Contents lists available at ScienceDirect

Economics of Transportation

journal homepage: www.elsevier.com/locate/ecotra

Optimizing road capacity and type

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ARTICLE INFO

Keywords:
Capacity
Free-flow speed
Highway design
Optimal highway investment
Congestion

ABSTRACT

We extend the traditional road investment model, with its focus on capacity and congestion as measures of capital and its utilization, to include free-flow speed as another dimension of capital. This has practical importance because one can view free-flow speed as a continuous proxy for road type (e.g. freeway, arterial, and urban street). We derive conditions for optimal investment in capacity and free-flow speed, and analyze the optimal balance between the two. We then estimate cost functions for capital and user costs and apply the resulting model using parameters representing large US urban areas. We show that providing high free-flow speed may be quite expensive, and there is sometimes a tradeoff between it and capacity. We find suggestive evidence that representative freeways in many large urban areas provide too high a free-flow speed relative to capacity, thus making the case for reexamination of typical design practice.

1. Introduction

The economic analysis of congestion and investment in road capacity is well developed. The research literature contains an abundance of optimality conditions, implications for pricing, and policy implications including such practical matters as second-best pricing, investment under conditions of suboptimal pricing, and financial balance between pricing revenues and investment costs.[1] In such analyses, roads are generally taken to be sufficiently characterized by a single dimension, capacity, with other issues such as safety or aesthetic ride quality dealt with as separate side issues.[2] In part, this emphasis is justified by the apparent dominance of congestion among the costs of urban road trips.[3]

Yet some of the most serious practical issues in road policy involve other aspects of roads such as their safety, environmental impacts, aesthetics, and impacts on neighborhoods and other considerations of urban design. As a result, passionate debates arise about not only the amount of road space to provide, but its type. In particular, the penetration of dense urban development by high-speed and high-capacity expressways has always been controversial.

Transportation economists have had less to say about these latter issues, and a major reason is the single capital dimension in the standard economic models of road investment. Yet it is entirely possible to build very different looking urban road networks of equal capacities, one using high-speed freeways and another using well-engineered arterials. These design tradeoffs require other measures of road capital than capacity.

The goal of this paper is to provide an expanded investment model that lends itself to analyzing such issues, by including free-flow speed as an additional design variable describing road capital. This is of course only a first step toward a more comprehensive goal, in which the planner simultaneously optimizes the many design elements making up road investment (some of which we enumerate in our empirical section), and does so for each road in a network serving diverse trips.[4] While not every issue of interest can be captured with our addition of just one new investment dimension, the advantages of tractability and transparency make this an attractive way to begin bringing the analysis of road types into mainstream transportation economics.

We start by developing the theoretical investment model with a long-run total cost function, consisting of capital costs and user costs, with capacity and free-flow speed as design variables.

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[1] Examples include Mohring and Harwitz (1962), Strotz (1965), Keeler and Small (1977) and Jansson (1984). For reviews see Lindsey and Verhoef (2000) and Small and Verhoef (2007, ch. 5).

[2] In three cases these other road characteristics are explicitly modeled, either as a type of scale economy (Jansson, 1984, ch. 10) or as a quality variable (Larsen, 1993, Walters, 1968). Walters acknowledges that capacity and road quality may vary independently but suggests that "as a very rough approximation it may … be sensible to treat the roads as giving a joint-product with *rigid* proportions." (pp. 35–36, italics in original).

[3] Small and Verhoef (2007), Section 3.4.6.

[4] A start on such a program is made by Ben-Akiva et al. (1985), who similarly argue for minimizing total costs as a design objective and apply this approach to geometric design of a climbing lane for heavy vehicles.

http://dx.doi.org/10.1016/j.ecotra.2014.02.001
2212-0122

Nomenclature

t	index for time periods, $t=1,2,\ldots,n$
q_t	duration of time period t
V_t	traffic volume at time t
V_K	capacity
v_t	volume–capacity ratio (V_t/V_K)
S_F	free-flow speed (including control delay at zero traffic volume for urban streets)
S_t	average speed
T_F	free-flow user time (entire trip)
T_t	average user time (entire trip)
ρ	annualized road capital cost (per mile)
r	interest rate
Λ	lifetime of road in years
L	trip length
$\Gamma(\cdot)$	road construction cost (per mile)
$A(\cdot)$	right-of-way acquisition cost (per mile)
c_t	average user cost per vehicle-mile at time t
U_t	total user cost per road-mile per hour at time t
C	total agency plus user cost (short run) per road-mile
$\tilde{C}$	total agency plus user cost (long run) per road-mile
α	value of time

The first-order conditions of the model lead to the familiar criterion for incremental investment in capacity, and a new criterion for incremental investment in free-flow speed. Combining these criteria gives us an "investment balance condition" that can be used to examine under what conditions a given road is well balanced between these two dimensions: i.e., when does a given road design provide too high or low a free-flow speed relative to its capacity?

To implement the model, we use empirical data to estimate both components of the total cost function. We estimate the capital-cost function using data on construction costs of various road types along with their free-flow speeds and capacities. We estimate the user-cost function from information about speeds and flows of different road types, differentiated by free-flow speed,[5] which we supplement with a queuing analysis to account for situations where input flow exceeds capacity. We then apply the estimation results to examine the investment balance condition for 24 standard road types under hypothetical conditions, and for representative freeways and arterials for a sample of US urban areas under actual conditions.

While our goal here is not primarily policy analysis, the model does permit another look at a question considered by Ng and Small (2012). Given that many high-speed urban expressways operate under severe congestion for several hours each day, is the extra expense of providing such high-speed service under more moderate traffic justified? In the extreme case where all traffic occurred during a peak period impacted by queues behind fixed-capacity bottlenecks, there would be no advantage to high free-flow speed. In more realistic cases, there are tradeoffs involving the duration of peak periods and the relative traffic volumes in peak and off-peak periods. Our earlier paper considers this question by comparing a few specific road types chosen to illustrate the tradeoff between free-flow speed and capacity, or between free-flow speed and construction cost. Here, we develop a more general model of road investment where both capital costs and user costs can vary depending on free-flow speed and capacity, each of which lies along a continuum.

We do find some evidence that typical freeways in large urban areas are over-designed for free-flow speed at the expense of capacity. This arises largely from the finding that the cost elasticity for increasing free-flow speed is, on average, three times that for expanding capacity (roughly 1.2 vs. 0.4); as a result even modest amounts of congestion favor incremental investments in capacity relative to free-flow speed. While the optimal road configuration is very case-specific, we can state a more general policy conclusion: road design needs to allow for variety and flexibility, rather than being constrained to meet a predetermined set of standards such as those for US Interstate Highways. There are probably many situations where urban areas are well served by parkways, high-type arterials, or urban streets with well-engineered intersections as a means of carrying large traffic flows efficiently.

[5] Such information is compiled in the Highway Capacity Manual (Transportation Research Board, 2000) from decades of engineering research.

2. Long-run cost functions with two dimensions of infrastructure

Total costs of road travel in our model consist of amortized capital cost and user costs. We adopt simple formulations for each, in order to emphasize what is new in this paper, namely the role of free-flow speed as a design variable. Thus, for example, we ignore road maintenance costs (assuming they would not affect design), accident costs (as there is mixed evidence in the literature regarding the impact of design speed on accident rates), other user costs aside from time (assuming they are proportional to vehicle flow and therefore also do not affect design), and environmental costs (which are best dealt with using other tools).[6] We also ignore capacity fluctuations due to accidents or weather, and the prospect of automated vehicles changing the speed-flow relationships.

Annualized capital cost is composed of initial costs of structures and land, each amortized at a constant rate over its lifetime. These costs depend on road design via the variables measuring capacity and free-flow speed:

$$\rho(V_K, S_F) = \frac{r}{1-e^{-r\Lambda}}\Gamma(V_K, S_F) + rA(V_K, S_F) \tag{1}$$

where V_K and S_F are design capacity and free-flow design speed, respectively, Γ is construction cost, A is right-of-way acquisition cost, r is the interest rate, and Λ is the road life in years, i.e. the time after which the structures and improvements (but not the land) have lost all their value. We assume that Γ and A are increasing in both V_K and S_F. This formulation assumes the annualized cost is constant over the road's lifetime.

Total user cost U_t per unit time during a discrete time interval t consists solely of time costs measured at a value of time, α, which for simplicity we take to be constant. User time depends both on

[6] Alam and Kall (2005) calculate that pavement resurfacing costs per lane-mile are higher for freeways than for arterials, not accounting for the fact that roads with higher traffic volumes (like freeways) also tend to be resurfaced more often. Average maintenance costs therefore appear to be correlated with average construction costs, and we believe that including maintenance costs would not change our results significantly. Meanwhile, as discussed in Ng and Small (2012), some of the design features that could result in lower free-flow speeds (like narrower lanes or a lower type of road such as a highway instead of a freeway) do not necessarily lead to higher accident rates, especially if the roads are accompanied by lower speed limits.