Does the US have an Infrastructure Cost Problem? Evidence from the Interstate Highway System

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Does the US have an Infrastructure Cost Problem?

To answer this question, we need to first answer the question, 'What is the cost of infrastructure?'

Our answer to this takes a little theory.

Optimal infrastructure - static

$$
\begin{aligned}
v(x) &\sim \text{infrastructure services, e.g., VMT, ton-miles, trips} \\
x &\sim \text{inputs to infrastructure services (lane miles, pavement quality)} \\
B(v) &\sim \text{social benefit of } v \\
C(v) &\sim \text{cost of } v
\end{aligned}
$$

- Planner problem

$$\max_x W(v(x)) = B(v(x)) - C(v(x))$$

- B is the subject of a large literature, which has not reached clear conclusions.

Cost minimizing infrastructure – static

- C has received less attention, but

$$
\begin{aligned}
&\max_x W(v(x)) = B(v(x)) - C(v(x)) \\
\implies &\min_x px \\
&\text{s.t. } v(x) \geq v^*
\end{aligned}
$$

We can break the problem into parts, and think about the benefits and costs separately.

- What is $v(x)$? It is a production function. How much v from inputs x.
- We study the US interstate, v is VMT, and $x = (q^{-1}, L)$ is pavement quality and lane miles, with prices (p^q, p^L).
- We know very little about v. Assume it is CRS.

Cost minimizing infrastructure - dynamic I

- Infrastructure is an asset, so we need a dynamic problem

$$\max_{x_t, t=0,..,\infty} W((v(x_t))_{t=0}^{\infty}) = \sum_{0}^{\infty} \delta^t \left(B(v(x_t)) - C(v(x_t))\right)$$

- The necessary cost minimization problem is,

$$C\big((v_t)_{t=0}^{\infty}\big) = \min_{x_t, t=0,..,\infty} \sum_{0}^{\infty} \delta^t p_t x_t$$

$$\text{s.t. } v(x_t) \geq v_t^*, \quad t = 0, .., \infty$$

That is, minimize PV of expenditure to produce a given path of output.

Cost minimizing infrastructure - dynamic II

- But there are some physical constraints on the evolution of roads; (1) lane miles never disappear (2) pavement quality degrades with use,$\Longrightarrow$

$$C\big((v_t)_{t=0}^{\infty}; L_0, q_0\big) = \min_{I_t^L, \imath_t^q} \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} \left(p_t^L I_t^L + p_t^q \imath_t^q L_t\right)$$

$$\begin{aligned} \text{subject to} \quad & v_t \leq v(q_t^{-1}, L_t) \\ & L_{t+1} = L_t + I_t^L \\ & q_{t+1} = q_t + \kappa v(q_t^{-1}, L_t) L_t^{-1} - \imath_t^q \ . \end{aligned}$$

- $L_t \sim$ lane miles. $q_t \sim$ inches of suspension travel per mile (IRI), $q_t^{-1} \sim$ road quality. $I_t^L \sim$ lane miles added in year t. $\imath_t^q \sim$ change inches per mile reduction in roughness. $\kappa \sim$ wear constant (inches per lane mile per VMT).
- Assume observed v_t is cost minimizing, $v(q_t^{-1}, L_t)$ is CRS.

Cost minimizing infrastructure - dynamic III

$$C\big((v_t)_{t=0}^{\infty}; L_0, q_0\big) = \min_{I_t^L, \imath_t^q} \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} \left(p_t^L I_t^L + p_t^q \imath_t^q L_t\right)$$

$$\begin{aligned}
\text{subject to} \quad & v_t \leq v(q_t^{-1}, L_t) \\
& L_{t+1} = L_t + I_t^L \\
& q_{t+1} = q_t + \kappa v(q_t^{-1}, L_t) L_t^{-1} - \imath_t^q \ .
\end{aligned}$$

- What is the cost of infrastructure services?
- The cost of an increment to v_t should be the change to $C\big((v_t)_{t=0}^{\infty}; L_0, q_0\big)$. For a small change, this is the shadow price/Lagrange multiplier of v_t
- We are going to focus on steady state solutions to this problem because we want easy forecasts future levels of service and prices and we want an analytical solution.

Cost minimizing infrastructure - dynamic IV

- Steady state optimum must satisfy

$$\tau = \frac{rp^L L + rp^q qL + \kappa p^q v}{v}$$

  for τ the (steady state) multiplier for the constraint involving v.

- τ is the sum of the capital cost of system lane miles, the capital cost of pavement quality, and expenditures to offset depreciation.
- Comments: (1) Without $v()$ CRS this expression involves $\partial v/\partial q$ and $\partial v/\partial L$, about which little is known, instead of readily observable v. (2) τ is a lower bound if planner does not optimize.

Cost minimizing infrastructure - dynamic V

$$\tau = \frac{rp^L L + rp^q qL + \kappa p^q v}{v}$$

- To evaluate τ, we need L, q, v and prices. For our US based example, information about highways and usage is easy. Prices of lane miles and quality are hard. Developing countries are probably opposite.
- What is the ‘cost of the interstate’? We *define* it as the user fee per mile that rationalizes observed path of investment for an optimizing planner (along a steady state path).
- Does the US have an infrastructure cost problem? Evaluate τ and we’ll see.

Highway engineering 101

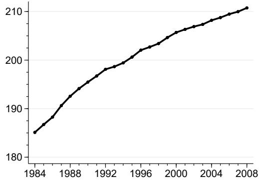
- *International Roughness Index* (IRI). This is ‘pavement quality’. NB: Quality is decreasing in IRI (watch for minus signs, etc.).
- *Average Annual Daily Travel*(AADT): Cars passing over a given segment in an average day. This is usage per lane mile.
- *Vehicle Miles Traveled* (VMT): AADT $\times$ segment length $\times$ 365. Sum over segments. This is total service provided by the system.
- Pavement types: *Flexible* = asphaltic concrete, *Rigid* = (Portland cement) concrete, *Composite* = layers of gravel, concrete, asphaltic concrete.
- *Structural Number*: Index of road strength. 1” asphaltic concrete is 0.4 units. 1” concrete is 1.
- *Equivalent Standard Axle Load* (ESAL): One combination truck or 2000 cars. A typical segment is depreciated after about 9m ESALs.

Data

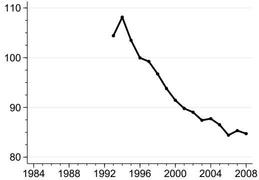
We rely on three main data sources:

- *Highway Statistics*, **state-year** data on expenditure for construction, resurfacing and maintenance (1984–).
  - Construction: 'ROW', 'New Construction', 'Major Widening'.
  - Resurfacing: 'Reconstruction', 'Rehabilitation, Restoration and Resurfacing'.
  - Maintenance: signage, emergency services, snow removal, etc.
- *HPMS Universe* data, **state-year** data on lane miles for ALL interstate segments (1980-2008).
- *HPMS Sample* data, **segment-year** level data on IRI and resurfacing for a sample of interstate segments. (1992-2008)
- Various other, mostly GIS data sets, track system characteristics over time, e.g., proximity to water.
- We estimate p^q using segment-year level data, *HPMS Sample*$\times$*Highway Statistics*. We estimate p^L using state-year data, *HPMS Universe*$\times$*Highway Statistics*.

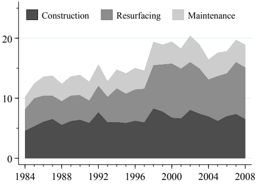
Trends in the interstate highway system



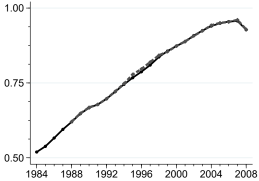
(a) Lane-miles/1,000



(b) IRI



(c) Expenditure/10^9



(d) AADT/10,000

Expenditure and VMT about double as extent increases and pavement quality improves. Resurfacing expenditure increases most.

$$\tau = \frac{rp^L L + rp^q qL + \kappa p^q v}{v}$$

Estimating equation: price of IRI, p^q (1)

Segment $j \in J$. State $s \in \{1, ..., 48\}$, year t.

$$\begin{aligned} L_{jst} &\sim \text{lane-miles} \\ \mathbb{1}_{jst}(q) &\sim \text{resurfacing indicator} \\ x_{jst} &\subset \text{ state, year, state-year and segment indicators} \end{aligned}$$

Effect of resurfacing on IRI over time,

$$\Delta q_{jst} = C_0 + C_1 \mathbb{1}_{jst}(q) + C_2[\mathbb{1}_{jst}(q)t] + C_3 x_{jst} + \epsilon_{jst}. \qquad (1)$$

C_1 is the conditional mean difference in IRI between resurfaced and unresurfaced segments when $t = 0$ (1992) and C_2 is the rate at which this difference changes over time.

Estimating equation: p^q (2)

But we want p^q_t...

- $\imath^q_{st} \sim$ expenditure per resurfaced mile in state s year t.
- Consider

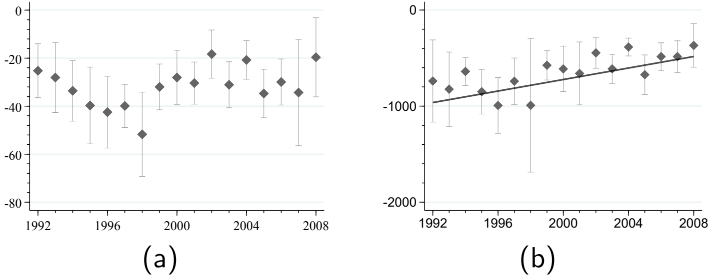
$$\Delta q_{jst} = A_0 + A_1 \left[\mathbb{1}_{jst}(q)\imath^q_{st}\right] + A_2 \left[\mathbb{1}_{jst}(q)\imath^q_{st} t\right] + A_3 x_{jst} + \epsilon_{jst}.$$

  This is just like the resurfacing regression, but reweighting by expenditure.

- Looking at units, we see that

$$\begin{aligned} \Delta \frac{\text{inches}}{\text{mile}} &= A_0 + A_1 \frac{\$\text{m}}{\text{mile}} + A_2 \frac{\$\text{m} \times \text{year}}{\text{mile}} + \ldots \\ \Longrightarrow & A_1 \sim \frac{\text{inches}}{\$m}, \ A_2 \sim \frac{\text{inches}}{\$\text{m} \times \text{year}} \\ \Longrightarrow & \frac{1}{A_1 + A_2 t} \sim p^q_t \end{aligned}$$

Resurfacing and the (inverse) price of IRI over time



(a) Mean difference between resurfaced and not, by year. About 40 inches reduction in IRI per resurfacing event in 1994. Weak trend up $\implies$ effect of resurfacing is not changing much.

(b) Same, weighted by expenditure. About 920 inches per million dollars in 1992, 490 in 2008. Inverting, $p^q_{1992} = 1,200\$/\text{inch}$, $p^q_{2008} = 2,050\$/\text{inch}$. Solid line is linear fit we use in our calibration.

Price of IRI, p_t^q

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{ist}(Q)\imath_{st}^q$	-619.29***	-607.60***	-646.12***	-921.00***	-922.91***	-992.86***
	(38.80)	(38.07)	(41.90)	(93.70)	(92.92)	(104.83)
t				-0.02	-0.02	0.00
				(0.07)	(0.07)	(0.08)
$\mathbb{1}_{ist}(Q)\imath_{st}^q \times t$				27.46***	27.29***	29.96***
				(7.01)	(6.89)	(7.64)
State FE	No	No	No	No	Yes	No
State-Year FE	No	Yes	Yes	No	No	No
Segment id FE	No	No	Yes	No	No	Yes
N	186,055	186,054	181,235	186,055	186,055	181,236

Note: Standard Errors Clustered at the State-Year Level. $^+$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Resurfacing is an industrial process that scrapes old material off the road and puts down new. Econometrics is not very important economically or statistically.

Estimating equation: p^L (1)

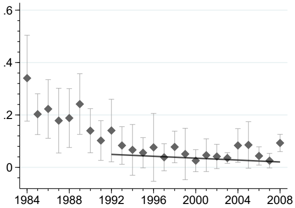
The HPMS Universe data is at the state-year level, not segment-year. Restrict p^q regression to fit.

- Segment State $s \in \{1, ..., 48\}$, year t.
- L_{st} lane-miles for state s year t,
- I^q_{st} state-year expenditure on new lane-miles.
- Consider

$$\Delta L_{st} = A_0 + A_1 I^L_{st} + A_2 [I^L_{st} t] + A_3 t + \epsilon_{st}.$$

- Using the same trick with units, $\frac{1}{A_1 + A_2 t} \sim p^L_t$

(Inverse) Price of lane-miles, p_t^L, over time (1)



- Mean new lane miles per million of state expenditure, by year.
- These are inverse prices. Prices explode near zero. Solid line is linear fit we use in our calibration.

Price of lane-miles, p_t^L, over time (2)

Table: Construction expenditure and new lane-miles

	OLS				TSLS
	(1)	(2)	(3)	(4)	(5)
I_{st}^L	0.0472*	-0.0008	0.1135**	0.0512	0.1584***
	(0.0230)	(0.0134)	(0.0328)	(0.0363)	(0.0458)
t			-0.6487*	-0.4112	-0.8271**
			(0.2910)	(0.3119)	(0.2815)
$I_{st}^L t$			-0.0045***	-0.0018	-0.0037
			(0.0012)	(0.0022)	(0.0025)
State FE	No	Yes	No	No	No
N	1,171	1,171	1,171	808	1,171
F					20.65

Note: Standard Errors in Parentheses Clustered at the State-Year Level. (1,2,3,5), 1984-2008; (4), 1992-2008 (to match p_t^q sample). Column 5 is TSLS, $z_{st} \sim$ state highway appropriations for $t-4$ per Leduc & Wilson (2013). $^+$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Calculate User Cost per VMT I

- Recall steady state expression for τ,

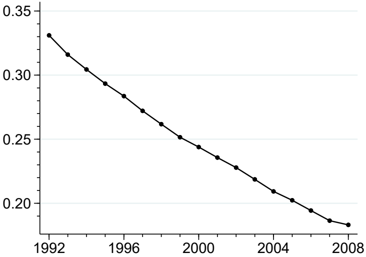
$$\tau = \left[rp^L L + rp^q qL + \kappa p^q \mathrm{VMT} \right] / \mathrm{VMT}.$$

- We observe L, q, VMT directly.
- r is the risk free rate, linear fit to 10 year treasury rate adjusted for inflation.
- We estimate p^q and p^L.
- κ from engineering books.

Calculate User Cost per VMT II

- Steady state expression for τ,

$$\tau = \left[rp^L L + rp^q qL + \kappa p^q \mathrm{VMT} \right] / \mathrm{VMT}.$$



- This shows how τ changes if we fix other variables in a particular year.
- Dynamic/Euler equations give much smaller and sometimes negative τ.

Calculate User Cost per VMT III

- Steady State expression for τ,

$$\tau = \left[rp^L L + rp^q qL + \kappa p^q \mathrm{VMT} \right] / \mathrm{VMT}.$$

- Let $o(k)$ denote a term of order 10^k, then we can evaluate the order of magnitude of the three terms in the numerator of τ,

$$\begin{aligned} rp^L L &\sim o(-2) \times o(7) \times o(5) = o(10) \\ rp^q qL &\sim o(-2) \times o(3) \times o(2) \times o(5) = o(8) \\ \kappa p^q \mathrm{VMT} &\sim 0(-6) \times o(3) \times o(11) = o(8). \end{aligned}$$

  Only the first term matters, the rental price for lane miles. Only the components of this term, p^L, r (and VMT) are important for τ. Quality and depreciation are not important determinants of user costs.

- This intuition probably does not generalize to developing countries.

Sensitivity and Counterfactuals

		2007	1992	2007/1992
A.	Baseline	0.19	0.33	0.59
B. Counterfactuals	VMT_{92}	0.26	0.33	0.81
	p^L_{92}	0.09	0.33	0.27
	p^q_{92}	0.18	0.33	0.56
	r_{92}	0.51	0.33	1.60
C. Sensitivity	IV 92-08	0.06	0.15	0.40
	IV All	0.08	0.15	0.50
	Non parametric (Smooth)	0.07	0.14	0.50

Note: Values of τ in 1992, 2007, and percentage change between the two years. Panel A gives baseline values based on the same data and calculation as presented in the figure. Panel B considers four counterfactual cases identical to the baseline, except with a single variable held fixed. Panel C considers three cases identical to the baseline except for the technique used to estimate p^L.

Conclusion I

- Between 1994 and 2008, the price of IRI about doubled. This probably reflects increases in materials prices. This affects almost half of 2008 interstate expenditure.
- Between 1984 and 2008 the price of new construction increased by about a factor of 7. This may reflect hard to observe changes in construction or 'citizen's voice' (Brooks and Liscow, 2020).
- Composition effects are important for level effects, not for trend. The urban and union premia decrease.
- The steady state user cost of the interstate is declining. Interest rate decreases and VMT increases more than offset price increases. If interest rates go up, we have a problem.

Conclusion II

Does the US have an infrastructure cost problem?

- Prices relevant to 80% of the interstate budget are increasing rapidly.
- This is probably not strictly about 'construction costs'. The cost of resurfacing increases primarily because of materials costs.
- Overall, user costs seem to be declining. Increases in the price of new construction are not as important as the decline in interest rate and increase in VMT.
- Suggestive evidence indicates that new lane miles are changing in ways that we can't quite see. Do these (speculative) design changes pass a cost benefit test?
  - Early roads probably did not do enough externality mitigation (Brooks and Liscow 2020, Brinkman and Lin (2020)).
  - The interstate carries twice as much traffic through more urban places in 2008 than 1990. More externality mitigation makes sense.

Conclusion III

How to extend to WB projects?

- WB should have much better price data than we do.
- Observing other quantities seems harder,
  - Pavement quality from landsat? (Cong Peng, 2024) Maybe from price levels?
  - Usage? Cell phones? Trade flows?
  - Maintenance? Use landsat again?