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Capacity-Allocation Methods for Reducing Urban Traffic Congestion

By Robert A. Johnston,[1] Jay R. Lund,[2] and Paul P. Craig[3]

(Reviewed by the Highway Division)

Abstract: It is unlikely that roadway construction or vehicle automation will be able to alleviate most major urban congestion in the near future (5–15 years). What else can be done to reasonably reduce congestion? Several approaches to reducing congestion by capacity allocation are reviewed: laissez-faire allocation, allocation by passenger load, ramp metering, road and parking pricing, allocation by trip purpose, rationing, and mixed strategies. These approaches are qualitatively compared against four criteria: effectiveness at reducing congestion, economic efficiency, income distribution effects, and flexibility of access for urgent trips. Recommendations are made regarding capacity-allocation measures with potential to reduce congestion and to increase economic efficiency. The equity impacts of these measures are identified and methods for mitigating these effects are proposed. Congestion pricing, together with free but metered on-ramps at freeways for nonpayers or with subsidies for lower-income households all are found to deserve further study and an incremental method of adoption is outlined.

INTRODUCTION

Continued increases in demand for highway use have created roadway congestion. In the past, such congestion would have been addressed by widening existing roadways or construction of new ones. Escalation of highway right-of-way acquisition and construction costs over the last decade has made this capacity expansion approach increasingly unattractive (Lindley 1987).

The present paper reviews a variety of existing and proposed methods for allocating existing highway capacity to lessen congestion and congestion costs. These schemes take a variety of approaches to distributing limited roadway capacity such that congestion is reduced and roadway use is available to certain groups of users.

Both equity and efficiency criteria are important for such allocations and pose difficult problems. Nevertheless, the potential capacity cost savings achievable with capacity-allocation methods may be considerable. Allocation methods might spread traffic-demand peaks, to more efficiently use existing roadway capacity, avoiding construction of new capacity that may only be needed for a few hours each day. Alternatively, allocation techniques might function like market prices to allocate a scarce resource to those valuing it most by creating incentives for deferral, consolidation, or elimination of discretionary trips.

Several roadway-capacity-allocation approaches are to be explored: (1) Laissez-faire allocation; (2) allocation by vehicle occupancy; (3) ramp metering; (4) road pricing; (5) allocation by trip purpose; (6) nontradable rations; (7) tradable rations; and (8) mixed strategies. These approaches are not conceptually new. All these approaches have been applied or discussed individually in transportation or other contexts. Thus, there is a large amount of experience and theory regarding the details of applying these approaches to roadway congestion, as well as on the prospects and problems of such applications. No research has compared all of these methods, as far as we know.

The present paper is a discussion and qualitative multiobjective evaluation of these measures, not an economic evaluation in the typical sense. We use economic analyses by other researchers, but also discuss other issues, such as capacity, which is really a political issue. Efficient pricing, for example, will not eliminate congestion at all time periods in central city areas, because of the high land costs for the roads. We consider roadway supply fixed, except for converting single-occupant vehicle (SOV) lanes to high-occupancy vehicle (HOV) lanes.

OBJECTIVES OF HIGHWAY CAPACITY ALLOCATION

Motivations for considering capacity-allocation methods for roadways are traffic congestion and the increasing expense of capacity expansion to relieve congestion. However, other societal

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objectives would be important for evaluating any capacity-allocation strategy. A minimun set of objectives would be (1) Effectiveness at reducing congestion; (2) economic efficiency; (3) income-distribution effects; and (4) flexibility of access for urgent travel needs. These are overlapping policy analysis categories, ones of concern to different interest groups.

We do not examine the objective of environmental protection, since that requires a broader evaluation of measures, including emission controls and land-use changes. We also do not look at revenue-raising potential per se (Small 1992; Giuliano 1992). We do examine selectivity (focus on peak-period nonessential travel), avoidance of evasion, understandability to the traveler, and not transferring congestion to unregulated areas (May 1986). These criteria are all contained in our criterion of effectiveness in reducing congestion.

Effectiveness at reducing traffic congestion is the objective most likely to motivate consideration of capacity-allocation measures. With demand for private urban transportation continuing to increase and little prospect for proportionate increases in roadway capacity, traffic congestion can be expected to increase for the foreseeable future. The effectiveness of a measure for reducing traffic congestion is difficult to measure, although some traditional traffic engineering methods can be used. These traditional measures of congestion include passenger-hours of delay over designed travel times, values of time lost to delay above designed travel times, and level of service indices.

The economic efficiency of a roadway-capacity-allocation scheme is an indicator of its ability to contribute to the economy as a whole and is typically measured in terms of the scheme's economic benefits minus its economic costs. All benefits and costs to everyone are considered equally. Surrogates or estimates are required to quantify in monetary terms the economic value of intangible benefits and costs. Travel time and distance effects can be predicted roughly with travel-demand models. Willingness-to-pay surveys can also be used to estimate benefits and costs to users.

Consideration of income-distribution effects is an effort to account for the typically greater utility of benefits and disutility of costs to households with lower incomes as well as the common societal objective of discouraging too great a disparity in household wealth within society. Measurement of the income-distribution effects of a roadway-capacity-allocation scheme would typically rely on statistical measure(s) of differences in the distribution of wealth with and without the allocation scheme. Logit mode choice models can be used to project consumer surplus (net benefits) by income group. Travel-demand models that retain household-income classes in the final trip tables can be used to project the travel effects of changes in facility operations by income class (for more detailed analysis see Harvey 1991).

Flexibility of access for urgent travel needs is important because all persons require some means of gaining rapid access to the freeways and other roads that are allocated. Such access must be available for a variety of emergency needs (such as trips to the hospital) and these probably can be unambiguously defined. The difficulty will be in defining urgent needs, which are not emergencies, but may involve lesser, but pressing, travel needs (such as trips to an airport). Any proposed allocation method must be able to define clearly and implement such access to be seriously considered by the public.

METHODS OF CAPACITY ALLOCATION AND THEIR EFFECTS

Several capacity-allocation approaches are considered roughly in the order of the amount of governmental effort required to implement them. We review the literature concerned with each measure and discuss the measure's potential for effectiveness in reducing congestion, economic efficiency, economic equity, and flexibility for immediate access.

Laissez-Faire Allocation

Laissez-faire allocation of roadway capacity is achieved if no control is exercised on entry to and exit from the roadway. Here, drivers continue to enter the roadway until the congestion cost they expect to experience exceeds the costs to them of taking an alternative route or mode or of deferring the trip. While this behavior is efficient for the individual driver, it imposes external congestion costs on other roadway users. This causes levels of congestion that are excessive compared to congestion levels that would maximize the total net benefits to all drivers (Walters 1961).

Laissez-faire allocation is easily implemented, of course, as it requires no action at all. This is not to say the laissez-faire allocation is an inexpensive option. Laissez-faire allocation imposes excessive congestion costs on roadway users, reduces roadway capacity below optimal levels, and causes some trips to be deferred, to avoid congestion, which should otherwise be taken and causes other less valuable trips to be taken that should be deferred (Downs 1962). It is also inequitable as time costs for wealthy travelers are higher (it has a progressive income effect). However, until recent technological developments, laissez-faire allocation was virtually the only available option. Most other options considered here typically would have been enormously expensive to implement. Additionally, the low levels of congestion prevailing over the road network did not motivate examination of more complex allocation methods. Laissez-faire is very ineffective, very inefficient, and somewhat inequitable, but allows immediate access for all at off-peak times and slow access to destinations during peak periods.

Allocation by Vehicle Passenger-Load

The earliest roadway allocation method implemented primarily to avoid congestion was to allocate one lane of multiple-lane highways to high-occupancy vehicles, so-called HOV lanes (Spielberg et al. 1980). This ensured buses, vanpools, and car pools relatively reliable and rapid travel, while reducing roadway capacity available for single- or low-occupancy vehicles (Leman 1993). (We assume a "take-a-lane" program that uses existing highway lanes, without restriping of shoulders.) The intent here is to both maximize the highway's capacity, in persons per hour, and to encourage carpooling and transit use by providing faster travel times for high-occupancy vehicles. Enforcement of the HOV lanes is largely by traditional police methods and reports from other motorists.

HOV lanes are more successful where land-use and travel patterns are conducive to bus use and carpooling. Where recruitment of passengers into car pools and buses is not encouraged by reduced HOV-lane travel times, HOV lanes remain underused and lower the passenger-carrying capacity of the roadway by removing a lane from mixed-flow traffic. HOV lanes over relatively short segments at bottlenecks and ramps may be sufficient in highly congested corridors, however, to induce sufficient carpooling and bus use.

HOV lanes have been useful for reducing traffic congestion in a number of metropolitan areas (Pratt and Copple 1981; Spielberg et al. 1980; "Proceedings" 1987, "Proceedings" 1988; "Proceedings" 1991). The use of HOV lanes in congested corridors can both increase passenger flows and decrease average per capita travel times. A study of the Seattle area found that an HOV lane operating at only 20–25% of its vehicle flow capacity carried up to 15% more people than a conventional non-HOV lane (Washington State Department of Transportation 1984). HOV lanes can greatly increase roadway "utilization" (passenger-mi/hr/lane), by factors of 2–30 "Effectiveness" 1988). In general, HOV programs require strong workplace vanpool and car-pool financial incentives or regulations to succeed. However, HOV lanes can never eliminate or even substantially eliminate congestion, since the success of an HOV lane rests on the existence of significant congestion in remaining non-HOV lanes to encourage ridersharing and use of bus transit. Thus, the use of road pricing or the use of ramp metering to reduce congestion may make the use of HOV lanes ineffective.

HOV lanes are moderately effective, but because willingness to pay is not a factor in gaining access, they are economically inefficient. HOV lanes are somewhat equitable and fairly good for immediate access.

Ramp Metering

Ramp metering, as practiced in many large metropolitan areas, consists of allocating freeway capacity on a first-come, first-served basis. Cars arriving at entrance ramps are delayed there by a fixed amount of time or until traffic flow on the freeway has been reduced to a certain level. This occurs naturally as vehicles already on the freeway leave by unrestricted exits. This allocation approach is fundamentally different from the allocation of scarce water or electricity by metering, with the installation of a meter on each user and the allocation of the resource to each user by the user's willingness to pay a price charged (Lund 1988). Ramp metering is first-come, first-served, like local telephone service and water rights (in most Western states).

The advantages of ramp metering are that it can be implemented fairly readily, requiring only installation of stoplights and extended lanes on entrance ramps and coordination of these lights and freeway sensors by computer and telemetry. Applications of ramp metering have produced reductions in average trip times and increased freeway vehicle flows, both on the order of 10–15% (Spielberg et al. 1980).

Socially, the first-come, first-served basis for ramp-metering allocation is perceived as fair. However, in an economic sense, such an allocation is inefficient. In any line waiting for entry to the freeway there are likely to be those near the front of the line who would trade spots with someone further back for some monetary compensation. There are also likely to be those further back in the line that would provide such compensation for a spot closer to the front. Allowing such trading would then improve the economic efficiency and perhaps the economic equity of ramp metering (Starkie 1986).

Ramp metering can be combined with HOV-lane policies by having ramp HOV bypass lanes. Early successful metering programs were reviewed by Dunlay and Soyk (1978), who found that metering was often combined with bus bypasses or HOV bypasses. Interactions between the two programs must be kept in mind, however. Ramp metering, by reducing travel delays, defers the need for HOV lanes. On the other hand, ramp metering with HOV bypass lanes can help increase the political acceptability of HOV bypass policies and delay the need for take-a-lane HOV lanes on the freeway itself (Howell 1989). In general, ramp metering is more effective than HOV lanes, because all vehicles are speeded up. The main drawback is that queues can back onto surface streets congesting the arterial portions of the transportation system (Howell 1989; May 1986). It is also not economically efficient, because of the time spent in the ramp queues. Metering is not very equitable because of people's differing values for time, but does allow immediate access quite well.

Road, Parking, and Area Pricing

Road pricing allocates roadway capacity according to willingness (and ability) to pay. Implementation of road pricing requires some method for setting prices for road use and some mechanism for collecting the price of road use from road users. The traditional implementation of this allocation approach is toll roads, toll bridges, and toll ferries. Here, vehicles are stopped and a toll collected at the time of use. Sharp et al. (1986) report that 28 states operate 36 toll-road systems and 43 bridge toll systems. There are also 29 county and 27 municipal toll systems (1983 data). Tolls are primarily a local revenue instrument in the United States and are often used to finance transit. Road pricing has been long discussed, but rarely used for reducing the economic inefficiency of congestion (Walters 1961; Mohring and Horwitz 1962; Smeed 1964; Mohring 1970; Vickrey 1968; Zettel and Carll 1964; Stratzheim 1977; Morrison 1986; Miller 1989). New technological developments (Kraus 1989) and the increasing difficulty of expanding roadway capacity have again raised discussions of road pricing for managing congestion. The federal Clean Air Act of 1990 allows pricing as a transportation control measure (TCM). The new surface transportation act will fund several pricing demonstration projects.

Road pricing is perhaps the most desirable form of roadway capacity allocation, from the perspective of economic theory. It allows prices to be set to balance the social costs of congestion against the transportation value of the roadway as perceived by individual roadway users. Road pricing is also rather flexible in that it presents potential road users with a range of choices. The user can choose his or her own route (and cost) from any combination allowed by the physical road network, and the user is not restricted as to time of travel, unless the individual is unwilling to pay the associated cost at that time. Furthermore, road pricing allocates limited roadway capacity to those users that value it most highly. In terms of economic theory, these are rather ideal characteristics for a roadway allocation device.

The classic case for congestion pricing has been made for airport runway pricing (Morrison 1987; Morrison and Winston 1989). Early roadway pricing proponents were Mohring and Harwitz (1962), Vickrey (1965), and Smeed (1964). Smeed (1964) recommended time-of-day road pricing to control congestion, rather than using surrogate taxes on parking, fuels, and central business district (CBD) employees or using area licensing. Mohring (1970) and Straszheim (1977) developed road-pricing theory more rigorously.

Else (1986) identifies problems in implementing congestion tolls. First, we do not have marginal cost pricing of related goods and so cannot determine easily the efficient prices for road travel. He argues, however, that only other travel modes need to be considered, due to the relative independence of demand for other goods versus for travel. He notes, though, that the subsidy to other modes must be taken into account in setting prices for road travel. A further complication is that all costs and benefits of road travel are not even counted in the pricing research. Else argues for the approach of adopting acceptable but arbitrary standards for flows and setting prices to achieve the standards.

Bhatt (1976) and Keeler and Small (1977) evaluated the full cost of freeway travel in an urban region and found it to be $0.50–0.60 per vehicle-mi in urban core areas at peak periods. Small et al. (1989) review studies of congestion pricing and conclude that tolls of $1–6 per trip (updating and generalizing their calculations) would be efficient and would reduce peak traffic volumes 10–25%. A recent study by a private group in Southern California has recommended congestion road pricing. Their analysis found that a $3.00 average daily charge would reduce daily vehicle miles traveled by about 5% in 2010 ("Transportation" 1991).

Peak pricing seems well accepted in many private services, such as telephone, computing, and electricity, as well as in airlines, theaters, and some restaurants. All-day pricing recently has been adopted for the freeways entering Bergen, Norway (to raise revenues) and area licenses for peak-period entry have been adopted in downtown Singapore (to reduce congestion) ("Market-based" 1990a, b). Only the Singapore experience has been well studied. A $2.50 daily area license fee resulted in a reduction in the auto work-trip share from 56% to 23% and a reduction in average travel costs (Morrison 1986). There is evidence, however, that many drivers shifted their travel to off-peak periods (the license period was originally only from 7:30 a.m. to 10:15 a.m.), so the evening peak was unaffected. There is also evidence for rerouting as a response, in that the outer roadways experienced more congestion in the morning peak (Dunlay and Soyk 1978).

The largest impact of peak-period pricing will be to more fairly allocate congestion costs to road users (Lee 1982; Straszheim 1977). If distance-based, such tolls could reduce sprawl by reducing the attractiveness of outer areas (Oron et al. 1973; Wachs 1981). Certain types of employment would probably decentralize, however, due to the higher travel costs in central areas. Straszheim (1977) believes that such decentralizing effects would be small, however, because tolling would increase speeds and that would reduce time costs, offsetting the greater direct costs.

Mogridge (1986) argues that the effect of roadway pricing on roadway use is determined largely by the character of alternative modes (transit). He argues that pricing freeways would not speed up auto travel in London very much, because riders who preferred the higher road speeds would shift from rail to auto until a new equilibrium was reached. Many writers observe that for pricing to work, there must be convenient HOV or bus lanes or rail transit available with enough capacity to handle the travelers who switch from autos (Dawson 1986).

Congestion pricing of freeways will push some trips onto surface streets and can congest the major parallel arterials in each corridor. Tolling arterials is much more difficult in terms of vehicle identification and payment, although this may be overcome with automatic vehicle identification (AVI) technology.

Impressive economic benefits are projected to come from road pricing. Small et al. (1989) cite a 1982 FHWA study claiming $5.65 billion in net savings to travelers per year, nationwide. Most of the savings are in time costs. It is unclear if these analyses account for the more frequent and longer trips that travelers would make on the less-congested toll roads.

Most analysts believe that congestion pricing will have a regressive equity effect (Layard 1977). The Bay Area Economic Forum ("Market-based" 1990a, b) evaluated the equity impacts of peak pricing and found that they would be small and could be offset with rebates to low-income travelers or with improvements to transit. Thompson ("Urban" 1978) argues that equity analysis should also be concerned with the access available to transit travelers. If some of the revenues from road pricing are spent on transit improvements, then *existing* transit travelers will benefit. This class is generally ignored in equity evaluations. Hau (1992a) reviews the road-pricing literature and develops ideas for implementation and for spending the revenues raised for improvements to roads and to transit.

Small et al. (1989) review several studies of the effects of congestion pricing and show that all income classes of travelers gain income when the spending of the revenues on such improvements is included in the analysis. Wealthy travelers gain more absolutely, but not in proportion to income. Harvey (1991) analyzed congestion tolls on the Bay Bridge leading to San Francisco from Oakland and found that about 20% of the bridge users in the morning peak would be severely disadvantaged, because their workplaces were not accessible by transit from where they live and there was insufficient affordable housing near where they work. He suggested that two levels of tolls could be set, so that lower-income travelers could still gain access to slower, lower-toll lanes and pay with greater time costs. One such solution that fully used the bridge capacity was peak-period toll surcharges of $1 (slow lanes) and $5 (fast lanes) (on top of the $1 base toll). Such a dual system, however, would create a situation in which the poorer would watch the wealthier speed by and so would take some effort to "sell." Else (1986) also believes that differential tolls and speeds are an efficient solution.

Lave (1994) develops families of demand curves for road-pricing scenarios that result in various travel speeds. With different shapes of curves (straight, convex upward), he shows that the welfare losses of those tolled off could be larger or smaller than the gains to those still on the facility and traveling faster. The shapes of the curves are determined by the quality of the next-best alternative modes. Political acceptance, then, depends on "the amount of inconvenience to those drivers who are pushed off by the new fees" (p. 3). Good transit may not be enough, however, to gain acceptance, because the losers will be riding buses or rail and may see the drivers left on the freeway going by at faster speeds, on a daily basis. Even if part of the revenues is refunded annually, it will not compensate for this perception of loss. The costs to this group are "direct and immediate" and the benefits are indirect and deferred. Relatively small groups of losers have complained about take-a-lane HOV projects in the United States and succeeded in getting the lanes returned to mixed-flow use. Lave thinks that even new toll roads, if parallel to existing freeways, may engender political opposition, because the toll roads must be operated at flows way below capacity in order to keep their speeds high and the speeds on the freeway relatively low. This analysis indicates the political difficulties faced by congestion pricing.

Higgins (1986) reviews the early attempts to introduce road pricing in the United States and concludes that opposition will be very difficult to overcome. He recommends parking pricing, as more feasible. Hau (1989) believes that some of the resistance can be overcome by dedicating the revenues raised to improvements in transportation with the use of a trust fund. Small (1992) presents an illustrative analysis of congestion pricing and of spending the revenues for the five-county region of Southern California. Two-thirds of the revenues are spent on travel allowances for workers and on reducing fuel, sales and property taxes, and one-third is spent on transportation-system improvements. He performs an equity analysis for different groups of travelers and shows that the first-order income effects are positive for all of them. It is necessary to spend some of the monies for reducing regressive taxes in order to benefit lower-income groups and also to not increase government spending greatly and have pricing be seen as a cover for such spending growth. Some of the monies need to be spent on transportation improvements in order to gain public acceptance, according to Small, and so the use of the revenues is determined by both economic equity and political principles.

Giuliano (1992) argues that it is not enough to propose to spend the revenues in a way to benefit all user groups, because the public will not trust the officials to do the right thing. This distrust would be widespread, in part because of the huge sums of money that would be raised by market-clearing levels of tolls in very congested urban regions. Also, the public would look back at the recent inefficient and regressive spending on rail transit systems, which benefitted middle-class and not poor households in most regions. She suggests that building new toll roads will probably be more politically acceptable than tolling existing roads, as the funds would be seen as resulting in new capacity. May (1992), however, cites a study showing that 62% of London respondents favored pricing of existing roadways if the revenues were spent on transportation improvements. A U.K. nationwide survey showed that 57% supported road pricing if the revenues were to be spent for improving transportation, including bicycling and walking facilities, and for increasing roadway safety (May 1992).

A surrogate for pure road pricing is the pricing or taxation of goods correlated with road use, such as fuels (Newbery 1989) or parking (Higgins 1986). Many countries use high fuel taxes to generally discourage roadway use and car ownership. Vehicle license fees and excise taxes on vehicles and parts can have a similar effect. For example, in the Netherlands, total road tax revenues (all forms) are 435% of that nation's total road-related expenditures. In contrast, in the United States, all road taxes account for 63% of the nation's road expenditures (Newbery 1989). Such taxes, however, do little to reduce peak-period road use per se. Controls on auto ownership are also not very effective in reducing congestion.

Parking pricing at places of employment can be seen as a closer substitute for peak-period road pricing, however. By properly adjusting salaries and wages, this measure can be financially neutral for the worker and the employer. A simulation in the San Francisco region showed that desubsidizing employee parking in San Francisco would reduce work vehicle trips by 56% and in Santa Clara County (San Jose, Silicon Valley) this policy would reduce such trips by 28% ("Final" 1990). (Both analyses assumed that all worker parking was free in the base case, so the projections are somewhat exaggerated.) In a simulation of Southern California it was projected that a $3 per day workplace parking charge would reduce daily vehicle-miles traveled (VMT) by 1.5% and trips by 1.8%. Such a reduction in daily trips would translate into about 5% of peak-period trips regionally and a much higher percentage reduction on roads leading to major employment centers where the parking charges would be higher than this regional average. Private off-street parking would be difficult to control, however. Parking controls also do not restrict through traffic during peak periods.

Area licensing is successful in reducing trips into the central city in Singapore (Hau 1992a), but such schemes have run into opposition in Kuala Lumpur and Bangkok (Armstrong-Wright 1986), and in Stockholm and Honolulu (May 1986). A pilot program with AVI in Hong Kong was technically successful, but died from political opposition, based on the loss of privacy (May 1986).

Road pricing by time of day would be very effective, very efficient, and (if revenues were spent appropriately) very equitable. Without additional measures, however, pricing would be very ineffective for immediate access for some very-low-income households (those without debit cards or regular credit cards or cash). There would be very few travelers without cash, however.

Allocation by Trip Purpose

Our existing traffic system already allocates some roadway capacity by the purpose of a user's trip. Emergency fire, medical, and police trips are allocated all the roadway capacity required for their trips. This is implemented by requiring all other traffic to leave the roadway, if necessary, to make such capacity available. The purposes of these trips are seen as so important that no delay of them is warranted for any reason.

Roadway allocation by trip purpose could become broader and more complex. Perhaps most difficult would be the development of some sort of prioritization of trip purposes. Most people agree on the overriding importance of fire, police, and ambulance trips. Are freight-delivery trips less important than commuting trips, however? Are shopping trips less important than commuting trips? Are vacation trips less important than shopping trips? Some sort of generally agreed-on prioritization would be required. Arriving at this sort of agreement would be difficult. Behavior is nonintuitive: for example, in most urban areas nonwork trips are the majority of trips during peak periods. There has been much serious discussion recently of restricting downtown freight deliveries to off-peak or even nighttime hours in the Los Angeles region. Allocation by trip purpose was studied in the London region, both as an alternative to pricing and as a complement to pricing. Such schemes are limited by fraud, however, and by the difficulty of accurately determining need to travel (May 1986).

Technical complexities also arise. First, vehicles would have to have some sort of verifiable identification that would broadcast their trip purpose (and destination), allowing enforcement of the prioritization scheme. Second, the levels of trip priorities allowed to use a road segment would also have to vary by roadway, time of day, and day of week. Perhaps all traffic within 6 mi of a metropolitan area's central business district would be restricted to commuters from 6:30 am until 8:30 am and between 4:00 pm and 6:00 pm on weekdays. Third, mixed-purpose trips would pose problems. Restrictions such as the one given would encourage commuters to stop and shop during their commutes, generating additional roadway use as they stray from direct routes to and from work. (However, such trip chaining would reduce roadway use for shopping trips elsewhere.)

Retail electricity is allocated by purpose in many states. Residential customers pay higher rates than commercial and industrial ones. Also, lower-income households get cheaper rates than other households. Some states also require "lifeline" phone rates for such families. In many states, farms and street-lighting customers (mainly local governments) pay lower rates than residential customers. Similar rate differentials are also common for water and sewer service. Electricity, natural gas, and water are also prioritized by many states in terms of who gets them during shortages.

The effectiveness of this approach for reducing road congestion is largely limited by the tendency of congested roads to be populated by vehicles with similar trip purposes. Most congestion results from commuter traffic or from vehicles destined for a particular recreation destination. Allocation of roadway capacity by trip purpose would be likely to reduce congestion only in cases where there is a substantial mix of trip purposes demanding roadway use at peak times. The afternoon peak period may be amenable to such a policy, since work trips are only about half of the demand then. Enforcement would be difficult, due to the need for surveillance and the need for fine distinctions among purposes.

Allocation by trip purpose would be somewhat effective, not very efficient, and somewhat equitable. It would be very good for immediate access.

Rationing

During World War II, the major capacity constraint on metropolitan travel was not roadway capacity, but the availability of gasoline and tires. Allocation of transportation capacity was achieved by rationing, by the distribution of coupons to individuals entitling them to the use of a specific amount of scarce gasoline and tires. Indeed, during the energy crises of the 1970s gasoline rationing was again much discussed. Rationing schemes have also been proposed and adopted for a wide variety of environmental resources (Hahn 1990).

Allocating roadway capacity by rationing could be a much more complex task, requiring "coupons" for the use of specific roadway segments at specific times of day for each individual. Fortunately, present and future advances in communications and computers allow much greater flexibility for administering rationing. Indeed, with automatic vehicle identification, "coupons" could be electronic, to increase flexibility and ease enforcement.

A critical decision concerning rationing is whether the coupons would be transferable (marketable) (Tobin 1952). One can imagine the issuance to each individual of a given number of VMT units for each day and time of day. These could be used for any location. To acquire enough coupons to get to and from work each day, a commuter would either have to join a car pool (which would also pool coupons) or would have to purchase VMT units for the appropriate time from a market for coupons, which would probably be electronic in nature and similar to the stock market. If coupons are not transferable, such flexibility and efficiencies are lost.

Rationing by allocating VMT simply by hour may not optimally reduce congestion, however, since demand for VMT is not evenly distributed over the road network. Typically, over a large road network, only a few segments are severely congested during peak periods. If the entire VMT supportable by the network is distributed, its use will likely be more concentrated on a few roads. Rationing by VMT per hour would also encourage use of more direct routes, which may be more congested.

Another form of rationing would ration permission to use specific segments of roadway. Drivers would request permission to travel certain routes at certain times of day and would be granted a limited number of passages, based on the number of applicants and the determined capacity of each roadway segment. Thus, if 5,000 drivers each desire to commute 240 times per year over a given roadway at a given time of day, but the roadway can only efficiently provide passage to 4,000 commuting drivers, each driver might be issued tickets to allow 192 commuting trips per year. Drivers would have to either work at home, carpool, or buy tickets from others for the other 48 work trips. The market price of the ration tickets for a particular roadway would also establish the marginal value of increasing the capacity of the roadway above 4,000 commuters per time period, an estimate directly useful for evaluating capacity expansion. There are obvious difficulties involved with individuals applying for more tickets than they need, as a form of profiteering. Again, this problem, as well as much flexibility and overall economic efficiency, are removed by making passage coupons nontransferable.

The rationing of goods correlated with road use may be an acceptable and effective surrogate. Land for parking could be limited or spaces could be rationed. Such parking space rations could be made transferable, much as a transferable development right (Roddewig and Inghram 1987). The same approach could be applied directly to car ownership. The small island of Bermuda limits car ownership to one car per household (May 1986). If car ownership rations were transferable, transit users or the poor could conceivably sell or lease these ownership rights to others valuing car ownership more.

One attribute of the allocation of roadway rations is that these rations would represent a form of wealth distributed by the governing transportation agency (Tobin 1952). This would be particularly true if rations were marketable. Since under reasonable market conditions the market value of rations would rise to where supplies of rations just equaled demand, members of lower-income groups valuing money more than some of their rations would essentially gain an income supplement, without losing access to the transportation system. Higher-income users with high values for travel in excess of their rations would need to purchase more (transferring income to the right holders in exchange for the right holders' loss of transportation access). A progressive income redistribution effect would result from such tradable rationing.

Cameron (1994) evaluated several travel-pricing scenarios for Southern California with the intention of increasing the equality of services, especially for households in the lowest income quintile. In an appendix, he briefly describes tradable rations as a possible method for consideration in the medium term. The rations would be deposited on electronic debit cards and the travel "costs" would be automatically debited by roadside devices according to time of day and location. Drivers could receive the monthly rations at machines like automated-teller machines (ATMs) and also use these ATMs for buying and selling rations. He advocates giving each adult an equal ration, to produce a progressive income distribution effect.

Tradable rationing would be difficult to administer and so would be only moderately effective. It would be somewhat efficient and very equitable. It would be very good at allowing immediate access. Nontradable rations would be inferior on all objectives.

Mixed Strategies

It is unlikely that a single measure from those discussed would prove adequate to address the problem of reducing congestion through capacity allocation. A mix of several measures, in concert with other nonallocation urban transportation measures, is more likely to make practical, economic, and political sense. The development of such a mix in practice would obviously have a large political component. Economic analysis could be useful in guiding the development of a mixed strategy, however. Some work in this direction has already been done, illustrating the congestion and other costs of different mixes of bus lanes, transit subsidies, and road pricing (Mohring 1979). Indeed, a mixed strategy might be essential, for instance, where transit improvements are needed to increase the effectiveness of road pricing (Mohring 1979). Hedges (TRB 1978) advocates the use of moderate levels of pricing to make other measures, such as HOV lanes, work better. The Greater London Council studied road pricing with limited permits for local residents to reduce inequities (May 1986). This scheme could overcome most of the problems with immediate access caused by pricing.

It is possible, for example, that full-cost pricing of employee parking and modest peak-period road pricing could reduce peak demands enough to make an existing lane available for free HOV use on many urban freeways, especially if employer trip-reduction (HOV-incentive) policies are also in effect. Some authors believe that transit and road improvements will need to be part of the mix, in order to gain political support (May 1986; Small 1992).

Daganzo (1992) has developed a proof under strong simplifying assumptions that a combination of rationing and pricing can benefit all travelers, even if none of the revenues are returned to them or used for transportation improvements. In his scheme, every vehicle owner is randomly prevented from using his or her vehicle by the same percentage of days per year, for any given bottleneck. Auto-captive travelers, who value their cars very highly, can pay a large toll to use the congested road segment on their prohibited days. This toll is smaller than their gain from using their car. For the other travelers, the loss in welfare from having to take transit or not take the trip would be smaller than the gain in welfare from faster travel on the nonrationed days. The proof requires that a travel mode exist that is only slightly worse for some travelers, that is, good transit service. The Daganzo scheme may be superior politically to the one studied in London (pricing with some rations/exemptions), by reducing money loss to travelers. It may also reduce the problem identified by Giuliano (1992) of pricing raising too much revenue to be politically acceptable.

The transportation engineer's and planner's repertoire of planning and management measures is very broad, consisting of traditional construction options and traditional flow and modal-split management measures (TSMs), in addition to the capacity-allocation measures described earlier (some of which are now accepted TSMs). The maintenance of an effective metropolitan transportation system is likely to require a mix of measures from each category. Moreover, the "optimal" mix is likely to vary by location and over long periods of time, with local conditions.

COMPARATIVE EVALUATION OF ALLOCATION METHODS

A relative evaluation of the different capacity-allocation measures discussed is of some interest in thinking about combined sets of measures. Table 1 summarizes, in general terms, the relative effectiveness of these capacity-allocation measures in terms of four basic transportation policy objectives. The ratings in the table are in rough ranges, reflecting the variabilities in how each measure could be implemented and the uncertainties involved in projecting the impacts of the measures. The performance of some measures is extremely dependent on how they are actually implemented. Road pricing, for example can be extremely effective in terms of most of the performance measures, if electronic toll collection is used, the price elasticity of road travel demand is relatively high, and prices are set correctly. The performance of road pricing can also be substantially worse where tolls must be collected manually, there are no inexpensive travel alternatives, and prices are inappropriately set. Still, this preliminary multiobjective analysis should be useful for illustrating the trade-offs involved in selecting a mix of capacity allocation measures.

Note, for instance, that tradable rations, of almost any type, seem to be either preferable or similar to nontradable rations for all the four policy objectives in the table. Nontradable rations are unlikely to perform better than tradable rations and are likely to merit less consideration. Urgent access flexibility is low for nontradable rations. The case of nontradable rations could be improved with some method for rapidly gaining an emergency ration for cause. Such a system would be subject to abuse, however.

The economic equity for poor persons is low for pricing if the revenues are put into general funds. The revenues, however, could be used for compensating lower-income persons directly with payments or indirectly by improving transit services. With such spending (assumed by us), equity will be very good.

Pricing is so efficient and effective that we should seek to address its weaknesses. Careful design of the program for spending the revenues seems to address the equity issue, at least technically (Small 1992). The use of electronic credits for very-low-income households could help with equity and also with immediate access. Such vehicle owners would not qualify for electronic debit cards for the AVI tolling system or for normal credit cards to be used as a backup. Emergency vehicles, of course, would have special cards for access at any time for free.

May (1986) reviewed several traffic constraint schemes, including vehicle taxes, traffic cells, ramp metering, CBD access permits, parking pricing, and road pricing. He found ramp metering to be ineffective, in that the delays on the surface streets roughly equaled the delay reductions on the freeways. He found parking pricing, vehicle taxes, and traffic cells (mazes) to be ineffective, because they are not focused on peak-period travel. Access permit schemes were found to suffer from fraud and from equity problems in the allocation of the permits. He recommends that combinations of restraints be studied, such as road pricing with permits exempting CBD residents or HOVs. He notes that any restraint should be part of a comprehensive policy of transportation improvements, for efficiency and equity reasons.

As another example, peak-period road pricing, combined with metered entrance ramps for those not willing to pay the toll, might be effective both in reducing congestion and also in improving economic efficiency, with acceptable equity effects. Such a policy set could keep the queues on the surface streets at tolerable levels. Equity would be improved by spending some of the revenues on transit. Rations for lower-income travelers who must travel to their jobs by auto would not be necessary, greatly simplifying administration. Such a hybrid system might have lower public costs and lower private transaction costs than either capacity-allocation method used alone. Mixed systems may be best at satisfying all of the objectives, so future research should examine such scenarios.

TABLE 1. Multiobjective Evaluation of Capacity Allocation Measures

	Ratings on Policy Objectives (high = best)			
Capacity allocation measures (1)	Practical congestion reduction effectiveness (2)	Economic efficiency (3)	Economic equity for poor (4)	Immediate access flexibility (5)
Road pricing	med-high	high	med-high	med-high
Tradable rations	med-high	med-high	med-high	med-high
Allocation by purpose	low-med	low-med	med	high
Ramp metering	low-med	low	med	high
Allocation by occupancy	low-med	low	med	med
Nontradable rations	low-med	low	med	low-med
Laissez-faire	low	low	med	high

PROSPECTS FOR IMPLEMENTATION

Road allocation by occupancy is rapidly becoming common in the United States. There are even HOV3+ lanes (for three or more passengers) and bus lanes in the largest urban areas. Bus lanes are common in England and other European countries. Ramp metering is also becoming commonplace in the United States.

Rations for road use have not been tried anywhere, however, to the best of our knowledge. Tradable permits for air pollution have been used successfully in Germany for years. The federal Clean Air Act has led to emissions trading in the United States. These rationing and tradable permit systems have not been for consumers, however, who require very low transaction costs.

Many regions in the United States now spend bridge tolls in part to subsidize transit, HOV lanes, ramp metering, and priority access for emergency vehicles on some roads. Many urban areas have higher peak-period transit fares. Elsewhere, flat road pricing is operating in Norway (in Bergen, Oslo, and Trondheim) and morning and (recently) evening peak charges for access to the downtown district are in use in Singapore. High motor fuel taxes (more than $2/gal.), a substitute for flat road-use charges, are used in Europe and Japan and indirectly subsidize transit.

Pricing is being examined very carefully in California. Several conferences have been held there to examine new toll roads and toll lanes, as well as peak-period bridge tolls and area licenses ("Conference" 1991; "Role" 1992). New toll lanes on existing freeways are being built in Southern California. Time-of-day pricing of a bridge in the San Francisco area has been accepted as a federal pricing demonstration project. A California task force has recommended such road-pricing experiments ("California" 1991) and the state energy commission has supported this recommendation (California Energy Commission, unpublished report, 1991). Transportation pricing policies, including fuel taxes, emissions taxes, and parking pricing, have been adopted in principle for implementation within a few years by the San Francisco Bay Area regional air-quality agency. The California Air Resources Board, the Environmental Defense Fund, and several other private groups are studying the equity effects of potential roadway and parking-pricing schemes in the state's urban regions.

AVI is now used in Texas, California, and several other states, and AVI electronic standards have been adopted by several states, including California, Hau (1992b) reviewed methods of automatic toll collection in detail for use in developing countries.

It seems advisable for regional transportation agencies to implement demonstration projects, because of the great potential of some of these measures. An obvious place to start is with existing toll roads and tolled bridges where good transit service is available. Perhaps agencies could begin with higher peak-period bridge and tunnel tolls and work toward gaining the acceptance of AVI technology by permitting faster passage through automatic tolling stations for vehicles with AVI equipment. This would permit the testing of monthly electronic billing on a portion of the vehicles, which percentage would grow over time if the experiment were successful. Once differential peak-period tolling was in place on congested road segments, rations could be tested on a small-scale basis in the form of "lifeline" credits for lower-income commuters. Vouchers have been tried successfully for schools, housing, and food in U.S. cities.

In regions without toll facilities but with well-developed freeway ramp metering systems, the ramp metering stations could be adapted to serve as AVI facilities as well. Allowing AVI vehicles to use the HOV bypass lanes, where they exist, would induce many vehicle owners to purchase the equipment. If after a few years, a large fraction of vehicles had AVI technology on board, the agencies involved could urge all vehicle owners to participate. Then the regional authorities could set up electronic tolling facilities on the ramps. Most vehicles would not have to stop to pay a toll, since they would have AVI transponders or could purchase solid-state debit cards to place inside the windshield. Such cards would be scanned and debited automatically at the ramps. The greater use of ramp metering could prepare the way for tolling.

Ideal would be a nationally coordinated program where different states and regions tried out different strategies with before-and-after research. Pairs of cities and pairs of noncompeting corridors in single urban regions could be used for comparisons. It would be in the interest of the nation to fund such demand-management projects with federal monies, since they have the potential to defer or eliminate much greater expenditures. Several such pricing demonstration projects could soon be funded in the United States. Bhatt and Higgins (1992) identify research needs for such pricing programs. Lave (1994) outlines a research strategy using vehicles with AVI and roadbed sensors for a before-and after experiment.

For roadway allocation to be implemented effectively in the long run, there must be slower, but less-costly modes available, such as transit and congested but toll-free auto lanes (Starkie 1986). For transit to be cost-effective, however, land-use patterns must be allowed to adapt. Zoning, which artificially limits densities below market demand in many urban locations, should be modified near bus lines and passenger rail stations. Some federal and state highway and transit funds should be conditioned on such zoning (Johnston 1983). Furthermore, federal and state transportation funds should be awarded for projects that reduce peak-period demand, as there are large capacity costs deferred by such projects and programs, whether they be highway allocation, transit improvements, or land-use changes.

CONCLUSIONS

A wide variety of demand-management measures have been suggested for allocating roadway capacity to reduce traffic congestion. Most of these measures are impractical today and many will be impractical in the near term. Nevertheless, as metropolitan regions continue to grow and decentralize, as per capita vehicle ownership and VMT continue to increase, and as expansion of roadway capacity becomes increasingly expensive and controversial, roadway-capacity-allocation measures will become relatively more desirable and will attract more political and professional attention.

The present paper has attempted to review capacity-allocation alternatives as supplements to traditional capacity construction, transit improvements, and land-use measures and to indicate their potential impacts. The intent has been to encourage transportation planners to think broadly and creatively about the potential role of capacity-allocation measures in the management of future congested urban transportation systems.

The selection of a capacity-allocation strategy for managing congestion is not a simple decision. A mixed capacity-allocation strategy is likely to work best in conjunction with other traditional transportation options. Indeed, our current capacity-allocation system is a mixed one of laissez-faire and allocation by trip purpose with occasional use of allocation by occupancy, ramp metering, and pricing. Still, some general guidance in selecting allocation alternatives can be offered.

Tradable rations seem generally superior to nontradable ones. Congestion pricing with either unpriced but metered on-ramps or with rations for lower-income households should be investigated. We have outlined an incremental pathway for the implementation of these systems or similar ones. Policy packages for spending the revenues to increase equity, similar to that suggested by Small (1992), would be a part of these schemes.

Under the Surface Transportation Act of 1990, up to five pricing demonstration projects will be funded for study. These experiences will help to identify effective programs. Other demonstrations should be permitted by Congress, perhaps after 2 or 3 years. Urban regions with bad congestion and good transit service seem like the best candidates. Large grants should be made available to the regions that undertake these experiments, as an incentive.

There is no avoiding a choice of a capacity-allocation approach in the design of any transportation system. A method of capacity allocation is integral to *any* transportation system with even episodically congested operations. This very important aspect of system management largely has been ignored in the past. But as traffic demands grow and the public becomes more unhappy with primarily laissez-faire allocation policies, other capacity-allocation measures are likely to be increasingly discussed and applied.

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