50 cents or more a mile account for 12.6 percent of expressway vehicle-miles traveled.

Imposing tolls on all links would spread traffic somewhat more evenly among them. Again, suppose that tolls would affect only the routing of trips, not their timing, mode, or, indeed, whether they are taken. In the morning, the fraction of vehicle miles on links with differences between marginal and average costs of less than five cents per vehicle mile would increase from 45.5 to 50.0 percent with tolls imposed. At the same time, links with gaps of 50 cents or more would account for 11.7 percent of total vehicle miles without tolls but only 3.9 percent with them.

Numbers for the afternoon peak are quite similar to those for the morning. The largest differences have to do with the somewhat-more-uniform distribution of travel over the road network in the afternoon. Thus, while links with differences between marginal and average travel-time costs of less than five cents per vehicle mile account for 45.5 percent of all links in the morning in the absence of tolls, they account for 49.3 percent in the afternoon. At the same time, without tolls, links with gaps of 50 cents per mile or more account for 11.7 percent

Figure 4
TCMA Interstate Network--Segment Mileages



[Segment length in miles]

Figure 5a

TCMA Interstate Network Morning Peak Travel Times and "Gaps": No Tolls

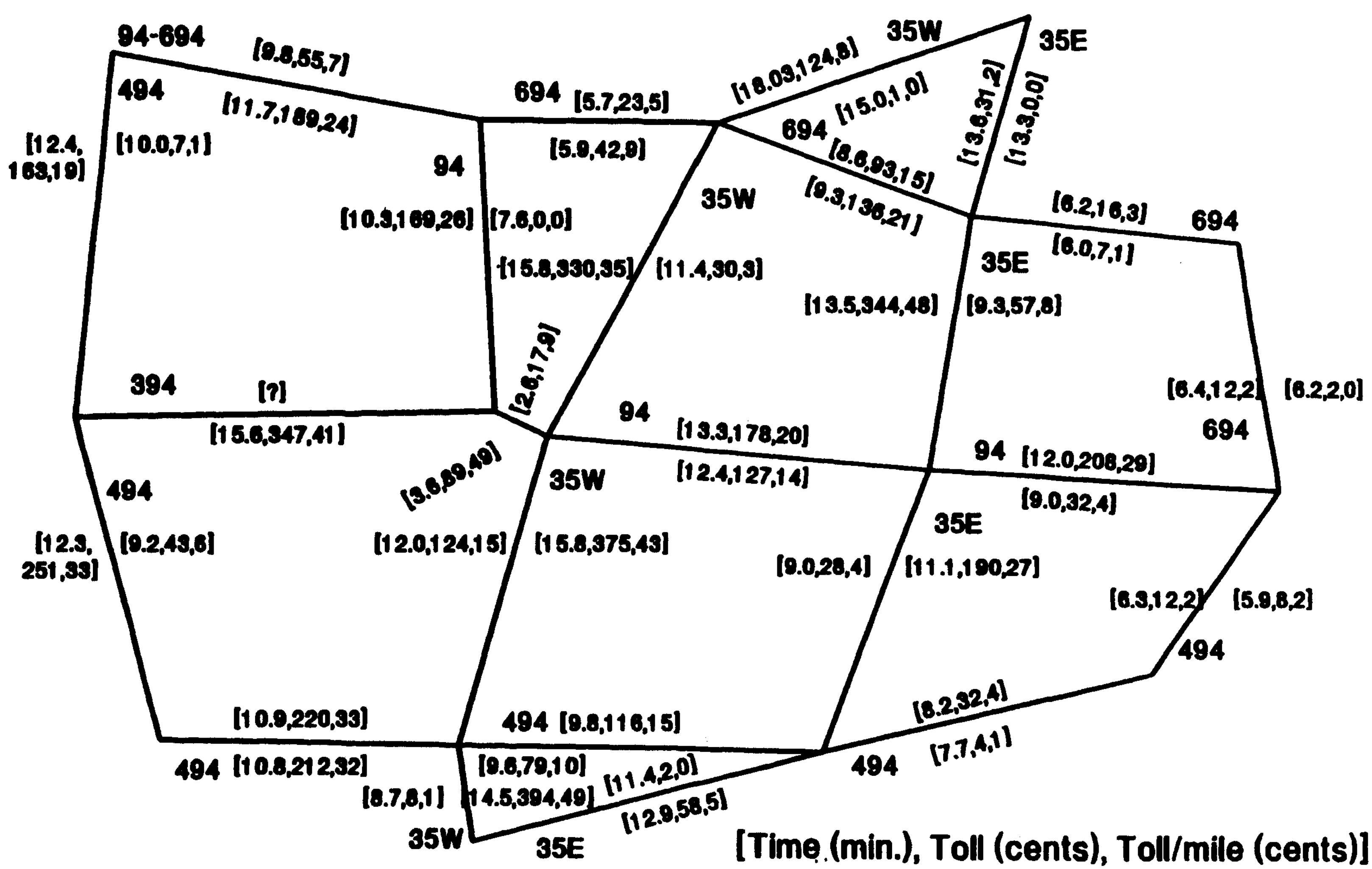
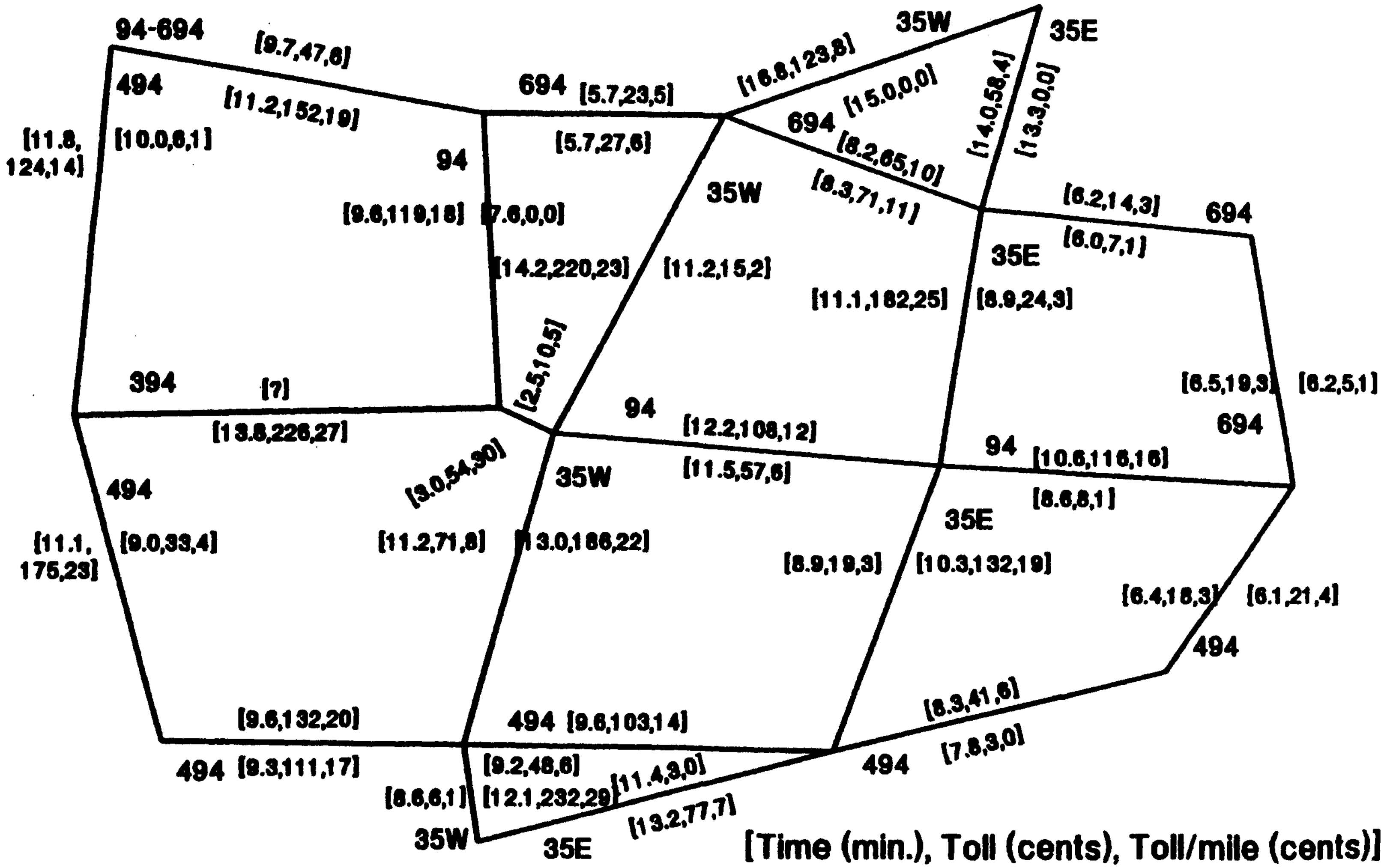


Figure 5b

TCMA Interstate Morning Peak Travel Times and Tolls: Zero Elasticity



[Time (min.), Toll (cents), Toll/mile (cents)]

Figure 5c

TCMA Interstate Morning Peak Travel Times and Tolls: Elasticity = -0.5

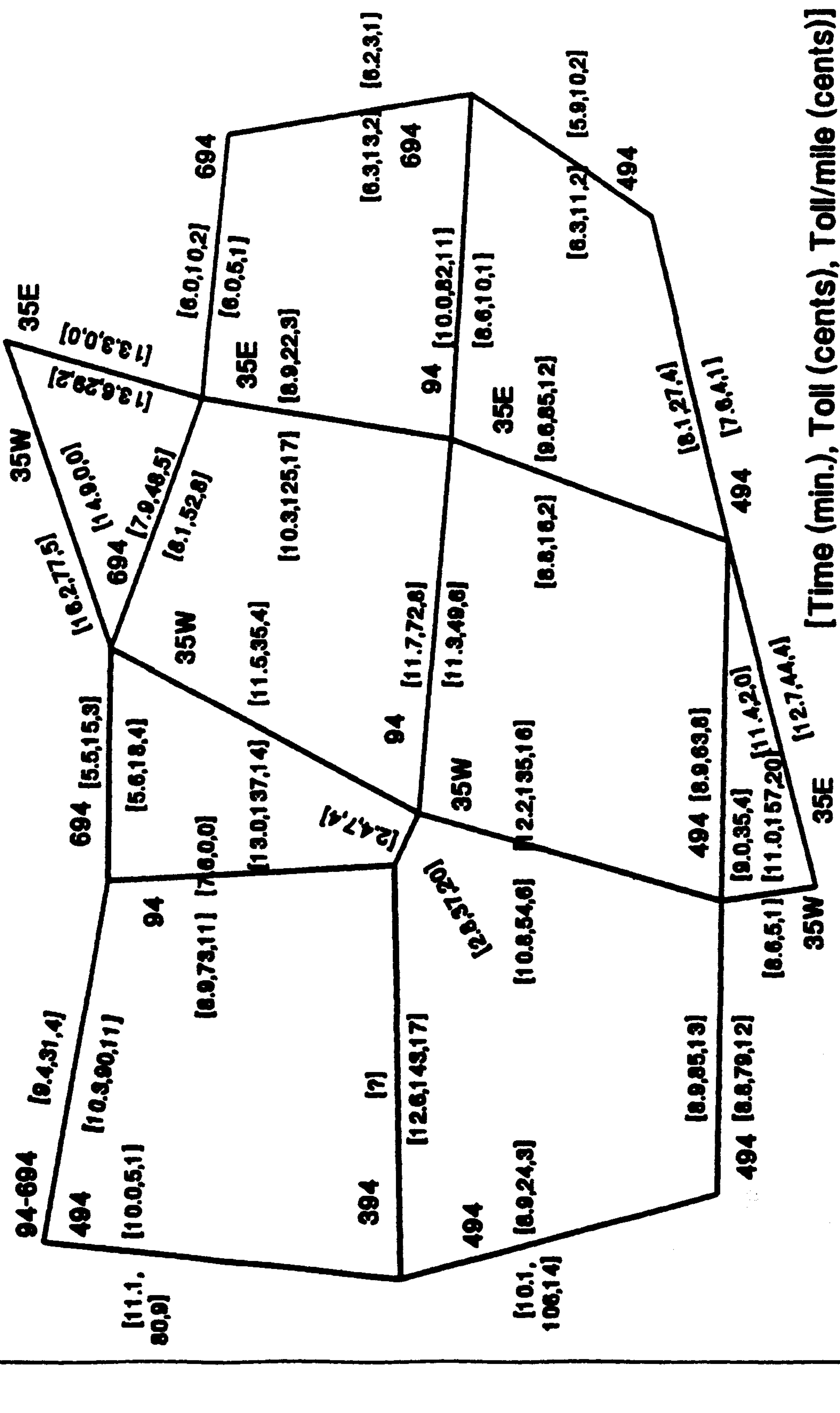


Figure 5d

TCMA Interstate Morning Peak Travel Times and Tolls: Elasticity = -1.0

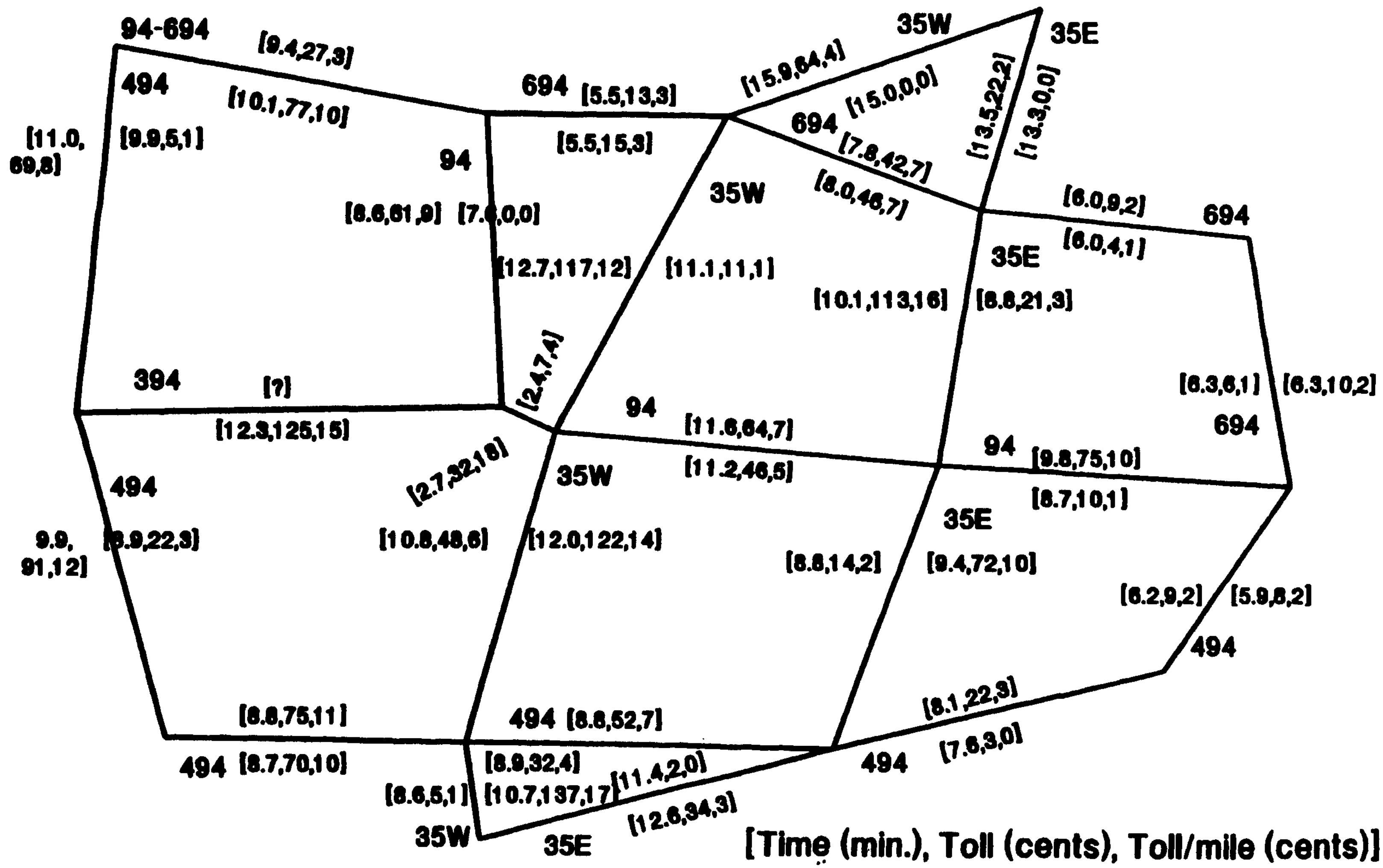


Figure 6a

TCMA Interstate Network Afternoon Peak Travel Times and "Gaps": No Tolls

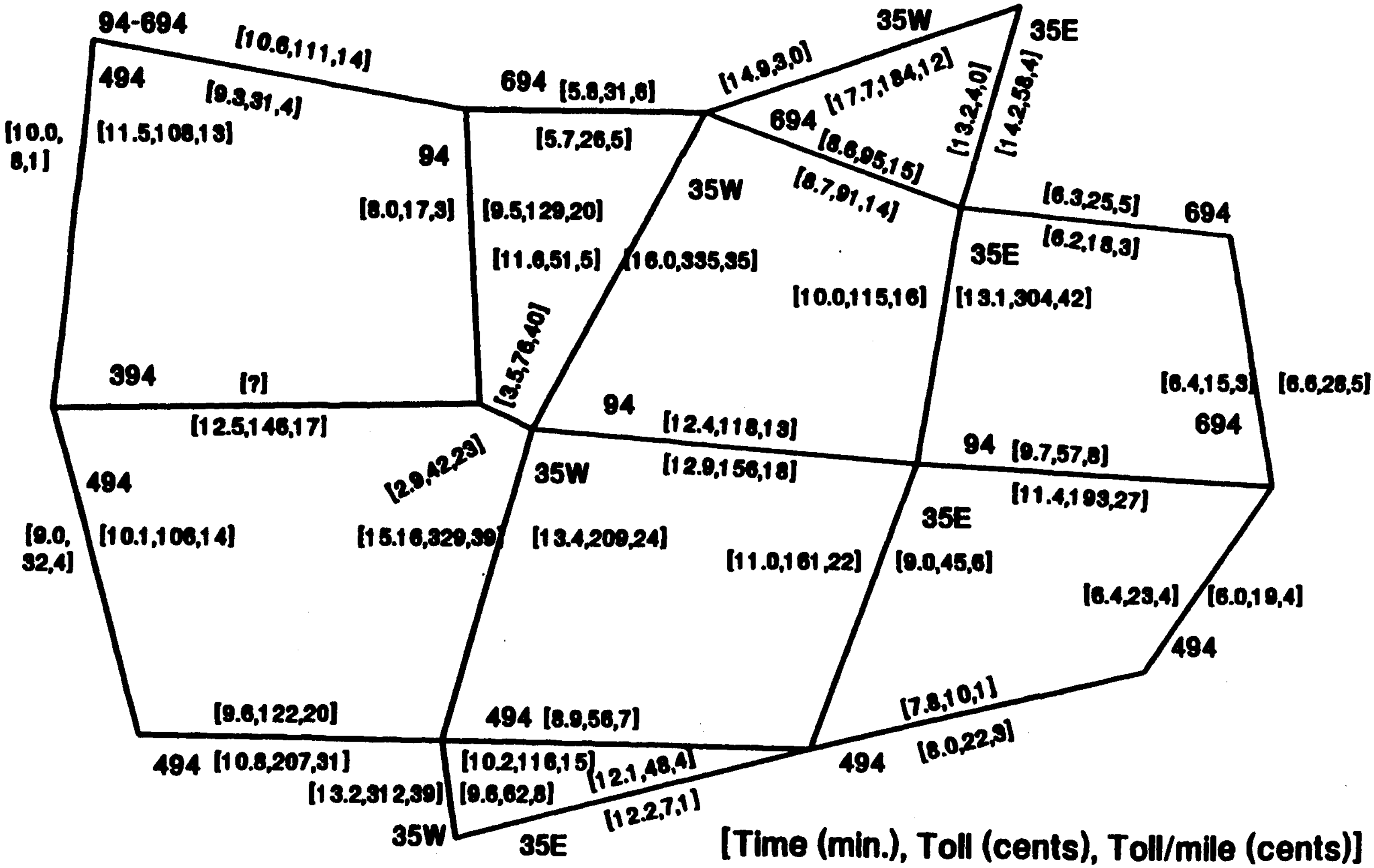
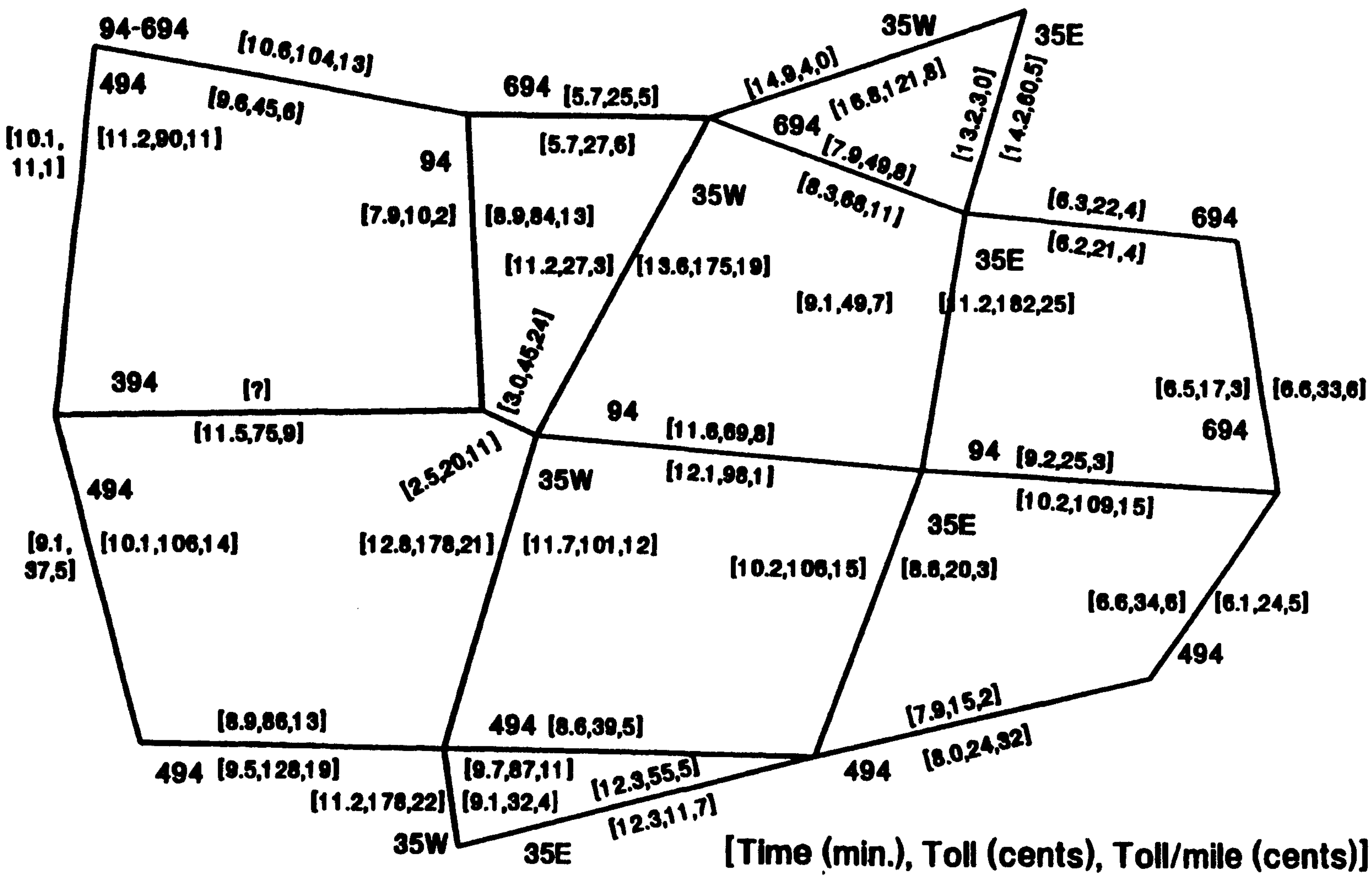


Figure 6b

TCMA Interstate Afternoon Peak Travel Times and Tolls: Zero Elasticity



of morning travel but only 8.1 percent in the afternoon.

Figure 4 provides a schematic diagram of the Interstate System in the Twin Cities Metropolitan Area and the lengths of the segments into which we have broken it for analysis. Figures 5a-5d give travel times and differences between marginal and average travel-time costs for each segment as a whole and per mile in the morning peak when no tolls are charged and when tolls are levied on all links and the full-price elasticity of demand is, alternatively, 0, -0.5, and -1.0. Figures 6a and 6b provide the same information for the afternoon peak as do Figures 5a and 5b for the morning. Once more for emphasis, as in all of our analysis reported to this point, critical assumptions underlying these figures are an average value of travel time per *vehicle* of $10 an hour and that travel time is the only travel cost that is affected by the level of congestion. In these figures, the numbers in parentheses are (travel time in minutes for the segment, toll or gap between marginal and average cost in dollars for the entire segment, and toll or gap per mile for the segment). Data for west- and east-bound segments appear above and below the segments, respectively. Data for north- and southbound segments appear to the right and the left of the segments, respectively.

It should come as no surprise that the most heavily congested segments of the Interstate system in the morning peak hour are those going toward the central business district of Minneapolis from its northern, western, and southern suburbs and toward the St. Paul CBD from its northern, eastern, and southern suburbs. The five most heavily congested segments (with the difference in cents between average and marginal cost *per mile* in parentheses when no tolls are charged and when tolls are charged and the full-price elasticity of demand for auto travel is, alternatively, 0, -0.5, and -1.0) are:

I-35W northbound from I-35E to I-494 (49, 29, 20, 17 cents)

I-94 eastbound from I-394 to I-35W (49, 30, 20, 18 cents)

I-35E southbound from I-694 to I-94 (48, 25, 17, 16 cents)

I-35W northbound from I-494 to I-94 (43, 22, 16, 14 cents)

I-394 eastbound from I-494 to I-94 (41, 27, 17, 15 cents).

Clearly, even if the full-price elasticity of demand for auto travel is very small, imposing congestion tolls would lead to substantial reductions in the differences between marginal and average travel-times on even the most congested expressways.

To summarize, peak-period congestion is very expensive in the Twin Cities Metropolitan Area. During the morning peak hour, the *marginal* time cost of the average auto trip is currently about 69 percent greater than its *average* time cost -- the cost which auto travelers directly experience and to which they respond in deciding when, where, and how to travel. If the occupants of the average vehicle value their total travel time at $10 an hour, their directly experienced cost of driving a mile is, on average, 30.1 cents while the costs they impose on other drivers by adding to the level of congestion is 20.7 cents, again on average. Congestion costs in the afternoon are somewhat smaller per mile but somewhat greater in the aggregate than are morning congestion costs.

Imposing congestion tolls on the entire road network would reduce the difference between peak-hour marginal and average time costs by about a third even if the elasticity of demand for auto travel is close to zero. Being required to pay marginal-cost tolls would induce travelers to shift to less congested but somewhat more circuitous routes. While increasing their travel distance, rerouting their trips would reduce total travel time even if tolls would have no effect on their decisions about where, when, and how to travel. If the full-price elasticities of demand for auto travel is in the range of -0.5 to -1.0 -- that is, if a one percent increase in the time *plus* money costs of travel would lead to a -0.5 to -1.0 percent reduction in auto travel -- tolls would result in a 9-14 percent reduction in both trips taken and miles traveled and an 18-23 percent reduction in total travel time.

Regardless of how elastic the demand for peak-period auto travel is, for most travelers, the value of the time savings that tolling would bring about will be substantially less than their outlay on tolls. Only for vehicle occupants whose total incomes are more than $80,000 would the time-saving benefits exceed toll outlays. For twin Cities auto travelers as a group, here are the approximate relative magnitudes of time savings and toll costs at alternative demand elasticities for present morning-peak-hour travelers:

	Full-Price Demand Elasticity for Morning-Peak Auto Travel		
	0	0.5	-1.0
Toll Collections	$695,975	$376,888	$309,144
Less Time Savings Value	$37,150	$67,703	$107,846
Equals Real Income Loss	$658,825	$309,185	$201,298

It is this sort of comparison that makes us regard it as essential for the success of congestion-toll proposals that they include explicit provisions for using toll revenues. Toll collections exceed the real-income loss to which tolls give rise. It would, therefore, be possible use these revenues in a fashion that would improve the welfare of a substantial majority of the populations of the urban areas in which tolls are proposed. Unless this is done, public acceptance of congestion pricing is unlikely.

VI The Spatial Implications of Congestion Pricing[16]

A line of research with origins in the early nineteenth century holds that land values and land uses are determined by the locational advantages that transportation systems confer. Central locations in emerging metropolitan areas -- the land best served by transport facilities and, hence, the most valuable -- are bid away from other users by specialized firms that benefit most from the center's greater access than any other spot to all points within the area. In addition, clustering improves the efficiency of their interactions particularly when face-to-face negotiation is regularly required. Activities with less frequent need for central access bid less and locate further from the center. The further it is from the center, the less valuable land is. It is there that residential uses originally predominated; metropolitan areas were broken into two sub-areas, one in which jobs far outnumbered residences, the other in which the reverse was true.

Commuting distances were initially short between these specialized regions. Growth increased these distances, however, inducing migration closer to their customer bases of retail and other services that are tightly linked to day-to-day household activities. Naturally enough, job migration accompanied this business migration reducing the initial imbalance between jobs and housing. Jobs and housing come into closer balance in what were once outlying areas as new growth moves beyond them. This gradual reduction in the jobs-housing imbalance is strengthened by the individual adjustments to long commuting journeys that follow (usually with an appreciable time lag) changes in job locations. It is perhaps for this reason that automobile commuting times are said to have fallen in 18 of the country's largest 20

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[16]We have relied heavily in this section on a draft paper by Elizabeth Deakin [1993], "Urban Transportation Congestion Pricing: Effects on Urban Form," University of California at Berkeley and on Anthony Downs [1992], *Stuck in Traffic*, Washington, DC: The Brookings Institution and Cambridge, MA: The Lincoln Institute of Land Policy.

areas between 1980 and 1985.[17]

Generally speaking, people value both living space and proximity of their residences to work places, recreational activities, stores, schools, and the like. As with so many other commodities, the desires for space and proximity are in conflict. The more proximate to widely desired destinations is a residence, the more expensive is its site and the more intensively that site is utilized. A household's budget constraint plus the tradeoff between space and proximity that the residential property market provides serves effectively to specify the minimum distance between the two that a household can achieve. Many considerations lead to separations greater than this minimum possible between a household's home and the work sites of its employed residents. Thus, when asked for the most important reason why they lived so far from their jobs, "good schools" was cited by 38 percent of a 1980 national sample of workers who commuted more than five miles daily. "Like our house" and "like our neighbors" followed with 24 and 17 percent respectively while 10 percent indicated that their own jobs were far from the jobs of other family members.[18]

Reductions in the (full) price of transportation can be interpreted as increasing the supply of proximity thereby lowering its price and allowing people to enjoy more space, more proximity, or both without increased financial sacrifice. Conversely, increased travel costs -- whether the result of congestion or congestion pricing -- increase the price of proximity to schools and neighbors that are distant from work places. Put differently, changes in transport costs change land values. The general expectation is that improvements which make the

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[17]Peter Gordon, *et al.*, [1991], "The Commuting Paradox," in *Achieving a Jobs-Housing Balance: Land Use Planning for Regional Growth Resource Manual*, Cambridge, MA: Lincoln Institute for Land Policy, sec. 2.3.

[18]William M. Rohe, *et al.* [1980], *Travel to Work Patterns: A Preliminary Analysis of Selected Data from the Annual Housing Survey Travel-to-Work File*, Chapel Hill, NC: University of North Carolina, Department of City and Regional Planning, p. 145.

center more accessible simultaneously lower the value of land there and increase it further out. Conversely, increased transport costs tend to increase central land values and, hence, increase the intensity with which this land is utilized. Overall, location theory tells us that transportation improvements tend simultaneously to increase employment at benefited sites and to decentralize workers' housing. Over time, however, these changes stimulate countervailing effects: increased employment generates demand for housing near work sites and dispersed housing creates a pull for service-oriented employment.

Two broad arguments have been made regarding the effects that congestion pricing will have on urban development patterns. The one which predominates in the economics literature is that unpriced congestion confers a subsidy on travel leading to lower-density land-use patterns and larger metropolitan areas than would occur with cost-based pricing and efficient investment. Congestion pricing would eliminate this subsidy thereby encouraging a more compact urban form. To the contrary, opponents have claimed, congestion pricing would reduce the attractiveness of destinations served by tolled facilities thereby accelerating the movement to less congested areas and increasing rather than reducing dispersion.

There are elements of truth in both views. Particularly in relatively uncongested areas such as the Twin Cities, congestion pricing will, if instituted, increase transport costs for most people. These cost increases will set adjustment processes into motion. While some households and business firms will find that certain trips must be made regardless of costs, more will be able to mitigate the adverse effects of transport-cost increases by using less congested or unpriced routes, by switching modes, by traveling at less congested times, and by changing destinations or even their own locations.

These adjustments will ultimately result in less transport-intensive business and household operations. Households will, on average, live closer to their work places. The market areas of retail establishments will diminish and their numbers will increase somewhat. The rate at which residential decentralization is taking place will diminish and could even reverse itself; higher transport costs will inevitably make tradeoffs between space and proximity less advantageous. Not all residential decentralization will cease, however. Firms that have, for whatever the reasons, chosen to locate at the periphery of the metropolitan area will find their employees relocating near them at a more rapid rate than would otherwise have been experienced.

To repeat, congestion pricing will increase the travel costs of most Twin Cities residents -- *most*, but not all: For affluent residents of the Twin Cities, the full cost of travel will decline; the value of the time they save will more than offset the added cost of the tolls they will pay. Particularly prominent in this group are the lawyers, corporate executives, bank officers, and others for whom frequently required face-to-face negotiations make central-business-district locations very valuable. For them, the speedier drives from Wayzata and Edina and Woodbury and Afton which congestion pricing will yield will make downtown Minneapolis and St. Paul more rather than less attractive places in which to do business and might well reverse some of the decentralization of these CBD activities that has taken place during the last two decades.

Appendix: The Elasticity of Demand for Peak Period Travel and the Consumer-Surplus Loss from Congestion Tolls

Imposing appreciable tolls on peak-period auto travel would undoubtedly result in some trips not being taken and others being diverted to less road-intensive modes, destinations, or times of day. Unfortunately, the economics literature is not of great help in predicting how substantial these diversions would be. Two recent surveys of research on the subject[a] describe more than a dozen statistical analyses that report estimates of the elasticity of demand for auto travel with respect to various measures of auto costs -- the percentage change in auto travel that would result from a one percent change in the cost measure. These estimates varied in the specific types of costs and of trips considered, the time period over which adjustments to a change were analyzed, the countries and cities from which data came, the statistical methodology employed, and other factors. In all cases, however, the elasticity measure used is what can be termed a *money*-price elasticity -- the percentage change in travel that results from a one-percent change in the *money* outlay required for a trip. A conceptual point: it is the *full*-price elasticity of travel that is relevant for our analysis -- the percentage change in auto travel that results from a one percent change in the money *plus* time costs of a trip -- not the money-price elasticity. It is possible to show that the following relationship holds:

Money-price Elasticity = (*Full*-price Elasticity) *times* ((Money price)/(full-price))

The average cost of driving an automobile one mile is commonly computed as being in the 30-35-cent range. If the aggregate value the occupants of a vehicle place on their travel time is $10 an hour and they average 30 *mph* on a trip, the money and time costs of traveling a mile are roughly equal. This reasoning suggests that *full*-price travel elasticities are on the order of twice their *money*-price counterparts.

In the studies cited, commuting and, more broadly, peak-period travel generally tended to be less price-sensitive than trips for other purposes. Also, the longer is the time period

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[a]P. B. Goodwin [1992], "A Review of New Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes" **26**, *Journal of Transport Economics and Policy*, 155-169 and Tae Oum, *et al.* [1992], "Concepts of Price Elasticities of Transport Demand and Recent Empirical Estimates," *Journal of Transport Economics and Policy* **26**, 139-154.

covered, the larger is the adjustment that any given price change induces. Even within subgroups of studies using similar trip types, times of day, and time periods, however, results varied appreciably. For the group as a whole, the lowest elasticity found is -0.038 while the highest is -0.97; the effect of a 10 percent increase in the cost of travel ranged between reductions of 0.38 percent and 9.7 percent in total travel. Several studies found elasticities of around -0.1. Successively smaller groups centered on elasticities of -0.25 and -0.5. Estimated elasticities with absolute values greater than 0.5 were rare.

An analysis of ours lends support to the high end of the range of these statistical studies. It is based on Thomas Lisco's doctoral-dissertation[b] findings which underlie our estimate of $10 per *vehicle* hour as the average value of travel time. Translating his results from the 1960s to present-day price levels yields a value of travel time for people with incomes in excess of $35,000 a year equal to half their equivalent hourly wage rate. Assuming 2,000 work hours a year yields $V = Y/4$ where V and Y respectively denote travel-time value in dollars per hour and annual incomes in thousands of dollars. For travelers with incomes of less than $35,000 a year, travel-time value as a fraction of income is proportional to income. For such travelers, V turns out to equal $Y^2/140$. We do not have individual-income data for the Twin Cities. The US Census Bureau does, however, publish family- and household-income data. Table A gives the results of applying the Lisco formulae to these data.

Suppose that, if they use automobiles for their trips, a third each of all travelers would average 15, 30, and 60 *mph*. Suppose also that all could take an alternative mode -- mass transit, car pool, bicycle, ... -- but that these trips would take 50 percent, 125 percent, and 200 percent more time than auto for a third each of the travelers. For any traveler, the difference between out-of-pocket costs -- auto operating costs plus tolls less cash outlays for the alternative mode -- divided by the difference between their travel times is, effectively, the price of saving time by using the faster mode. If a traveler's time value exceeds this price, he or she

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[b]Thomas E. Lisco [1967], *The Value of Commuters' Travel Time: A Study in Urban Transportation*, PhD Dissertation, University of Chicago.

Table A

Distribution of Income and Travel Time Values for Twin City Metropolitan Area Households and Families
(1990 data)

*Income ($K/year)**	*Travel Time Value* (\$/Hour)**	*Household Percent*	*Household Cumulative Percent*	*Family Percent*	*Family Cumulative Percent*
0.00	0.000	3.08	3.08	1.59	1.59
5.00	0.179	7.01	10.10	4.01	5.60
10.00	0.714	3.37	13.47	1.89	7.48
12.50	1.116	3.11	16.58	2.04	9.52
15.00	1.607	3.64	20.22	2.53	12.05
17.50	2.188	3.61	23.83	2.61	14.66
20.00	2.857	4.17	28.00	3.23	17.88
22.50	3.616	3.68	31.69	3.17	21.06
25.00	4.464	4.19	35.88	3.64	24.70
27.50	5.402	3.53	39.40	3.37	28.07
30.00	6.429	4.45	43.86	4.15	32.22
32.50	7.545	3.54	47.40	3.65	35.87
35.00	8.750	4.17	51.56	4.42	40.29
37.50	9.375	3.46	55.03	3.84	44.14
40.00	10.000	4.15	59.17	4.64	48.78
42.50	10.625	3.29	62.46	3.89	52.67
45.00	11.250	3.56	66.02	4.20	56.87
47.50	11.875	2.87	68.89	3.58	60.44
50.00	12.500	5.75	74.64	7.09	67.53
55.00	13.750	4.62	79.26	5.84	73.37
60.00	15.000	9.30	88.56	11.77	85.14
75.00	18.750	6.30	94.86	8.11	93.25
100.00	25.000	2.33	97.19	3.06	96.31
125.00	31.250	0.93	98.12	1.22	97.53
150.00	37.500	1.88	100.00	2.47	100.00
225.00	56.250	0.00	100.00	0.00	100.00

*Entries are for the bottom of each income bracket.

Source: US Census Bureau and authors' calculations; see text.

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would rationally choose auto, more expensive in dollar terms though it may be. Using the household distribution of travel-time values, Table B gives the percentages of all travelers who would divert to their alternate modes at successively larger dollar-cost disadvantages for auto travel and the approximate price elasticities of demand associated with these changes. Contrary to the normal case with demand schedules, the auto demand elasticities displayed in Table B tend to diminish as the auto dollar-cost penalty increases; with a penalty of 10 cents a vehicle

Table B

Simulated Share of Travelers Who Would Divert to Other Modes at Various Tolls Per Mile

All Auto Speeds and All Mode Time Penalties Included
Household Distribution of Travel-Time Values

Auto Cost Difference ($/Mile)	*Share Diverted (Percent)*	*Demand Elasticity*
0.05	17.152	-0.500
0.10	27.623	-0.734
0.15	35.747	-0.662
0.20	42.687	-0.636
0.25	48.814	-0.616
0.30	53.619	-0.526
0.35	58.436	-0.569
0.40	62.732	-0.541
0.45	66.371	-0.487
0.50	69.543	-0.450
0.55	71.903	-0.356
0.60	74.223	-0.370
0.65	76.480	-0.379
0.70	78.092	-0.285
0.75	79.716	-0.302
0.80	81.561	-0.359
0.85	82.881	-0.268
0.90	84.102	-0.259
0.95	85.218	-0.247
1.00	86.315	-0.252
1.05	87.188	-0.209
1.10	87.923	-0.183
1.15	88.653	-0.188
1.20	89.431	-0.208
1.25	90.678	-0.343

Source: Authors' computations; see text.

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mile, the elasticity is -0.73 while, with a penalty of $1.25 per mile, it is only -0.34. A possible explanation for this anomaly is that construction of Table B rests on the implicit assumption that only the mode chosen, not whether or when a trip is taken, is affected by changes in the auto-cost differential. High dollar outlays are likely to discourage even the very rich from taking some trips.

In addition, tolls of the magnitude suggested by Figures 5-6 are likely to lead to much greater shifts away from peak periods of activity opening and closing hours than have occurred even in highly congested areas. Over the long haul, such shifts could lead to substantially more elastic peak-period travel-demand schedules than those revealed by recent statistical analyses. For these reasons, we have chosen to explore the implications for equilibrium toll schedules and travel patterns of demand elasticities equal, alternatively, to -0.5 and -1.0.

In beginning to incorporate non-zero demand elasticities into our analysis, it seems plausible to suppose that trips from one group of neighboring traffic-analysis zones to a second group of neighboring zones would follow similar paths and experience similar congestion levels. If so, it should be possible to analyze travel between individual zonal pairs in isolation without introducing great error. Consider, then, a situation of the sort depicted in Figure A. It shows the average and marginal costs of trips between a pair of TAZs and a "constant-elasticity demand schedule" -- one for which the price elasticity of demand is the same at all prices. The equation for this sort of demand schedule is

$$N = a\,P^{-b} \qquad \text{(a)}$$

where P is the full price of a trip and N is the number of trips that would be taken at that price, i.e., the demand for trips. As it turns out, *-b* is the demand elasticity, -1.0 in Figure A. The figure's average and marginal cost schedules are of the sort obtained by multiplying equations (1) and (3) in Section V by the average value of travel time. Knowing the initial equilibrium travel flow, volume/capacity ratio, and full *average*-cost price of a trip at point *A* in Figure A, it is possible to compute the full *marginal*-cost price for that same volume of traffic at *B*. From these two pieces of information, in turn, the equilibrium marginal-cost full price at *C* can be computed.

Area *DCEA* in Figure A is commonly referred to in the economics literature as a "consumers-surplus loss." In this case, it results from a change in the full price of trips. It has two parts. The first, area *CDEF*, equals the difference between the pre- and post-tax cost to travelers of the trips they take in the post-tax equilibrium. The second, area *ACF*, is the difference between the value they attached at the pre-tax full price to the *FA* trips they no

Figure A

Toll and No-Toll Equilibria for Elastic Demand Market

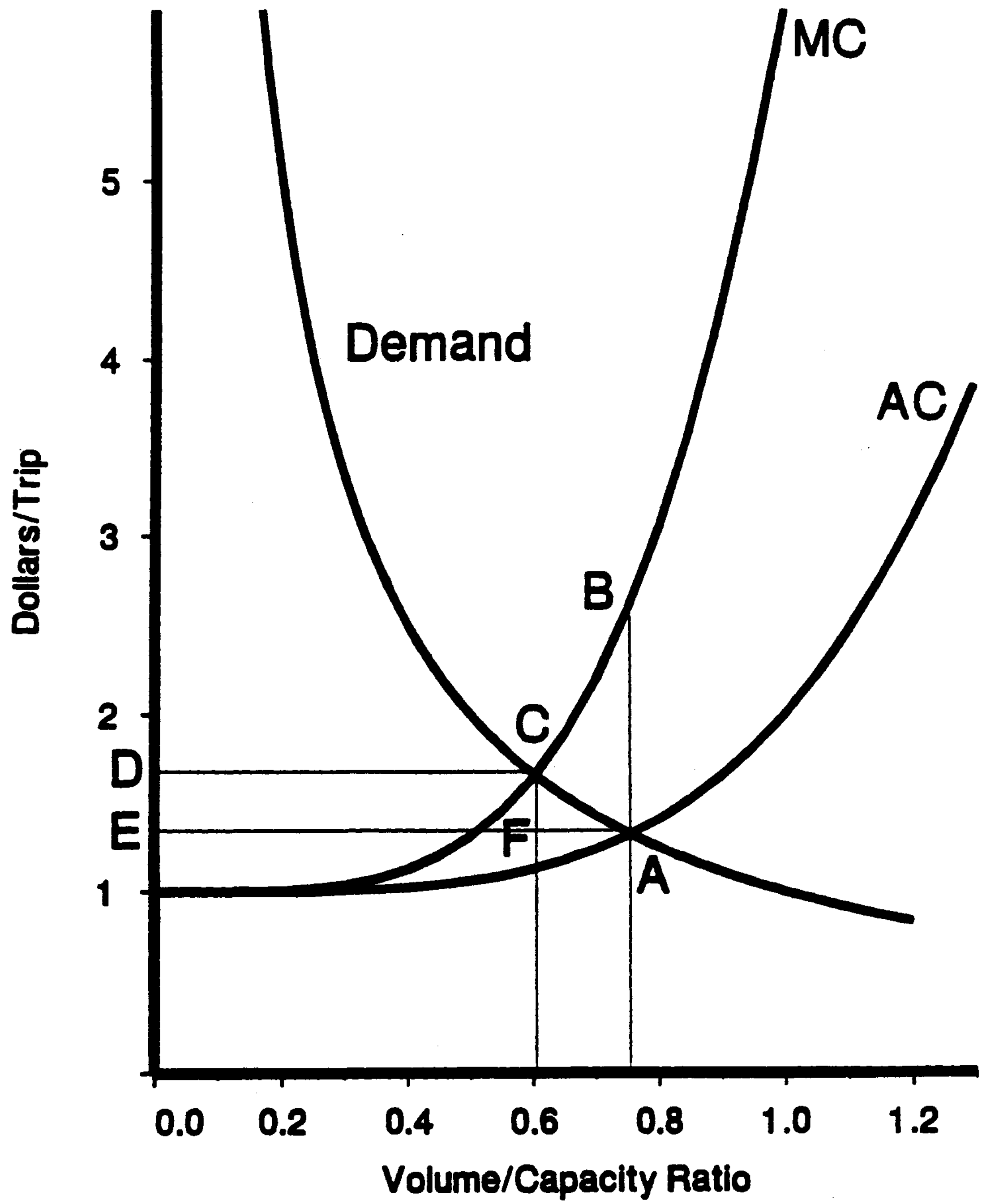

Table C

Implications of -0.5 and -1.0 Price Elasticities of Demand for the Effects of Congestion Pricing on Equilibrium Full Prices, Travel Rates, and Congestion Tolls

Volume/ Capacity	*Initial Full Price*	*"Gap"*	*New Equilibrium*		
			Volume	*Full Price*	*Toll*
			Elasticity of Demand = -0.5		
0.10	$1.000	$0.000	100.00	$1.000	$0.000
0.30	$1.001	$0.005	99.70	$1.007	$0.006
0.50	$1.009	$0.038	98.25	$1.046	$0.037
0.75	$1.047	$0.190	93.95	$1.187	$0.150
1.00	$1.150	$0.600	88.62	$1.464	$0.372
1.50	$1.759	$3.038	81.31	$2.661	$1.329
2.00	$3.400	$9.600	78.39	$5.533	$3.627
3.00	$13.150	$48.600	76.89	$22.240	$16.993
			Elasticity of Demand = -1.0		
0.10	$1.000	$0.000	100.00	$1.000	$0.000
0.30	$1.001	$0.005	99.36	$1.007	$0.006
0.50	$1.009	$0.038	96.77	$1.043	$0.035
0.75	$1.047	$0.190	90.31	$1.160	$0.128
1.00	$1.150	$0.600	83.81	$1.372	$0.298
1.50	$1.759	$3.038	76.47	$2.301	$1.041
2.00	$3.400	$9.600	73.98	$4.596	$2.877
3.00	$13.150	$48.600	72.80	$18.064	$13.651

Source: Authors' calculations; see text.

longer take. The sum of these two areas is approximately the loss in real income that imposing tolls has caused them or, put differently, the additional income they would have to be given to make them indifferent between the original income and trip price on the one hand and the new income and price on the other.

Table C spells out the implications of -0.5 and -1.0 elasticities when 100 people take a trip which, at a volume/capacity ratio of zero, would have a full price of $1. The first column indicates the volume/capacity ratio on the road they travel assumed to exist in the absence of congestion tolls. The second column shows the resulting full price for the trip while the third column gives the implied gap between the average- and marginal-cost full prices at this volume/capacity ratio. Columns 3-5 contain the equilibrium traffic flow, full marginal-cost price, and toll that would result from imposing congestion tolls.

For the relationships depicted in Figure A, it can be shown that important ratios that can be computed from the data in Table C are functions of only the elasticity of demand and roads' volume/capacity ratios in the absence of tolls; they do not involve the parameter, T_{to}, that fixes the position of Tranplan's default travel time-volume/capacity relationship given by equation (1) on page 29. For example, if travel on an arterial street and an expressway happen to be at the same volume/capacity ratio in the absence of tolls and are subject to the same demand elasticity, imposing congestion tolls would result in the same percentage reduction in travel and the same ratio of the toll to the full price of a trip on the two roads. Knowing the demand elasticity and the distribution of volume/capacity ratios on the road network would suffice to approximate[c] the reduction in total travel that imposing congestion tolls would yield.

To translate the numbers in Table C into more familiar terms, consider a trip on an expressway that is currently experiencing a volume/*practical* capacity ratio of 1.5, the equivalent of a volume/*ideal* capacity ratio of approximately 0.93. At this volume/capacity ratio, travel time per mile is 1.76 minutes and marginal time per mile is 4.8 minutes so that the gap between average and marginal travel times is 3.04 minutes. At $10 per travel hour, the value of this gap is 50.6 cents while the direct time cost of a one-mile trip is 29.3 cents. Given this no-toll equilibrium and a demand elasticity of -1.0, the congestion toll at which the full price of a one-mile trip equals its marginal cost is 17.3 cents per mile while the trip's direct costs work out to be 22.2 cents. The income equivalent of the cost to consumers who originally traveled 100 miles of taking fewer trips at a higher price is $786, but government toll revenues are $1,327. With a demand elasticity of -0.5, the corresponding numbers would be a toll of 22.1 cents per vehicle mile and a volume/capacity ratio of 76%, a real income loss of $1,213, and congestion tolls $1,801.

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[c] "Approximate" rather than "determine" because demand elasticities differ by trip type and, even if this were not the case, each trip must take place with a constant volume/capacity ratio for the procedure to work exactly. Nonlinearities in the relationship being analyzed introduce errors as a result of being forced to assume that the volume/capacity ratio for each trip is constant over its entire length.