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Optimizing Road Capacity and Type

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June 2013

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In the economic analysis of road investment, road capacity (the maximum traffic flow obtainable on a given roadway – expressed in vehicles per hour) is generally taken to be the primary point of consideration. Yet, if a key objective in road design is to minimize travel-time costs, there are other design variables which should be considered. In this study, Small and Ng present an expanded investment model which includes free-flow speed (the average speed of vehicles when congestion is negligible) as an additional design variable. This updated model permits the authors to address questions like the following: 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 justified? More specifically, the new model allows the authors to re-analyze existing road designs and discover design changes which, if adopted at initial construction, could have led to reduced travel-times costs without increasing capital costs.

In the analysis, the authors find some evidence that typical freeways in large urban areas are over-designed for free-flow speed at the expense of capacity. While the optimal road configuration is very case-specific, their analysis leads to 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.

Analysis

Small and Ng begin the analysis by modifying existing long-run cost functions, which have historically only accounted for capacity, to also account for free-flow speed. Two cost functions ensue: a function for capital costs which accounts for the initial costs of construction and land, and a function for user costs which accounts for road users' travel time costs.

The authors proceed to apply the model to some examples of roads to see under what conditions these roads embody the optimal balance between free-flow speed and capacity. A road is optimally balanced if the mix of these two design variables minimizes total travel-time costs for a given capital cost. They first consider a wide selection of roads and traffic levels in order to explore the range of conditions when each type of road is appropriate. They then look at representative roads in various cities to see if they would be better served with a different type of design. Finally, they examine absolute criteria (i.e., benefit-cost ratios) for investing in capacity or free-flow speed for the same sample of cities.

Results

Applying the model to common road types – are they optimally designed?

When Small and Ng apply the model to 24 common road types, they find that when peak congestion levels are mild, investing in more free-flow speed produces greater travel-time cost reductions per unit of capital cost than does investing in more capacity, for all types of roads except two-lane urban streets. Under highly-congested conditions, by contrast, investment in free-flow speed is never favored; rather, it is always better at the design stage to sacrifice some free-flow speed in order to increase capacity. With an intermediate level of congestion, the balance differs for different types of roads; all the highways and expressways of four lanes or more offer inefficiently high free-flow speeds relative to their capacities, whereas the opposite is true for two-lane highways and two- to five-lane urban streets. In other words, at intermediate levels of congestion, the optimal balance lies somewhere between existing designs for minor highways and streets and those for major highways and expressways.

Investment balance for typical urban roads in the United States

Small and Ng examine the investment balance condition for some road conditions observed in U.S. urban areas in 2011. In the analysis, a good investment balance implies that no significant reductions in travel times could be realized by adjusting the investment from free-flow speed to capacity, or vice versa. Results are shown in Table 1 for seven cities, presented separately for freeways and arterial roads (note: an arterial road is a multilane road with few if any traffic lights). The overall picture is that freeways demonstrate an over-investment in free-flow speed relative to capacity, whereas for arterials these two dimensions are quite well balanced.

Table 1. Investment balance for average road conditions in 7 urban cities, 2011

	Very large areas				Large areas		
	Los Angeles	Dallas-Fort Worth	Miami	Boston	Denver	St. Louis	Jackson-ville
Freeways:							
Average no. of lanes	8.7	5.8	6.7	6.4	5.8	6.5	5.8
Free-flow speed (mi/h)	64.6	64.1	64	63.4	62.3	56	63.4
Peak speed (mi/h)	48.6	54	56.7	54.2	50.9	44.4	58.9
Peak volume-capacity ratio	1.016	1.003	0.994	0.999	1.004	0.993	0.976
Imbalance (+ favors investment in free-flow speed)	-1.6	-1.23	-0.54	-0.88	-1.18	-0.21	-0.01
Arterials:							
Average no. of lanes	3.6	3.7	4.6	2.3	3.5	3.2	3.7
Free-flow speed (mi/h)	43.7	39.1	39.2	36	38	34.9	43.3
Peak speed (mi/h)	37.4	33.1	31.7	29.5	32.1	29.8	37.4
Peak volume-capacity ratio	0.811	0.695	0.758	0.639	0.662	0.534	0.788
Imbalance (+ favors investment in free-flow speed)	-0.08	0.04	0.08	-0.12	0.04	0.08	-0.04

Each city's roads are defined by the average number of lanes, free-flow speed, peak speed (the average speed during the period of peak congestion), and the peak volume-capacity ratio (the ratio of the actual volume of vehicles during the period of peak congestion to the maximum volume for which the roadway is designed). The key indicator in Table 1 is the imbalance measure - a more positive (negative) value favors investment in free-flow speed (capacity). An imbalance measure of -1.6 in Los Angeles freeways, for example, tells us that Los Angeles is over-invested in free-flow speed. Travel-time costs could be reduced (with no change in capital costs) if investments were shifted to capacity. Alternatively, an imbalance measure of .04 in Denver arterials tells us that capacity and free-flow speed are well balanced. No significant reductions in travel-time costs would be realized by shifting the investment mix in Denver arterials.

Absolute investment criteria

Small and Ng analyze benefit-cost ratios (B/C) for either capacity or free-flow speed, each holding the other constant. B/C ratios are defined as the ratio of total travel time savings from an incremental increase in capacity or free-flow speed divided by the corresponding increase in annualized capital cost. The results of this analysis are presented in Table 2. The case for investment is strong in both capacity and free-flow speed, in all cities.

Table 2. Absolute benefit-cost ratios from incremental investments in capacity or free-flow speed

	Very large areas				Large areas		
	Los Angeles	Dallas-Fort Worth	Miami	Boston	Denver	St. Louis	Jackson-ville
Freeways:							
Free-flow speed (mi/h)	64.6	64.1	64	63.4	62.3	56	63.4
Capacity (veh/h)	18,519	12,307	14,268	13,616	12,382	13,736	12,322
Capital cost (1000 $ per year per mi)	2,789	2,278	2,426	2,356	2,224	2,147	2,256
B/C: incremental investment in capacity	49.2	37	23.4	30.8	37.8	25	9.4
B/C: incremental investment in free-flow speed	18.3	9.6	12	11.7	10.9	19.6	9.2
Arterials:							
Free-flow speed (mi/h)	43.7	39.1	39.2	36	38	34.9	43.3
Capacity (veh/h)	3,216	3,337	4,284	1,589	3,123	2,751	3,393
Capital cost (1000 $ per year per mi)	879	732	810	522	682	563	877
B/C: incremental investment in capacity	8.6	5.9	8.4	11.4	5.6	3.9	7.1
B/C: incremental investment in free-flow speed	5.4	7.2	11.4	3.8	7	6.2	5.7

Each city is described by its average free-flow speed, capacity, and capital cost/year/mile for the two types of roads. Results are presented separately for freeways and arterials. The variation in B/C ratios across cities is not surprising, considering the results in Table 1. The case for investment in freeway capacity is extremely strong in Los Angeles and much less so in relatively uncongested Jacksonville. For arterials, the case for capacity investment is strongest in Boston and weakest in St. Louis. The case for investment in greater free-flow speed is especially strong for Miami arterials.

Policy Implications

The empirical analysis provides suggestive evidence that in many large congested cities, standard expressway designs are unbalanced in the sense of providing more free-flow speed than is desirable relative to capacity, whereas the same is not true for urban streets and arterial highways. This observation in turn suggests giving greater attention to the possibilities of more low-footprint roads which offer considerable capacity even though speeds are only moderate even at low traffic levels. More generally, road design needs to allow for variety and flexibility, rather than being constrained to meet a predetermined set of standards such as those for U.S. Interstate Highways.