This PDF is a selection from a published volume from the National Bureau of Economic Research

Volume Title: Economic Analysis and Infrastructure Investment

Volume Authors/Editors: Edward L. Glaeser and James M. Poterba, editors

Volume Publisher: University of Chicago Press

Volume ISBNs: 978-0-226-80058-5 (cloth), 978-0-226-80061-5 (electronic)

Volume URL: https://www.nber.org/books-and-chapters/economic-analysis-and-infrastructure-investment

Conference Date: November 15-16, 2019

Publication Date: November 2021

Chapter Title: Transportation Infrastructure in the US

Chapter Author(s): Gilles Duranton, Geetika Nagpal, Matthew A. Turner

Chapter URL: https://www.nber.org/books-and-chapters/economic-analysis-and-infrastructure-investment/transportation-infrastructure-us

Chapter pages in book: p. 165 – 210

3 Transportation Infrastructure in the US

Gilles Duranton, Geetika Nagpal,
and Matthew A. Turner

We need major federal investments to rebuild our crumbling infrastructure and put millions of Americans back to work in decent paying jobs in both the public and private sectors.
—2016 Democratic Party platform

We propose to remove from the Highway Trust Fund programs that should not be the business of the federal government.
—2016 Republican Party platform

3.1 Introduction

Support for massive investments in transportation infrastructure, possibly with a change in the share of spending on transit, seems widespread. Such proposals are often motivated by the belief that our infrastructure is crumbling, that infrastructure causes economic growth, that current funding regimes disadvantage rural drivers at the expense of urban public transit, or that capacity expansions will reduce congestion. We provide an empirical and conceptual foundation for this important debate and highlight questions on which further research is needed.

We proceed in four stages. First, we document the quantity and quality of the Interstate Highway network, bridges of all types, public transit buses, and subways in each year over the past 20 to 30 years. Second, we investigate total expenditure and the unit cost for each of the four types of infrastructure over about the same time period. Third, we survey available estimates of

Gilles Duranton is the Dean's Chair in Real Estate Professor at the Wharton School at the University of Pennsylvania, a Centre for Economic Policy Research (CEPR) Research Fellow, a research affiliate of the International Growth Centre, and a research associate of the National Bureau of Economic Research.

Geetika Nagpal is a PhD student in economics at Brown University.

Matthew A. Turner is a professor of economics at Brown University, a research affiliate of the International Growth Centre, and a research associate of the National Bureau of Economic Research.

The authors gratefully acknowledge support from the Smith Richardson Foundation and the Zell-Lurie Center for Real Estate; valuable research assistance from Lin Fan, Margaux Kelley, Sunny Lee, and Julia Lynn; and helpful discussions and comments from Edward Glaeser, Erick Guerra, James Poterba, and Stephen Redding. For acknowledgments, sources of research support, and disclosure of the authors' material financial relationships, if any, please see https://www.nber.org/books-and-chapters/economic-analysis-and-infrastructure-investment/transportation-infrastructure-us.

the effects of infrastructure on economic growth and congestion. Finally, we propose a simple theoretical framework with which to organize this information and to think about whether current investments can be rationalized as a part of a socially optimal infrastructure policy.

On average, most US transportation infrastructure is not crumbling, except (probably) for our subways. Over the past generation, the condition of the Interstate Highway network improved consistently, its extent increased modestly, and traffic about doubled. Over about the same time period, the condition of bridges remained about the same, the number of bridges increased slowly, and bridge traffic increased modestly. The stock of public transit motor buses is younger than it was a generation ago and about 30 percent larger, although ridership has been about constant. The mean age of a subway car stayed about the same from 1992 to 2017, but at more than 20 years old, this average car is quite old. Subways carry about twice as many riders as they did a generation ago. Speed of travel by car, bus, and subway, all declined between 1995 and 2017, most likely as a consequence of large increases in road traffic and subway ridership. Like public transit, the Interstate system is largely organized around the provision of short trips in urban areas.

Expenditure on transportation infrastructure and its cost have both increased. Expenditure on the Interstate Highway network about doubled from 1984 to 2008, and building new highways has become markedly more expensive. Expenditure on bridges about tripled from 1984 to 2008. This expenditure resulted in modest expansions and maintained the condition of an aging stock of bridges. Expenditure on transit buses does not show any clear trend on a per rider basis. Subways also operate at about constant expenditure per rider. In 2008, total expenditure on the public transit bus fleet was about the same as the sum of capital and maintenance expenditure on the Interstate Highway System and about double total US expenditure on subway operation and maintenance.

To sum up, US transportation infrastructure is, for the most part, not crumbling, and expenditure is rising rapidly. However, still larger investment may make sense if such investment contributes to economic growth or reduces congestion. We review the recent literature estimating the effects of transportation infrastructure on economic activity. While this body of research strongly suggests that transportation infrastructure plays an important role in determining where economic activity takes place, it provides little compelling evidence about transportation infrastructure creating economic growth. We also review the recent literature relating capacity expansions to congestion. This literature points to demand management as the most effective policy to combat congestion. Capacity expansions typically meet with offsetting expansions in travel demand and do little to increase the speed of travel. Investments in transportation infrastructure intended to boost the overall level of economic activity or reduce congestion are risky at best.

The allocation of expenditure across modes of transportation requires scrutiny. That we spend about the same amount on public transit buses, which provide about two billion rides per year, as on the Interstate Highway System, which provides about 700 billion miles of vehicle travel per year, primarily for local travel, is a central and surprising feature of US transportation policy. To assess the reasonableness of this allocation, we imagine a planner whose object is to provide trips and who accounts for the public cost of capital and user inputs. This simple model suggests that the US federal government values a passenger mile of bus travel at about two and a half times as much as a passenger mile of car travel. Households are implicitly willing to trade the same two quantities at a rate of one and a half to one. The rationale for so strong a federal preference for transit over roads is unclear. It may be consistent with redistributive objectives or that bus miles in central cities are more valuable than car miles on exurban highways. Regardless, this policy preference merits further, careful consideration.

Massive investments in transportation infrastructure seem to draw support from across the political spectrum. These policies are often motivated by claims that our current infrastructure is crumbling or that such investments will spur economic growth. The available evidence does not support these claims. Expenditure on transportation infrastructure is growing and, for the most part, allows maintenance to match or outpace depreciation. Moreover, the available empirical evidence does not allow for much confidence in the claim that capacity expansions will lead to economic growth or reduce congestion. With that said, ongoing debates over the allocation of funds across modes seem justified. US spending on buses seems large relative to their ability to attract riders. Put another way, rationalizing current policy requires that the planner value travel by car much less than travel by bus. This relative valuation merits further debate and analysis.

Beyond this, we draw attention to the need for further research into the effects of transportation infrastructure on economic development, for the development of more and better data to monitor personal and truck travel, and for the development of even a rudimentary inventory of US water and sewer infrastructure. Finally, we discuss long-standing recommendations of transport economists for demand management as an alternative to capacity expansion for congested roads, and for "per axle weight" fees for trucks to incentivize the use of trucks that are less damaging to the highways and roads.

3.2 Usage, Stock, and Condition of Highways, Bridges, and Public Transit

3.2.1 Interstate Highways

The federal government bears some financial responsibility for roads in the Federal-Aid Highway System. This system is a subset of all roads but

Table 3.1 US roads and highways in 2008

	Rural			Urban		
Highway statistics	Miles	Lane miles	VMT (10^9)	Miles	Lane miles	VMT (10^9)
Interstate	30,196	122,825	243	16,554	90,763	476
Federal-Aid System	678,445	1,494,380	804	12,577	886,092	1,714
Total	2,977,222	6,091,943	990	1,065,556	2,392,026	1,983

Note: Extent and usage of rural and urban portions for different parts of the US road network as reported in various *Highway Statistics* tables for 2008.

strictly contains the Interstate Highway System. Table 3.1 provides some basic facts about the road system in the United States in 2008.[1] In rural areas, the Interstate Highway System accounts for about 1 percent of all mileage and about 2 percent of all lane miles, but about 24 percent of all vehicle miles traveled (VMT). Rural Interstate Highways are also important compared with the rest of the rural Federal-Aid Highway System. Rural Interstates account for less than 10 percent of rural Federal-Aid lane miles, but 30 percent of VMT in the Federal-Aid Highway System. The Interstate Highway System is similarly important in urbanized areas.

The urban portion of the Interstate consists of about half as many miles as does the rural portion. However, rural Interstates average about four lanes, while urban Interstates are almost six, so the urban Interstate consists of about three-quarters as many lane miles as does the rural Interstate. While the urban portion of the Interstate is network is smaller than the rural portion, it carries almost twice as much traffic in total, and almost 2.7 times as much on a per-lane-mile basis. In this sense, like transit, the Interstate primarily serves urban trips.

In what follows, we focus attention on the Interstate Highway System for three reasons. First, data availability is better. Second, the system is more extensively studied and so more is known about it. Third, the Interstate Highway System is an important part of the network. That said, the remainder of the network is understudied, and while we will not remedy this problem here, the rest of the network is an obvious subject for further research.

The federal government funds most Interstate Highway construction and maintenance and keeps a careful inventory of the roadways for which the federal government assumes financial responsibility. This inventory results in an annual database called the Highway Performance Monitoring System

1. The division of roads into "rural" and "urban" is pervasive in federal reporting on highways. Roads inherit their urban or rural status from the region they traverse. Urban roads lie in urbanized areas, rural roads do not. Given the importance of the tension between rural roads and urban public transportation in policy debates, we preserve the rural classification in table 3.1.

(HPMS). HPMS data are collected by various state highway authorities under the direction of the Federal Highway Administration, and these data describe the Interstate Highway network in detail. Mehrotra, Uribe, and Turner (2020) and Turner (2019) analyze these data and describe the evolution of usage, extent, and condition of the network from about 1980 until 2007.[2]

Figure 3.1 presents six figures based on data from Mehrotra, Uribe, and Turner (2020). Average annual daily traffic (AADT) per lane is defined as the number of vehicles traversing a given lane of roadway on an average day during the year. This is a common measure of the intensity with which a roadway is used. The solid line in panel A of figure 3.1 reports systemwide mean AADT (lane-mile weighted) for every year between 1980 and 2007 in thousands of vehicles per day. Thus, an average lane of the Interstate Highway System carried about 4,500 vehicles per day in 1980, and this figure more than doubled to about 10,000 vehicles per day by 2010. AADT on the Interstate Highway network increased by about 3 percent per year. The dashed and dotted lines in panel A of figure 3.1 report AADT on the urban and rural portions of the Interstate, respectively. AADT on the urban portion of the Interstate is about triple that on the rural portion; however, both parts of the network are following similar trends.[3]

Panel B of figure 3.1 reports a second measure of aggregate usage, total vehicle miles traveled (VMT) on the Interstate Highway System. We calculate this measure by multiplying segment-level AADT by segment length and again by 365. This gives an estimate of the number of vehicle miles of travel provided by a particular Interstate Highway segment. Summing over all segments gives an estimate of total VMT provided by the entire network in a year. The solid line in panel B of figure 3.1 reports aggregate Interstate VMT annually from 1980 until 2007. This figure shows that Interstate VMT increased from about 300 to 700 billion miles per year between 1980 and 2007. Over 27 years, this is an increase of about 3.2 percent per year. That VMT increased more rapidly than AADT reflects the fact that lane miles also increased during this time, even as AADT was rising. The dashed and dotted lines reflect urban and rural VMT. We see that most of the increase in VMT comes from the urban portion of the network. This partly reflects the increasing share of urban highways in the Interstate network.

In addition to tracking usage, the HPMS measures the extent and condition of the Interstate Highway System. Panel C of figure 3.1 reports lane miles of Interstate Highways in operation by year from 1980 until 2007.

2. HPMS data are not available for 2009 and are available for only a subset of states in 2008. HPMS data are also available from 2010 until 2016. However, a change in the format of the data in 2010 makes it difficult to compare post-2010 data with data from earlier years.

3. We note that the Interstate is becoming "more urban" over time as urbanized areas expand to include more of the network. Thus, the urban and rural AADT series in figure 3.1 do not reflect constant samples of roads.

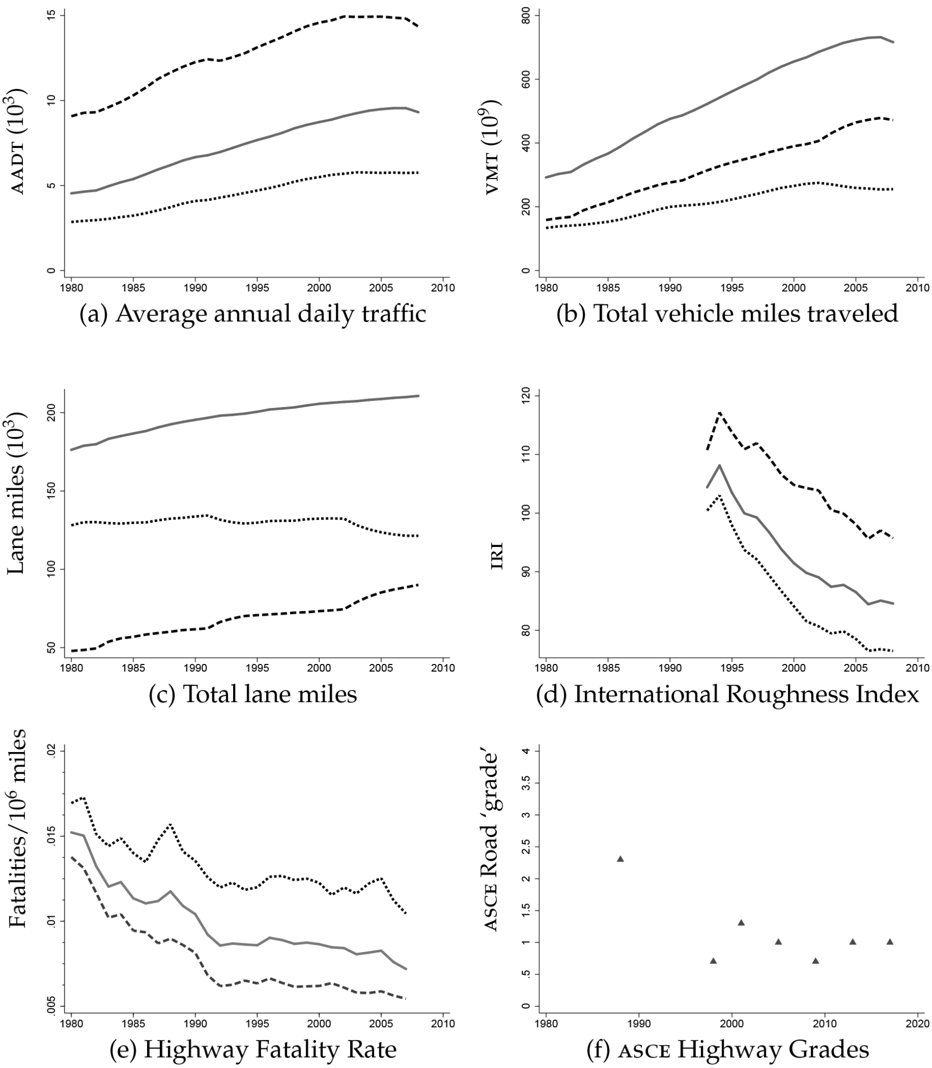


Fig. 3.1 Interstate Highways: Usage, stock, and condition

Note: Panels A–E are based on HPMS data. In A–E the solid line describes the national total, the dashed line describes the urban portion of the Interstate, and the dotted line describes the rural portion. A. AADT is lane-mile weighted. B. Total vehicle miles traveled on Interstate Highways. C. Total lane miles. D. Lane-mile-weighted international roughness index. E. Annual Interstate fatalities per million of VMT. F. American Society of Civil Engineers grades for US road infrastructure by year.

We see that lane miles increased from about 175,000 to about 210,000 over this period, an increase of about 20 percent, or 0.7 percent annually over 27 years. The preponderance of this increase reflects the widening of existing segments, not the construction of new mileage. The dashed and dotted lines in this figure describe urban and rural lane miles. We see that urban lane miles have increased, while rural lane miles are about constant. This partly reflects the reclassification of rural segments to urban.

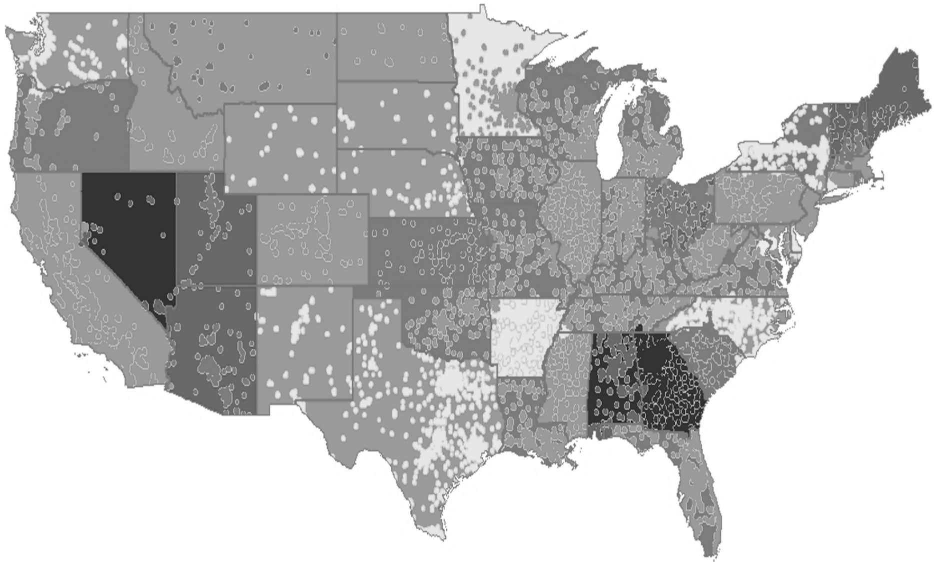
Finally, the HPMS tracks the condition of the Interstate Highway System. To do so, the HPMS relies on annual measurements of the international roughness index (IRI). IRI measures the number of inches of suspension travel a typical car would experience in traveling a particular mile of roadway. As part of HPMS, state highway authorities measure IRI on every segment of the Interstate Highway System, more or less, every year.[4] Figure 3.1 reports lane-mile-weighted IRI for the Interstate Highway System from 1992 until 2007. The units of IRI are inches per mile, so a decline in IRI reflects an improvement in pavement quality.[5] The dashed and solid lines report IRI on urban and rural portions of the Interstate. Rural highways are in better condition than urban highways. Both rural and urban highways exhibit the same trend in condition. Both improve dramatically over our study period.

For reference, the Federal Highway Administration considers roads to be in *good* or *acceptable* condition when their IRI value is below 95 or between 95 and 170. Roads with IRI above 170 inches per mile are in *poor* condition (US Department of Transportation 2013). Panel D of figure 3.1 shows a decline in mean IRI from just under 110 inches per mile in 1992 to about 85 inches per mile in 2007—that is, from a little above the "good condition" threshold to a little below. The improvement in the condition of Interstate Highways has been almost monotonic. The only exception occurs between 1992 and 1993, when mean IRI increased slightly. As this was the first year when IRI reporting was required, we suspect that this increase reflects problems with initial reporting of IRI rather than actual deterioration of the network.

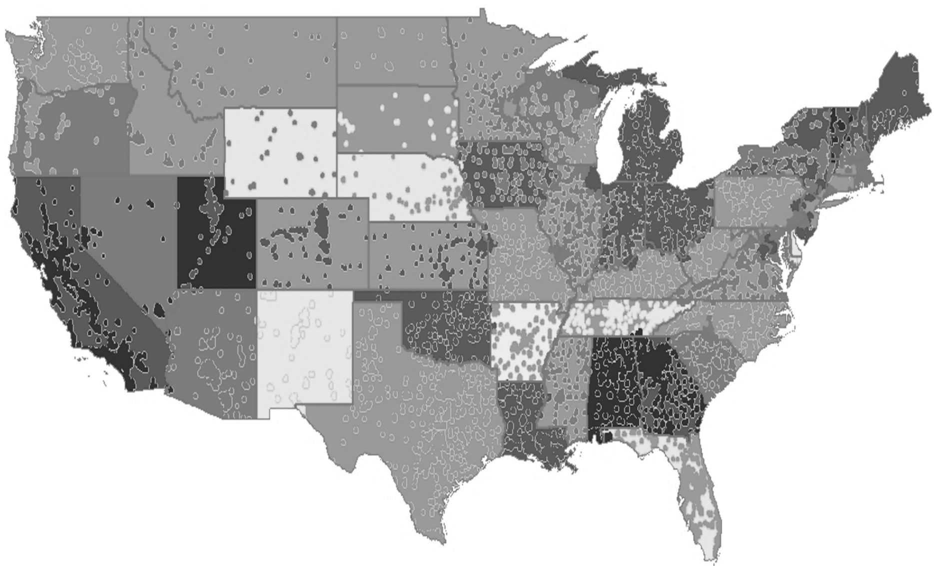
The two panels of figure 3.2 provide more detail about how IRI varies across the country. To make these figures, we divide each state into its rural and urbanized portions, adding the entirely urban District of Columbia, to get to 97 regions. We next construct mean IRI for the rural and urban portions of the Interstate in each state over the years 1993, 1994, and 1995. The range of these state-by-region IRI means is 37 to 175 inches per mile. We partition this range into six bins of equal width, 23 inches. Recalling that low values of IRI are good, in panel A of figure 3.2, we assign each bin a color ranging from light gray for the lowest and best bin to black for the

4. For more detail on the measurement and reporting of IRI, see Federal Highway Administration (2016) and Office of Highway Policy Information (2016).

5. HPMS has required IRI reporting for the universe of Interstate segments only from 1992 onward, so this measure begins later than those reported in other panels of figure 3.1.



(a) International roughness index, 1993-5



(b) Change in international roughness index, 1993-5 to 2005-7

Fig. 3.2 Urban and rural international roughness index (IRI) in 1993–1995 and changes in IRI from 1993–1995 to 2005–2007

Note: Panel A shows the state mean IRI for rural and urban Interstate Highways averaged over 1993–1995. Panel B shows the state mean change in IRI for rural and urban Interstate Highways from 1993–1995 to 2005–2007.

highest and worst bin. For legibility, we exaggerate the size of the urbanized areas in each state.

Recalling Federal Highway Administration quality definitions, the good/acceptable threshold occurs at 95 inches, in the dark gray (like Oregon in both years) regions, while the acceptable/poor threshold occurs at 170 inches, in the dark gray and black regions. Therefore, this figure, while it reveals considerable heterogeneity in road quality, overwhelmingly indicates that in the 1992–1995 period, the Interstate was in pretty good shape, at least as indicated by the Federal Highway Administration's standards. Indeed, only Nevada, Alabama, and Georgia have Interstate conditions anywhere near the acceptable/poor threshold, and in Alabama and Georgia, only the rural portions of the Interstate approach this threshold.

Panel B of figure 3.2 is similar but reports on changes in IRI between the initial three-year period, 1993–1995, and the final three-year period, 2005–2007. The range of within-region change in IRI over this period was −77 to 20 inches per mile. We divide this region into six bins, each 17 inches wide. Recalling that decreases in IRI are good, in panel B of figure 3.2, we assign each bin a color ranging from light gray, for the largest decrease, to black, for the largest increase.

Medium gray describes the bin ranging from −9 to 8 inches—that is, the bin where mean regional IRI stays about constant. We assign black to the bin containing all regions where mean Interstate IRI increased between 9 and 20 inches over our period of about 12 years. From the figure, we see that only a handful of regions of the country experienced even such modest deterioration of their highways: urban California, urban Nevada, rural Utah, Alabama, rural Georgia, and urban Vermont. Most of the rest of the country saw reductions in IRI. Alabama and Georgia are striking in that the initial conditions of their roads were relatively poor and their deterioration relatively rapid.

Returning our attention to figure 3.1, in panel E we report Interstate fatalities per million vehicle miles traveled.[6] Panel E presents fatalities per million miles on rural Interstates (dotted line), urban Interstates (dashed line), and overall (solid line). The rural Interstate system is dramatically more dangerous than the urban Interstate, and this gap grows slightly over time. While much of the reduction in fatalities is surely a reflection of improvements in cars, at a minimum, any deterioration in the safety of the Interstates has not been sufficient to outpace improvements in vehicle safety.

Panel F of figure 3.1 reports the American Society of Civil Engineers (ASCE) annual grades for US road infrastructure, converted from letter grades to a four-point scale: A = 4.0, B = 3.0, C = 2.0 and D = 1.0.[7] These

6. Interstate fatalities are reported in US Federal Highway Administration (2019), tables FI210 and FI220.

7. Downloaded from https://www.infrastructurereportcard.org/making-the-grade/report-card-history/, January 2020.

Table 3.2 US travel speeds by mode and year from the NHTS

Year	Car	Bus	Subway
1995	26.35	15.70	15.00
2001	25.30	13.68	11.85
2009	25.46	12.63	10.42
2017	23.54	11.08	10.59

Note: Speed of travel (miles per hour) on an average trip by mode as reported in various years of the NHTS (called Nationwide Personal Transportation Surveys, or NPTS, prior to 2001). Trip speeds reported in 1995 and 2017 are adjusted to minor changes in survey questions and distance measurement introduced in these years.

highly publicized grades are constructed about every four years, starting in 1988. While the precise methodology used to calculate each year's score is not available, the report that accompanies each year's grade describes the factors that are reflected in the score. For roads in 2015, these factors were capacity, condition, funding, future need, public safety, innovation, and resilience. The ASCE grade for roads reflects conditions on all public roads. So while figure 3.1 invites a comparison of the ASCE road grade with various time series describing the Interstate system, we note that this is not really a fair comparison.

With that said, the difference between the ACSE measure of road condition and the IRI series is striking. The ASCE time series shows roads that are at best maintaining their D grade. The IRI series, on the other hand, shows almost monotone improvements in smoothness. Clearly, the ASCE infrastructure grades are not strictly about the physical condition of the Interstate, and a poor ASCE grade should probably not suggest that the Interstate network is crumbling.

Finally, table 3.2 reports the average speed of travel on an average trip by car, bus, or subway for each of the years in which the National Household Transportation Survey (NHTS) is administered, 1995, 2001, 2009, and 2017. Looking down the second column, we see an almost monotone decrease in the speed of travel by car over the 1995–2017 period. Given the well-known inverse relationship between speed and flow, this decrease seems consistent with the dramatic increase in VMT that we see in figure 3.1, again with the caveat that figure 3.1 describes the Interstate, while table 3.2 describes trips on all roads.

We note that the different waves of the NHTS on which table 3.2 is based define speed slightly differently, complicating cross-year comparisons. In particular, the 1995 wave uses a slightly different wording to elicit information about travel time, while the 2017 wave measures travel distance using a different methodology. Given this difference in definitions, the numbers we report for these years are based on (slight) statistical adjustments of reports for 1995 and 2017. We note that these sorts of inconsistencies compromise the usefulness of the whole NHTS program. Given the expense of this program and recent advances in using smartphones to measure travel behavior (for example, Akbar et al. 2020; Kreindler 2018), this suggests that phasing out the NHTS in favor of smartphone-based travel monitoring and surveys deserves serious consideration.

To sum up, an average segment of the Interstate carries about twice the traffic in 2007 as it did in 1980. This increase in the intensity of use occurs in spite of an about 20 percent increase in the extent of the network over this period. The increases to network extent, together with increased AADT, mean that the Interstate Highway System provided well over twice as much travel in 2007 as in 1980. Unsurprisingly, this increase in intensity of use is matched by a decrease in the average speed of travel by car, although our NHTS-based measure of speed reflects all car travel, not just travel on the Interstate.

For reference, the US population increased from about 226 million in 1980 to about 309 million in 2010, an increase of about 37 percent or about 1.0 percent per year. Thus, the lane miles of Interstate Highways grew at just above two-thirds the rate for population (about 0.7 versus about 1.0 percent), while the number of vehicle miles provided by the network grew about three times as fast as population.

In spite of the increased intensity with which the network was used during this period, the mean quality of the network, as measured by IRI, improved consistently from 1992 until 2007. Similarly, the rate of traffic fatalities on the Interstate falls over our study period. These two measures of service stand in contrast to the time series of grades given to US road infrastructure by the ASCE. This series indicates constant or deteriorating quality over the same period, although the ASCE "road grades" are based on the whole road network, rather than just the Interstate. It is, however, clear that the ASCE road grades should not be regarded as a measure of the physical condition of the US Interstate system.

Rural portions of the Interstate Highway System are used less intensively than the urban portions, and rural segments are in better condition than their urban counterparts. Perhaps more surprisingly, the basic trends are the same for both portions of the network. Usage increases and condition improves at about the same rate for both parts of the network. Figure 3.2 maps initial IRI and changes over our study period and does not reveal obvious patterns. Interstates in the rust belt and California deteriorate. Interstates improve from a high base in most of the mountain states. Interstates in Alabama and Georgia are noteworthy for deteriorating from relatively poor initial conditions.

3.2.2 Bridges

The federal government also maintains the National Bridge Inventory (NBI). These data are similar to the HPMS and are intended to serve a similar function, but for the nation's bridges rather than its highways. The NBI is available from about 1990 through to 2017.

For the purposes of the NBI, a bridge is defined as

> a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening. (Federal Highway Administration 1995)

For each bridge satisfying this definition, the NBI records a basic description of the structure, its location, its condition, and how it is used. Thus, the NBI allows a similar analysis of bridges as does the HPMS for highways.

Figure 3.3 provides a summary description of the state of US bridges. Our expenditure data will describe expenditure on Interstate bridges alone, so each panel of figure 3.3 reports the evolution of all bridges (solid line) and the evolution of the stock of Interstate bridges (dashed line).[8]

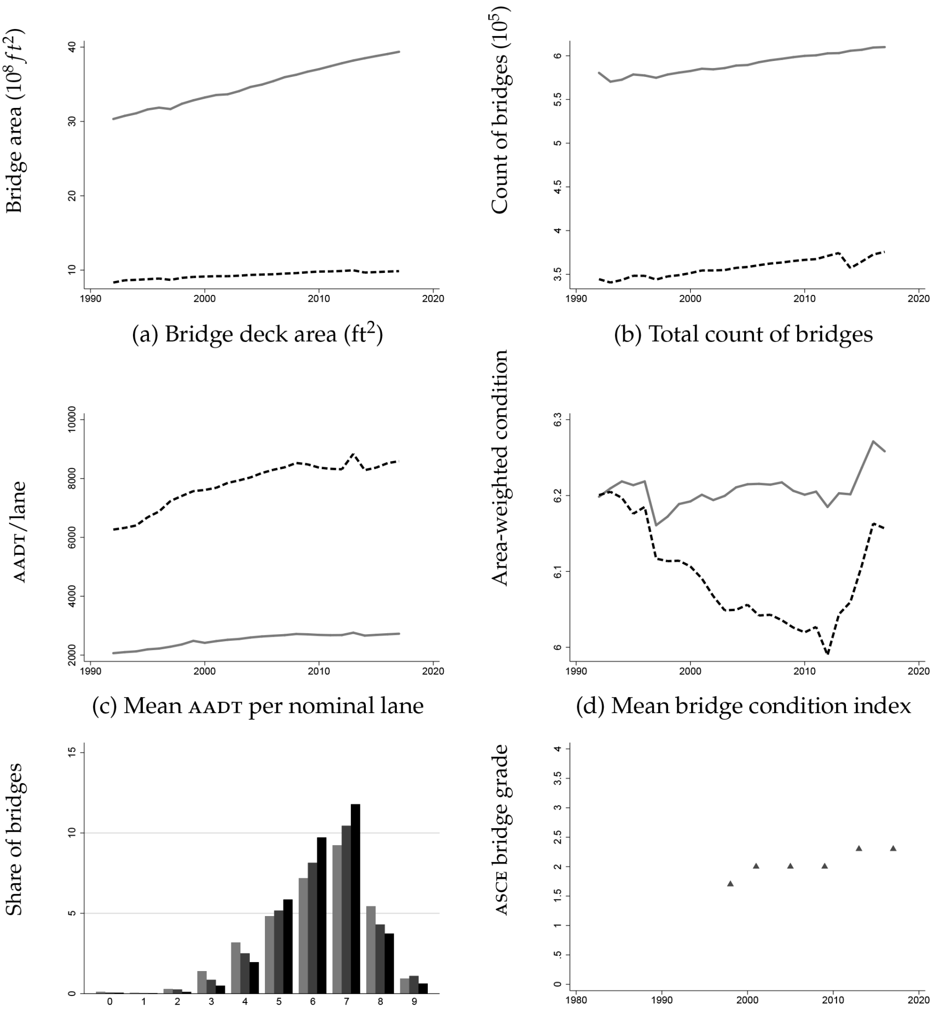
Panel A describes the stock of bridges. In order to weight large bridges more heavily than small bridges, we measure the stock of bridges by deck area (in square feet) rather than in the count of spans. In panel A, we see the deck area of US bridges increased from about three to about four billion square feet between 1990 and 2017, an increase of about 28 percent. Over the 27-year span of NBI data, this is an increase of about 0.9 percent per year. Thus, bridge area is growing modestly faster than Interstate lane miles and marginally slower than population. A caveat applies to these calculations: they are calculated over the slightly different time periods dictated by HPMS and NBI availability.

Panel B reports on the number of bridges over time. We see that the number of bridges in the NBI increased from about 570,000 to about 610,000. This is about a 7 percent increase, or an increase of about 0.25 percent per year over a 27-year period. This rate of growth is distinctly smaller than the rate of growth of lane miles of highways, which is itself less than the growth rate of population. Inspection of panel B shows that most new bridges were Interstate bridges.

The NBI does not report the number of lanes per bridge but does report the width of the bridge deck. We impute number of lanes per bridge by dividing by 12 feet, the width of a typical lane of Interstate Highway.[9] This done, we divide the reported value of AADT per bridge by imputed lanes, to arrive at an estimate of AADT per lane. This measure of AADT is comparable

8. The NBI identifies bridges as Interstate or not on the basis of their route signs. This will lead to a slight divergence from the HPMS, which reports on the legal status of the road.

9. See, for example, *Highway Statistics 2008*, table HM-33.



(a) Bridge deck area (ft^2)

(b) Total count of bridges

(c) Mean AADT per nominal lane

(d) Mean bridge condition index

(e) Distributions of bridge condition

(f) ASCE bridge grade

Fig. 3.3 Bridges: Usage, stock, and condition

Note: Panels A–E are based on NBI data. In A–D the dashed line describes the subset of interstate bridges while the solid line describes the universe of all bridges in the NBI. In panel D, bridges are weighted by deck area. Panel E shows a distribution of bridge condition in three years, 1992 (light), 2000 (medium), 2007 (dark). Panel F reports the ASCE bridge infrastructure grade by year.

to what we report in figure 3.1 for the Interstate Highway System, subject to the fact that bridge lanes are likely somewhat narrower than an average Interstate lane. Panel C of figure 3.3 reports the resulting measure of mean AADT. We see that AADT on an average lane of a bridge increases from about 2,000 to about 2,800, an increase of 40 percent or about 1.25 percent per year. This is rapid compared with the increase in the number of bridges, but this increase is also slightly more than the increase in bridge deck area. AADT on Interstate bridges is higher but grows at about the same rate.

Measuring the condition of a bridge is complicated, and the NBI reports on condition in some detail. In particular, for each of superstructure, decking, substructure, and channel, the NBI reports an ordinal measure of condition ranging from 0 to 9, with higher values indicating better repair.

To summarize these condition indexes, the NBI reports the minimum of the four as the "bridge condition index."[10] Panel D of figure 3.3 reports the deck-area-weighted mean bridge condition index. While this measure exhibits some variance, its range seems small, about 0.25 of a point or one quarter of a category on any of the component condition measures. More important, this index does not show a strong trend. The lighter dashed line shows the evolution of the condition of Interstate bridges. This index dips about 0.2 points between 1990 and 2010, before recovering to almost its initial level in 2017.

We experimented with variants of the condition index. We constructed an alternative condition index by summing each of the superstructure, deck, substructure, and channel condition measures, and we considered bridge-weighted (as opposed to deck-area-weighted) averages. Of these, only the bridge-weighted measure of the NBI index shows a downward trend; the others are either flat or increasing. In sum, "bridge condition" is difficult to describe. However, to the extent that the NBI allows us to measure bridge condition, the data do not indicate that the US stock of bridges is deteriorating but instead that maintenance is about offsetting deterioration.

Because bridge collapse is catastrophic, bridge condition codes indicating severe deterioration are of particular interest. These codes are: 0 for *failed condition*, out of service; 1 for *imminent failure condition*, bridge closed; 2 for *critical condition*, unless closely monitored closure may be required.[11] These three codes indicate a bridge that is badly deteriorated and in need of immediate repair, replacement, or closure. To track the prevalence of these badly deteriorated bridges, panel E of figure 3.3 reports histograms showing the share of bridges assigned each of the 10 possible bridge condition index values in 1992 (light gray), 2000 (medium gray), and 2007 (dark gray). These

10. See https://www.fhwa.dot.gov/bridge/britab.cfm#def for more detail on NBI bridge condition reporting.

11. More precise definitions for these codes and codes 3–9 are provided in US Federal Highway Administration (1995).

histograms show that the modal bridge condition is 7 (good condition) in all three years. Over time, the distribution of scores compresses as deteriorated bridges are improved and bridges in better condition deteriorate. The incidence of dangerous bridges is very low in all years and falling over time. Note that this figure describes all bridges in the National Bridge Inventory. This corresponds to the sample that generates the solid line of panel D of figure 3.3. Restricting attention to just Interstate bridges (not shown) leads to qualitatively similar conclusions: the modal bridge is in good condition, and the number of dangerous bridges has decreased over time.

Panel F of figure 3.3 reports the ASCE grades for US bridge infrastructure. These data are similar to those presented in figure 3.1 for highways and are the result of a similar process. Like the ASCE road condition index, the ASCE bridge grades are available about every four years, but the bridge grades start in 1998 rather than 1988. Thus, the ASCE bridge grades cover just about the same period as do the NBI data on bridge condition. Over the 1998–2017 period, the ASCE bridge condition improves from a C−, or 1.7 on our numerical scale, to a C+, or 2.3 on our scale.

Changes in the ASCE bridge index seem to match changes in the NBI bridge condition index more closely than the ASCE road grades match Interstate IRI. Neither fluctuates much over our study period. With that said, the ASCE seems to be grading bridges quite harshly. The modal bridge has an NBI index score of 7, or good, from 1992 to 2007, while the mean bridge has a score between 6 (satisfactory condition) and 7 throughout the period. Thus, as for the ASCE road condition grades, a poor ASCE bridge condition grade seems not to indicate pervasive disrepair, at least as measured by the National Bridge Inventory.

3.2.3 Transit

We now describe public transit service and capital stocks from about 1990 until 2017. This description is based on various data sets made available as part of the National Transit Database (NTD) available from the National Transit Administration. The unit of observation in these data is a transit district year. The number of transit districts covered by this database has increased over time, from 473 in 1992 to about 2,247 in 2017.

Public transit in the US consists of many different modes of travel, from jitney buses to cog railways to ferry boats, and the NTD is exhaustive. Table 3.3 reports on the numbers of riders, vehicles, service miles, and total expenditure by mode for 2017 and 2008 in the continental US. It aggregates the modes reported in the NTD somewhat. Our data on buses reflect three NTD modes: motor buses (mb), trolley buses (tb), and bus rapid transit (rb). Our data on light rail reflect two NTD modes, light rail (lr) and streetcar rail (sr). Subways report the NTD heavy rail (hr) data. Commuter rail is the NTD mode cr. Demand response aggregates both demand response buses

Table 3.3 Transit aggregate statistics by mode in 2008 and 2017 for the continental US

	Bus	Light rail	Subway	Commercial rail	Van pool	Demand response
2017						
Riders (10^6)	4,679.4	554.7	3,808.9	497.8	35.24	157.2
Vehicles	68,972	2,553	11,671	7,121	15,174	57487
Service miles (10^6)	1,972.7	124.0	681.4	347.0	229.5	1186.1
Passenger miles (10^6)	16,843.3	2,690.3	17,555.5	12,250.7	1,254.6	933.2
Expenditure (10^6)	25,272.2	5,521.2	13,480.8	9,029.7	189.5	5,083.2
# NTDs	1,148	40	14	25	107	1,894
2008						
Riders (10^6)	5,513.2	450.9	3,538.6	471.3	29.45	130.6
Vehicles	63,761.5	1,947	11,293	6,792	10,624	31,470
Service miles (10^6)	2,029.3	86.26	652.1	309.0	154.4	967.2
Passenger miles (10^6)	20,972.0	2,080.3	16,805.1	11,032.0	968.0	832.5
Expenditure (10^6)	21,396.4	4,344.4	12,107.9	6,919.8	137.3	3,168.4
# NTDs	500	28	14	22	59	466

Note: Riders and passenger and service miles are in millions. Expenditure is in millions of 2010 dollars and transit districts ("# NTDs") are counted only if they have a positive number of vehicles.

and taxis (dr and dt). By almost any measure, the preponderance of transit travel involves buses and subways. Given this, we focus our attention on these two modes of public transit.

The NTD classifies transit districts into two main categories: "full reporters" and "partial reporters." Transit districts are classified as partial reporters if they operate fewer than 30 vehicles during the year. About 20 percent of transit districts are partial reporters, and such districts are exempted from reporting certain data that is required of larger districts. In particular, partial reporters are not required to report "total passenger miles traveled," a quantity that we report on later.

Table 3.4 describes the way that public transit is distributed across transit districts on the basis of 2014–2017 averages of ridership and expenditure. Column 1 of the table reports the national percentage of transit riders across all modes for the six transit districts with the greatest ridership. New York accounts for about 40 percent of all transit rides in the entire country. Chicago is second, with 6 percent, followed by DC, Los Angeles, Boston, and Philadelphia. In total, these six districts account for about 60 percent of all transit rides in the country. Public transit usage is highly concentrated in a few large cities, particularly New York.

The rest of table 3.4 provides disaggregated information about bus and subway ridership and expenditure for these six transit cities and for the country as a whole. The concentration of transit into a small number of cities primarily reflects the dominance of the New York subway network. The

Table 3.4 Buses and subways in five biggest transit districts: Means 2014–2017

	All modes	Bus				Subway			
	% riders	Riders	%	Expenditures	% total expenditures	Riders	%	Expenditures	% total expenditures
New York	40.3	722.9	15.4	2,765.7	10.9	2,699.5	70.9	7,098.4	49.8
Chicago	5.6	249.2	5.3	836.3	3.3	230.2	6.0	884.9	6.2
DC	4.1	123.1	2.6	715.0	2.8	227.1	6.0	1,390.9	9.7
Los Angeles	4.0	290.0	6.2	1,254.0	4.9	45.6	1.2	792.3	5.6
Boston	3.3	118.9	2.5	527.0	2.1	164.1	4.3	499.5	3.5
Philadelphia	3.1	169.4	3.6	697.7	2.7	93.9	2.5	308.4	2.2
Total	100.0	4,679.4	100.0	25,412.0	100.0	3,808.9	100.0	14,266.7	100.0

Note: All counts of riders are given in millions per year. Expenditures are total capital and operating expenditures in millions of 2010 dollars. Second column gives total riders summed over all modes. The next four columns describe buses. The last four columns describe subways. Percentages describe the percentage of national totals in a city.

New York subway system carries about 71 percent of all subway riders and about 31 percent of all public transit riders in the entire country.

The remaining five of the top six transit districts account for another 20 percent of all subway riders, with the residual 9 percent distributed across eight smaller subway systems. Even excluding New York, subway ridership is still concentrated in a small number of places.

Unlike subway ridership, bus ridership is widely distributed. New York is also the biggest provider of bus trips but provides only 15 percent of the national total. The top six transit cities provide only about 36 percent of all bus trips.

Expenditure on buses and subways approximately tracks ridership, and, in particular, the share of total expenditure is closely related to share of ridership. A few points about expenditure are noteworthy. First, the New York subway system provides 70 percent of all subway rides but accounts for only about 50 percent of expenditure. This suggests that this system is relatively efficient. A caveat applies. Our data on expenditure reflect current capital and operating expenses. To the extent that subway systems are depreciating or augmenting their capital stocks, this is not reflected in our expenditure measures. Second, comparing bus and subway expenditure shares with ridership shares suggests that these large transit districts are providing public transit at a lower cost than smaller districts.

3.2.3.1 Buses

Panel A of figure 3.4 reports the total number of rides provided by the US bus fleet by year. The solid line gives national totals, the dashed line gives the annual total for the six transit districts listed in table 3.4, and the dotted line gives totals for the remaining smaller transit districts.

Total bus ridership ranges between about 4.5 billion and 5.5 billion but shows no clear trend. Both the large and small transit districts follow about the same path. Bus ridership is higher in the years following the 2008 financial crisis and lower otherwise. To put this number in perspective, with about 300 million people in the US, 5 billion rides per year implies about 17 bus trips per person per year. In contrast, by 2007, the Interstate Highway System was providing about 700 billion VMT per year, or about 2,300 miles per person per year.[12] Panel B of figure 3.4 reports total passenger miles traveled by bus. This figure tracks ridership closely but exhibits higher variance. Service miles increase and then decrease by about 50 percent over our study period, while ridership increases and then decreases by only about 20 percent. Both the large and small transit districts follow about the same path,

12. Note that we here report vehicle miles traveled. On average, each car in the US carries about 1.25 people (Couture, Duranton, and Turner 2018), so the figure for person miles traveled is about 25 percent larger.

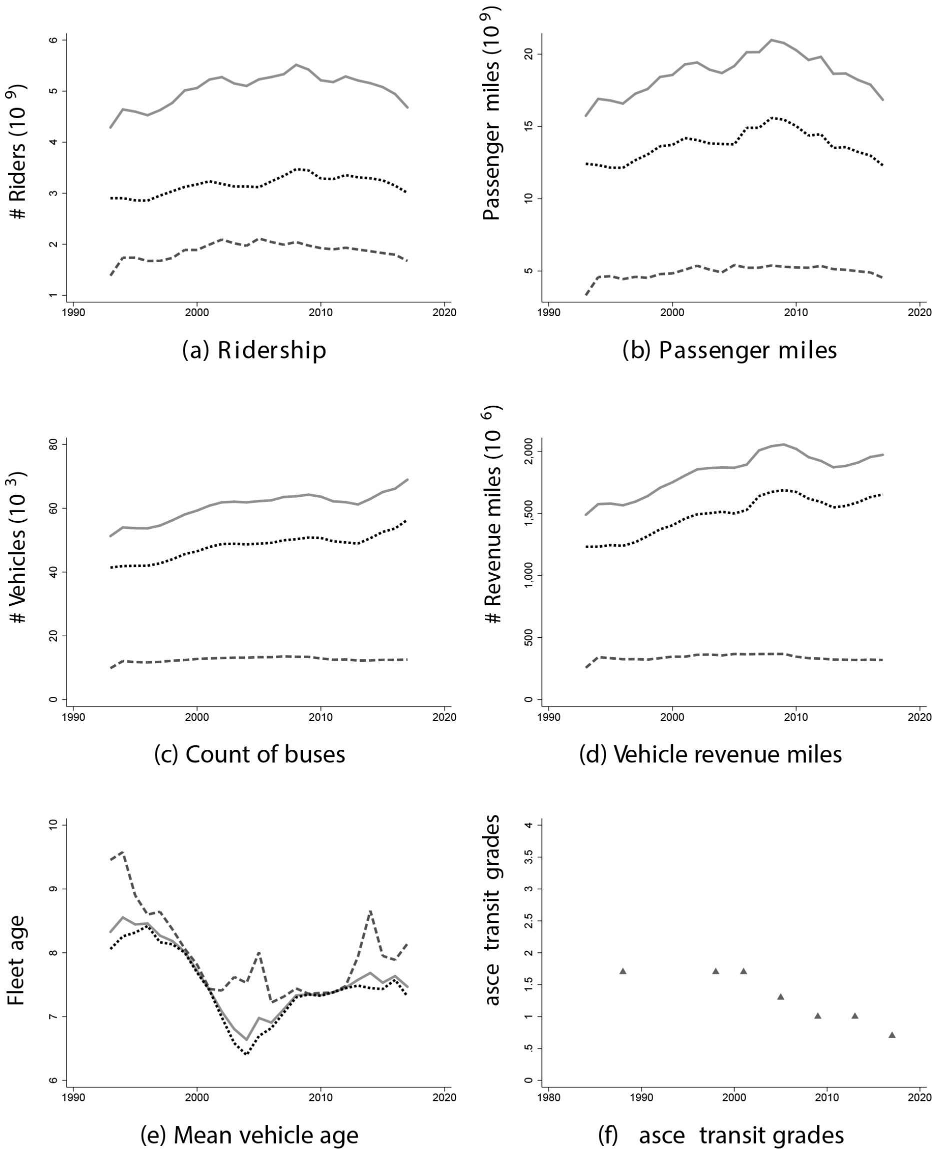


Fig. 3.4 Buses: Usage, stock, and age of the fleet

Note: Panels A–E are from the National Transit Database. In panel B, passenger miles traveled on buses are only for "full reporter" transit districts. In panels A–E, the solid line gives national totals, the dashed line gives the total for the six transit districts listed in table 3.4, and the dotted line gives totals for the remaining transit districts.

although more of the national variation in passenger miles comes from small transit districts.

Panel C of figure 3.4 reports the number of buses in service. Unlike ridership and passenger miles, the stock of buses increased monotonically over the study period, from about 50,000 in 1992 to about 68,000 in 2017, an increase of 36 percent, or about 1.4 percent per year. The count of buses in large districts is almost perfectly constant over this period, so that the increase in buses is primarily in small transit districts. Panel D reports total revenue miles for the bus fleet for each year. Like the count of buses, revenue miles increase fairly steadily, from about 1.5 to 2.0 billion, an increase of about 33 percent. This is an increase of about 1.2 percent per year, marginally less fast than the growth rate of the stock of buses. The divergence between large and small districts is even sharper for vehicle revenue miles than for vehicles. Revenue miles are about constant in large districts but increase dramatically in small districts.

Panel E of figure 3.4 reports on mean fleet age by year. We see that mean fleet age ranges between about 6.5 and 8.5 years, decreasing from about 8.5 to about 7.5 years over the period 1992–2017. The ages of vehicles in large and small districts track each other closely, although bigger districts generally have slightly older buses.

Table 3.2 reports the speed in miles per hour of an average trip on a public transit bus (excluding school buses) in years from 1995 to 2017. Like the corresponding speeds for car trips, these speeds are based on survey responses reported in different waves of the NHTS. Looking down this column, we see a dramatic decrease in the speed of an average bus trip over this period, from about 15 miles per hour to about 11 miles per hour. This is an even more dramatic decrease than we observe for the speed of trips by car. While one can imagine that this decrease reflects change in the composition of bus trips, toward more congested places, it seem likely that the decline at least partly reflects a decline in the speed of bus travel when routes are held constant and that this decline largely reflects the dramatic increases in AADT that we note in figure 3.1.

For reference, panel F of figure 3.4 reports the ASCE transit infrastructure grades. Like the ASCE road and bridge grades reported earlier, these scores are reported as letter grades that we convert to a four-point scale. Panel F shows a clear decline over the 1988 to 2017 period for which these scores are available, from a C– in 1988 to a D– in 2017. Comparing these scores to bus age seems problematic, both because bus age is clearly a partial measure of the state of bus infrastructure and also because the ASCE index aggregates information about all transit, not just buses. With that said, and recalling from table 3.3 that buses are the most important public transit mode, it is noteworthy that the ASCE transit index should show so clear a negative trend over a period when the count of buses is increasing monotonically and the mean fleet age is decreasing. Given this dramatic divergence, we probably should not regard the ASCE index as providing much information about the level or condition of bus-based public transit.

Unlike highways and bridges, aggregate bus usage is not increasing rapidly. Also unlike highways and bridges, the growth of the stock of buses is much more rapid than ridership. Like highways and bridges, the stock of buses, at least as measured by age, is not deteriorating over time. To the contrary, like highways, the condition of the US bus fleet seems to be improving. New bus capacity is dispersed among smaller transit districts. The stock of buses in the largest districts is about constant.

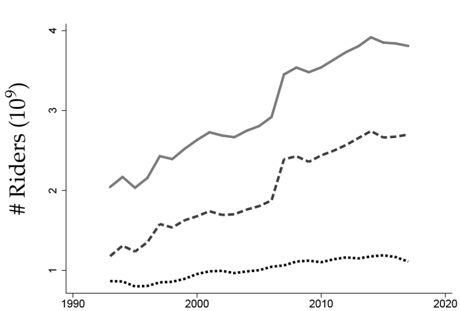
It is worth contrasting the relatively recent US experience with bus travel with that from 1935–1963. Meyer, Kain, and Wohl (1965) document that the number of riders carried by US motor buses peaked in 1945 at about 9.8 billion and began to fall in the postwar years, to 6.4 billion in 1960 and further to 5.8 billion in 1963, when the authors' data end. For comparison, in table 3.3 we see that bus ridership was about 5.5 billion in 2008 and 4.7 billion by 2017; US population in 1945, 1960, and 2008 was about 131 million, 151 million, and 304 million, respectively. Bus riding was a much more important part of American life during the postwar years than it is now. In part, this decline is attributable to the rising motorization of the poor (Blumenberg, Manville, and Taylor 2019).

3.2.3.2 Subways

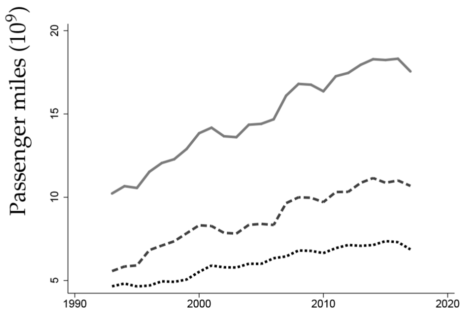
Figure 3.5 replicates figure 3.4 for subways. Panel A of figure 3.5 reports billions of riders. Between 1992 and 2017, ridership increased from about 2 billion to about 4 billion. This is an increase of about 100 percent, or about 2.8 percent per year. Panel B reports increases in passenger miles served by subways. This figure increases from about 10 billion to about 16 billion miles per year, an increase of about 60 percent. That this increase is smaller than the increase in riders indicates that the mean length of a subway trip declined over the study period. At about 2.8 percent per year, the growth rate in subway ridership is close to the 3.2 percent growth rate of VMT on the Interstate Highway System and significantly larger than the 1.2 percent growth rate of population.

Given the importance of the New York subway system, figure 3.5 reports separately on the New York subway, the dashed line, and all other subways, the dotted line. Panel A of figure 3.5 shows that almost all of the national increase in subway ridership over our study period reflects increases in ridership on the New York subway.

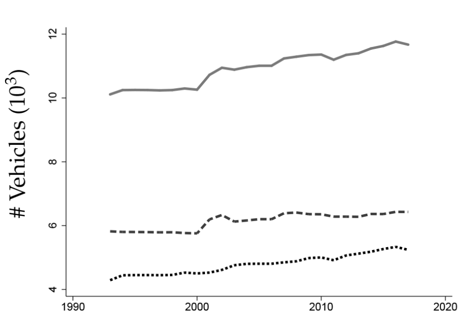
Panel C of figure 3.5 reports the stock of subway cars by year. We see that the number of subway cars in operation increased from about 10,000 in 1992 to about 11,500 by 2017. This is a 15 percent increase, or 0.6 percent per year. This is half the rate of national population growth and less than one-third the rate of ridership growth. Panel D reports aggregate revenue miles by year. Revenue miles increased from about 500 million to about



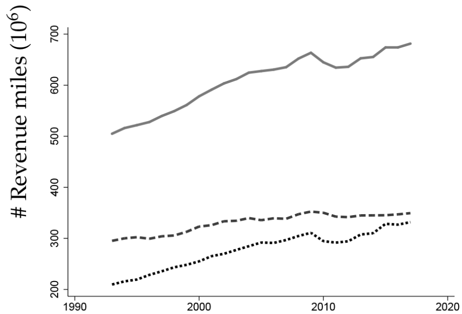
(a) Ridership



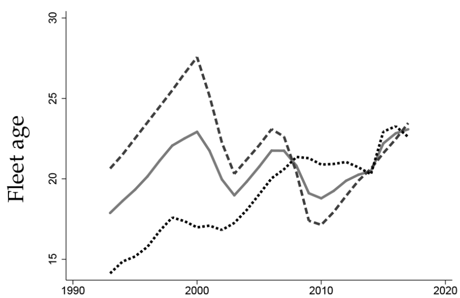
(b) Passenger miles



(c) Count of subway cars



(d) Vehicle revenue miles



(e) Mean age of subway car fleet

Fig. 3.5 Subways: Usage, stock, and age of the fleet

Note: All data from the National Transit Database. In all panels, the solid line gives national totals, the dashed line gives the total for the New York subway system, and the dotted line gives totals for the remaining transit districts.

700 million, an increase of about 40 percent. This is also much smaller than the increase in ridership. Since the number of subway cars increased by about 15 percent, this means that an average car is traveling farther. In all, over this period, the supply of cars and service miles increased much more slowly than did ridership. Smaller systems account for a much larger share of the increase in passenger miles than of ridership. This suggests that the New York subway is providing many more short trips, while the smaller systems are providing a small number of new trips, but trip length is increasing. As for trips by car and bus, we see in table 3.2 that the average speed of travel by subway is declining over our sample period.

Meyer, Kain, and Wohl (1965) report on subway ridership during the period between 1935 and 1963. Curiously, subway ridership was fairly stable throughout this period, at about two billion riders per year. Comparing their report to panel A of figure 3.5, we see that this is dramatically lower than current levels. While bus transit is failing to attract riders, we seem to be living in a golden age of subway ridership.

Panel E of figure 3.5 shows the mean age of the fleet of subway cars. We see that the mean age of the subway car fleet varies within about a four-year band, from 18 to 22 years, but without a clear trend. Investment seems to be approximately matching depreciation, although the fleet is quite old. Subway cars in smaller districts are clearly aging, while the mean age of the New York fleet is volatile but seems to be trending down slightly.

From panel F of figure 3.4 we see that the ASCE transit grades declined from a C– to a D– over the period 1988–2017. Again, this grade reflects all US transit infrastructure, not just subways. The monotone decline in the ASCE index is not matched by a corresponding increase in the age of subway cars. With this said, we regard our information about the condition of the subway capital stock to be quite incomplete, so this comparison should be regarded with some skepticism.

The NTD does not report information about subway track in a systematic way, and so we are not able to report on what is surely a far more important measure of physical capital. Anecdotal evidence suggests that, in fact, subway systems have been allowed to depreciate dramatically.[13] A more detailed examination of subway capital stocks remains an important topic for further research.

3.3 Expenditure and Cost of Services for Highways, Bridges, and Public Transit

We have so far described the level, condition, and usage of four of the primary stocks of physical capital involved in the transportation of people

13. For example, "How Politics and Bad Decisions Starved New York's Subways," *New York Times Magazine*, November 18, 2017.

and, for highways and bridges, goods. We now turn attention to the cost of these capital stocks.

Ideally, a measure of the "cost of infrastructure" would reflect capital costs, depreciation, and maybe externalities, probably on a per-trip basis. We are not able to provide such a calculation but can take some steps in this direction. In particular, for each of the infrastructure stocks described, we are able to measure total annual expenditure and to estimate the unit cost of service by year. Our measures are an improvement on what is currently available and reveal interesting trends. However, some distance remains between our estimates and the ideal.

3.3.1 Highways

Two recent papers describe the evolution of expenditure on the Interstate Highway System and of the cost to build this system, Brooks and Liscow (2019) and Mehrotra, Uribe, and Turner (2020). Before we discuss their findings, it makes sense to be explicit about what, exactly, they are describing.

As we saw in table 3.1, the Interstate Highway System serves a high fraction of VMT relative to its share in total US lane miles. However, about three-fourths of all vehicle miles driven in the US are not on the Interstate Highway System. We would like to consider the Interstate Highway System's share of the US road budget in light of this fact.

Total expenditure on roads and highways by all levels of government stood at $181.4 billion in 2008.[14] Of this total, the Interstate Highway System received $22.5 billion, including $20 billion for capital expenditure and $2.5 billion for maintenance.[15] The Interstate Highway System accounts for about 12.5 percent of all government expenditure on roads. Comparing with table 3.1, this is larger than the Interstate Highway System's share of lane miles and not far off from its share of all VMT.

Brooks and Liscow (2019) estimate the cost of building a mile of Interstate Highway in every year from 1956 through 1993. To do so, they rely on "PR511 data" to document the construction of Interstate mileage by state and year. These data, which also formed the basis for Baum-Snow (2007), were collected as part of the procurement of the Interstate Highway System. Brooks and Liscow match state-year level construction data to the state-year level expenditure data reported in the highway statistics series (for example, US Federal Highway Administration 1985), which are available from about 1956 through to the present.

Panel A of figure 3.6 reproduces figure 2 from Brooks and Liscow (2019). The figure shows the ratio of total expenditure on the Interstate Highway System to total miles constructed in five-year bins from 1960 to 1995. The

14. *Highway Statistics 2008*, table HF-2.

15. The larger Federal-Aid Highway System received $68.8 billion, including $59.2 billion for capital expenditure and $9.6 billion for maintenance (*Highway Statistics 2008*, table HF-12b).

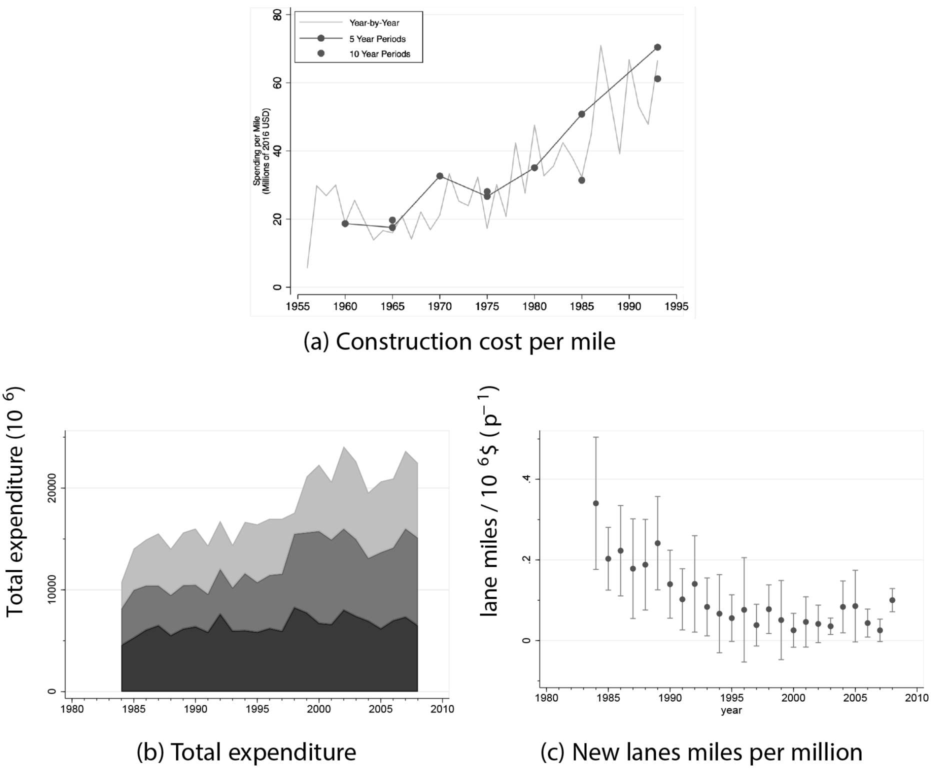


Fig. 3.6 Total expenditure and construction cost per lane mile of Interstate Highway over time

Note: A. Mean expenditure per mile of new Interstate Highway between 1960 and 1995. B. Total expenditure on the Interstate Highway System by year in three categories; construction, resurfacing, and maintenance. The height of each band gives expenditure in the category, and the upper envelope gives aggregate expenditure. C. Estimate lane miles of new construction per million dollars of expenditure over time. Panel A is reproduced from Brooks and Liscow (2019); panels B and C are from Mehrotra, Uribe, and Turner (2020).

figure shows a dramatic increase, from about $20 million (2016) per mile, to about $70 million per mile. This is about a 250 percent increase in real terms, or about 7 percent per year. Brooks and Liscow (2019) show that this increase probably reflects neither increases in input and labor costs nor changes in the location or terrain where highways were built.

Mehrotra, Uribe, and Turner (2020) also estimate the cost of Interstate Highway System but rely on the HPMS to measure changes in state-year level lane miles of the Interstate Highway System. As described earlier, the HPMS runs from 1980 through 2007, and so the study period in Mehrotra, Uribe, and Turner (2020) is more recent and shorter than that of Brooks and Liscow (2019). Like Brooks and Liscow (2019), Mehrotra, Uribe, and

Turner (2020) rely on highway statistics data for state-year level expenditure data. However, starting in 1984, highway statistics began to disaggregate state-year expenditure into construction, resurfacing, and maintenance. To exploit these more disaggregated expenditure data, Mehrotra, Uribe, and Turner (2020) begin their analysis in 1984, a few years after the beginning of the HPMS.

Panel B of figure 3.6 reports total expenditure on the Interstate Highway System over time in three categories: construction, resurfacing, and maintenance. The dark band on the bottom of the graph reports construction expenditure. This amount varies between about \$5 billion and \$7 billion (2010) per year and trends up only slightly over the study period. The intermediate band of the figure reports resurfacing expenditure. This varies between about \$3 billion and \$10 billion and trends up over the period. Unsurprisingly, as the system ages, resurfacing is progressively more important. The dark band at the top of the figure reflects other expenditure, for instance, snow removal, signage, and minor maintenance.[16] This amount trends up from about \$3 billion to about \$7 billion over the course of the study period. The upper envelope of the three bands gives total expenditure, and we see that this has trended up, from about \$10 billion per year to about \$21 billion per year.

Panel C of figure 3.6 is also reproduced from Mehrotra, Uribe, and Turner (2020). Like panel A, panel C describes the cost to construct the Interstate; however, it differs in three ways. First, it is inverted. It reports miles per million dollars instead of millions of dollars per mile. Second, it covers the period from 1984 to 2007. Third, it reports millions of dollars *per lane mile* rather than *per mile* of highway. Examining panel C, we see that in 1984–1990, \$1 million of expenditure purchased about 0.2 lane miles. This fell to about 0.05 lane miles per million dollars in 2002–2007. Thus, the dramatic increase in construction costs documented by Brooks and Liscow (2019) continued at least through 2007.

One of the advantages of the HPMS is that it also tracks when Interstate Highways are resurfaced. Thus, Mehrotra, Uribe, and Turner (2020) are also able to track changes in the cost of resurfacing the Interstate Highway System. As for new construction, they find that resurfacing costs increase dramatically, although less fast than new construction.

It is well established in the engineering and economics literature that most of the damage to the Interstate is done by trucks, not cars. For the purpose of pavement engineering, the standard measure of usage is an "Equivalent Single Axel Load" (ESAL) of 18,000 pounds. This is about the equivalent of a single heavily loaded five-axel combination truck—in other words,

16. Because bridge expenditure does not affect system length or condition, we also include expenditure on bridges as "maintenance" in this figure. We analyze bridge expenditure separately.

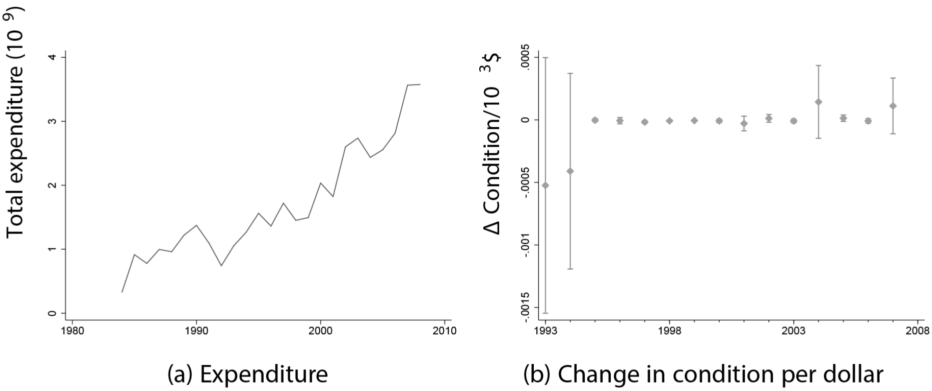


Fig. 3.7 Expenditure and mean change in condition per dollar over time

Note: A. Billions of total expenditure by state and federal governments by year on all Interstate bridges, from *Highway Statistics* table SF12a. B. Mean change in condition per one thousand dollars spent by year, weighted by bridge deck area.

a typical tractor trailer rig (see, for example, Small, Winston, and Evans 2012; or Mannering, Kilareski, and Washburn 2007). A little more specifically, the damage done to a pavement surface increases approximately quadratically in axel weight (Small, Winston, and Evans 2012). On the basis of calculations available in Mannering, Kilareski, and Washburn (2007), and recalling that a single lane of Interstate Highway can carry about 2,200 cars per hour, a single combination truck causes about as much damage to a highway as about 2.1 commute hours of automobile traffic.[17]

This finding has two implications. First, as pointed out by Small, Winston, and Evans (2012), if user fees are to target the vehicles that cause damage to the roads, they must target trucks—in particular, trucks carrying heavy loads on a small number of axels. The HPMS reports crude measures of truck traffic such as mean truck AADT per hour. Given how sensitive pavement damage is to axel weight, data recording more detail about the portfolio of loadings carried by a highway segment is likely to be of considerable value to administrators, engineers, and social scientists alike.

3.3.2 Bridges

Panel A of figure 3.7 reports annual aggregate maintenance expenditure on Interstate bridges from highway statistics.[18] Total expenditure on Inter-

17. See Mannering, Kilareski, and Washburn (2007), example 4.1. A 2,000-pound car is about 0.0002 ESALs, while a typical combination truck is about 0.93 ESALs. The ratio of these two is about 4,600.

18. To be clear, expenditure on Interstate bridges is reported in highway statistics as part of capital expenditure in highway statistics. We here treat it separately. Since expenditure on bridges can have at most a trivial effect on the length or smoothness of Interstate Highways,

state bridges increased from about $1 billion to about $3.5 billion between 1984 and 2008. This is about a 9 percent rate of increase. Since the number of Interstate bridges increased only slightly from a base of about 350,000 over this period, this means that expenditure on an average Interstate bridge increased from about $2.8 million to $8.4 million per year over this period. Thus, the approximately constant mean bridge condition that we see in panel C of figure 3.3 reflects a dramatic increase in expenditure.

We can exploit state-year variation in the relationship between bridge maintenance and expenditure to estimate the cost of improving a state's bridge condition index over time. To accomplish this, let t denote years, s denote states, and $\Delta_{st}\text{BCI}$ denote changes in the state mean bridge condition index between $t - 1$ and t. Finally, let y_{st} be state-year maintenance expenditure and $1_{st}(\tau = t)$ an indicator that takes the value one if $\tau = t$ and zero otherwise.

With this notation in place, we can estimate the following regression:

$$\frac{\Delta_{st}\text{BCI}}{y_{st}} = \sum_{\tau=1994}^{2016} \beta_\tau 1_{st}(\tau = t) + \varepsilon_{st}. \tag{1}$$

Panel B of figure 3.7 plots the resulting β_t values together with 95 percent confidence intervals. These estimates reflect the change in state mean bridge condition index resulting from $1,000 of expenditure. This figure is essentially flat, though a few years are estimated very imprecisely. Experimenting with different variants of the bridge condition index or with expenditure per square foot of bridge area leads to similar results.

This outcome is puzzling—the more so when we compare panel A of figure 3.7 to panel D of figure 3.3. Noting the differences in the range of the x-axis in the two figures, this comparison indicates that condition declined as expenditure increased by a factor of three. Thus, not only does panel B of figure 3.7 indicate that expenditure on bridge maintenance and construction has no measurable effect on mean bridge condition, it shows this result when the aggregate relationship is negative. We suspect that the estimated zero relationship between the bridge condition index and expenditure in panel B of figure 3.7 reflects the nature of the index construction. Expenditure that improves any aspect of a bridge other than the worst has no impact on the index. Given this fact, we expect the bridge condition to reflect maintenance expenditure very poorly. This is just what we see in panel B of figure 3.7. This outcome highlights the interest of using the more homogenous Interstate system as a laboratory in which to investigate changes in construction and maintenance costs, as in Brooks and Liscow (2019) and Mehrotra, Uribe, and Turner (2020).

in our discussion of the Interstate Highway System, we counted bridge expenditure as part of maintenance.

3.3.3 Public Transit

Like the NBI, the NTD reports information about the costs of providing public transit. In particular, the NTD reports operating and capital costs by transit district, year, and mode. Capital costs reflect capital expenditures on rolling stock, passenger stations, track, facilities, and administration.

Public transit in the US operates under two primary institutional arrangements. In one, the transit district owns and operates vehicles. In the other, the transit district contracts with a private firm to operate vehicles. Accounting for capital and operating costs in the second case is complicated, and the rules for this accounting changed in 1992, 1996, and 1997.

This caveat in place, the NTD permits us to calculate total expenditure by mode and year and to estimate total cost per rider by year and mode.

3.3.3.1 Buses

The solid line in panel A of figure 3.8 reports total expenditure on motor bus service in the US by year from 1992 until 2017. Total expenditure on buses increases from about \$15 billion to about \$26 billion over this period. This is an increase of 73 percent, or about 2.8 percent per year. The dashed line in this figure describes total expenditure on buses in the largest six transit cities, while the dotted line describes total expenditure in the smaller districts. Both series are trending up, although expenditure is rising somewhat more rapidly in smaller districts than in large districts.

US expenditure on buses, \$26 billion, is enormous: it is more than public expenditure on the Interstate Highway System. In exchange for this expenditure, motor buses provided about 20 billion passenger miles, versus 700 billion vehicle miles traveled on the Interstate Highway System. Obviously, this is not an entirely fair comparison. Interstate VMT also reflects considerable private expenditure that is not reflected in our expenditure data. We consider this issue in section 3.5.

To investigate trends in the cost of bus-based transit over time, we estimate a regression similar to the one we conducted for bridges (equation [1]). More specifically, we estimate the following regression separately for the six large transit districts and the remaining smaller districts:

$$\frac{c_{ist}}{y_{ist}} = \sum_{\tau=1992}^{2017} \beta_\tau 1_{ist}(\tau = t) + \varepsilon_{ist}. \quad (2)$$

Here, i, s, t index transit districts, states, and years; c denotes total expenditure on buses; and y indicates a measure of output, here riders. Thus, this is a regression of district year level expenditure per trip on year indicators. The magnitudes of the βs indicate transit-district-weighted annual means of total expenditure per rider.

Panel B of figure 3.8 reports these fixed effects, along with confidence

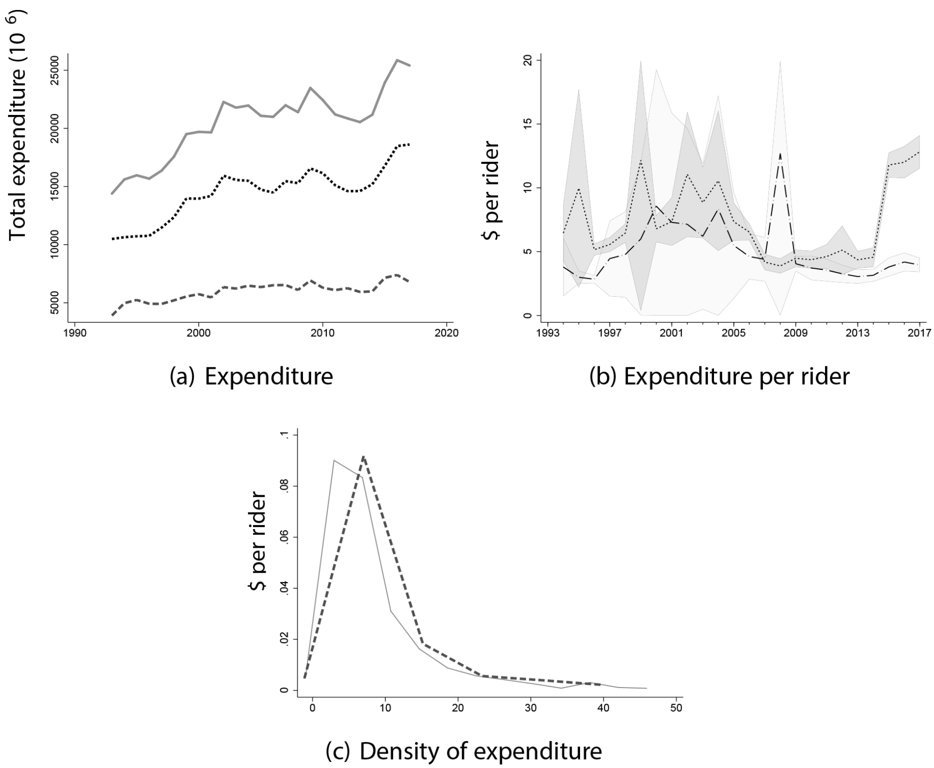


Fig. 3.8 Total expenditure and unit cost for US bus service over time

Note: A. Total expenditure on the US bus network in millions of 2010 dollars by year. Dashed line is total for six largest districts, dotted line is total for all smaller districts, and solid line is national total. B. Mean dollars of total expenditure per rider by year for large and for all districts. Dashed line is mean annual cost for large districts and light gray shading describes pointwise confidence bounds. Dotted line is mean annual cost per rider for all districts, and medium gray shading describes pointwise confidence bounds. C. Probability density function (PDF) of district mean cost per rider from 2014 to 2017. Dashed line gives the PDF of total expenditure per rider. Solid line gives the PDF of operating costs per rider.

intervals based on standard errors clustered at the state level. In this figure, the dashed line describes mean cost per rider in large districts, and the light gray area describes associated pointwise confidence bounds. The dotted line and medium gray shading provide the corresponding estimates for all districts. Several of the year means are estimated imprecisely. We suspect this is partly a result of the changes in accounting rules mentioned earlier. However, most year effects are estimated precisely, and the figure does not indicate a strong trend. Overall, the mean cost per rider is about five dollars in the large districts and a little higher on average, about what we would guess from table 3.3. There is a clear step-up in the average during the past few years, to about $12 per rider. Cost per rider in large districts is about constant over the whole course of the sample and has been trending downward since about 2000.

Panel C of figure 3.8 reports the density of mean cost per rider from 2014 to 2017, by transit district. The dashed line in this figure gives the density of total expenditure per rider. The mode of this density is about \$9 per rider, but there is considerable variation around this mode. The solid line describes the density of operating costs per rider. Since operating costs are a portion of total costs, it follows that this density lies to the left of the density of total expenditure. The extent of cost dispersion across districts suggests that there may be considerable scope for inefficient transit districts to learn from efficient ones.

3.3.3.2 Subways

Figure 3.9 replicates figure 3.8 for subways. In light of the dominance of the New York subway system, we analyze New York and all smaller systems separately. In panel A of figure 3.9, we report total expenditure on subways by year. This amount rises from \$8 billion to about \$16 billion 2010 dollars from 1992 to 2017, an increase of about 100 percent.

This is striking for two reasons. First, this is close to the amount of public expenditure on the Interstate Highway System. Second, the increase is about proportional to the increase in ridership over this time.

In table 3.4, we saw that New York accounted for about half of all subway expenditure from 2014 to 2017. In panel A of figure 3.9 we see that this relationship has been about constant over the course of our study period. New York has accounted for about half of all US expenditure on subways, even as expenditure has doubled.

Panel B of figure 3.9 repeats the cost per rider exercise described in equation (2) for all subway districts and reports the cost per rider for the New York system. These estimates suggest that costs per rider have been trending up slowly on average even as cost per rider falls in New York. Costs per rider have increased from about \$5.50 to about \$7 on average and decreased from about \$4 to about \$3 in New York. As we mentioned earlier, our measure of total expenditure does not reflect capital depreciation or augmentation, so these estimates should be regarded with some caution.

3.4 Transportation Infrastructure and Economic Activity

Over the past generation we have seen US highways, bridges, and subways (but not buses) used much more intensively. Nevertheless, objective measures of condition improved or stayed constant (although our data for subways measure only subway cars and may thus be too partial to be really useful). This result has been achieved as a consequence of increases in expenditure on all four classes of infrastructure. This expenditure has allowed at least modest expansions of capacity and maintenance that at least matches

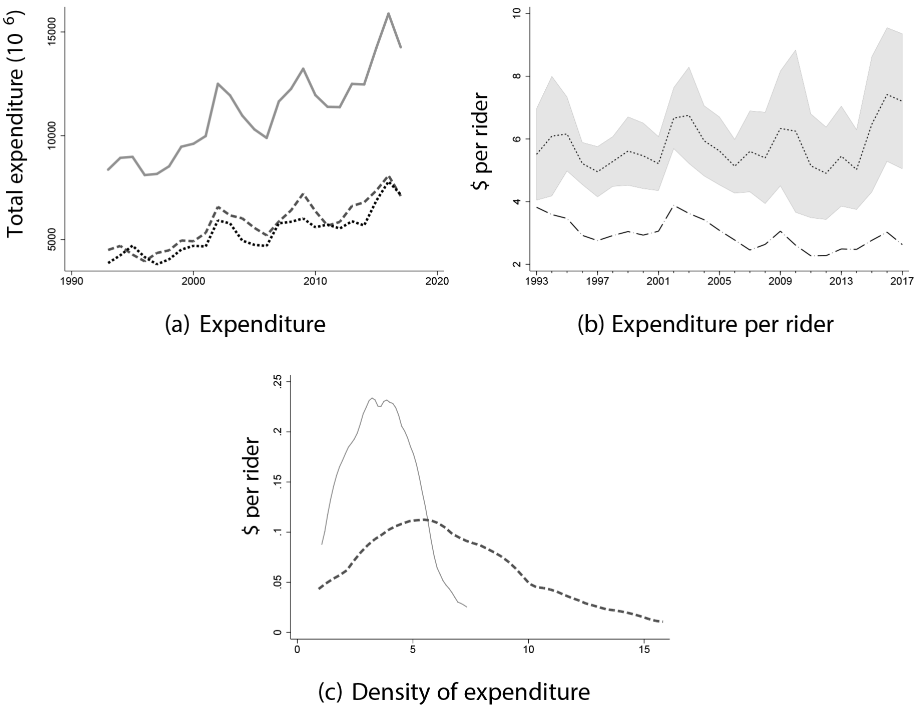


Fig. 3.9 Total expenditure and unit cost for US subway service over time

Note: A. Total expenditure on the US subway networks in millions of 2010 dollars by year. Dashed line is total for New York, dotted line is total for all smaller districts, and solid line is national total. B. Mean dollars of total expenditure per rider by year for New York and all districts. Dashed line is mean annual cost for New York. Dotted line is mean annual cost per rider for all districts, and medium gray shading describes pointwise confidence bounds. C. Probability density function (PDF) of district mean cost per rider from 2014 to 2017. Dashed line gives PDF of total expenditure per rider. Solid line gives PDF of operating costs per rider.

depreciation. Massive increases in infrastructure are not required to reverse the decline of US transportation infrastructure. Not only is this infrastructure, for the most part, not deteriorating, but much of it is in good condition or improving.[19]

An alternative justification for increases in infrastructure spending relies on the existence of "wider economic benefits." Simply put, infrastructure investment may be an engine of economic growth through a range of spillover effects. We here provide a brief survey of what is known about how

19. We are aware that international comparisons suggest US transportation infrastructure lags behind that of a number of other developed countries (Schwab 2019). Addressing this issue is beyond our scope here. We nonetheless note that lagging behind does necessarily not mean that world leaders in infrastructure have invested their resources wisely nor that it would be worth emulating them.

transportation infrastructure affects the level and location of economic activity. A more exhaustive survey is available in Redding and Turner (2015).

Perhaps the most compelling of the available empirical results is that people and economic activity move in response to the availability of transportation infrastructure. Chandra and Thompson (2000) examine the effect of the Interstate Highway network on economic activity in rural counties that were traversed by Interstate Highways. They find that economic activity increased in these counties, but that these increases were about exactly offset by losses in neighboring counties that were just a little further from the new highways. Baum-Snow (2007) finds that almost all of the decentralization of US central cities between 1950 and 1990 can be attributed to radial Interstate Highways that facilitated travel between the old center and the new suburbs. A number of other papers find qualitatively similar results about highways—for example, Baum-Snow (2019); Baum-Snow et al. (2017); and Garcia-López, Holl, and Viladecans-Marsal (2015). A smaller literature finds qualitatively similar effects for public transit—for example, Gonzalez-Navarro and Turner (2018); Heblich, Redding, and Sturm (2018); and Tsivanidis (2019). To sum up, the empirical evidence is as clear as could be hoped: as transportation infrastructure reduces transportation costs, people and (usually) economic activity spread out.

Evidence that transportation infrastructure leads to increases in economic activity is less compelling. Duranton and Turner (2012) estimate the relationship between 1983–2003 changes in metropolitan area employment and the initial stock of Interstate lane miles. They find that a 10 percent increase in the stock of roads causes about 1.5 percent increase in employment over their study period. This effect is of about twice as large as the effect of an increase of one standard deviation in metropolitan-area mean educational attainment. Within their model, Allen and Arkolakis (2014) evaluate the effect of reductions in cross-metropolitan area transportation costs caused by the Interstate Highway System on aggregate economic output. They find that the Interstate Highway System increased economic output in the US by between 1 and 1.5 percent. Both Duranton and Turner (2012) and Allen and Arkolakis (2014) compare their estimated benefits to back-of-the-envelope cost estimates. Benefits of the Interstate Highway System estimated by Duranton and Turner are dramatically smaller than the costs estimated by either paper, while the Allen and Arkolakis estimate is above their cost estimate, but below the higher cost estimate of Duranton and Turner (2012).

On the other hand, Baum-Snow et al. (2017) compare 1990–2010 changes in employment and economic output in large Chinese cities to changes in their stock of highway lane miles and find no effect. Baum-Snow (2019) conducts a similar exercise on the 100 largest US metropolitan areas and also finds no effect. Note the difference between these two papers and Duranton and Turner (2012). The former two papers conduct a regression of changes on changes, whereas the latter regresses changes on levels. In a similar vein, Duranton, Morrow, and Turner (2014) find that a metropolitan area's level of Interstate Highway miles has no measurable effect on the total value of its annual trade with other metropolitan areas though it affects their specialization.[20]

We have less evidence on the effects of subways and public transit on economic output. Gonzalez-Navarro and Turner (2018) examine population growth in every subway city in the world between 1950 and 2010 and find no relationship between population growth and subway system extent. They find a similar result for the relationship between subway system extent and the intensity of citywide lights at night. On the other hand, Ahlfeldt et al. (2015) and Heblich, Redding, and Sturm (2018) develop a theoretical framework to structurally estimate the effects of subways on Berlin and London. They infer large effects of transportation improvements on the population of cities. This said, in their framework, better transportation leads to a decrease in income per worker as agglomeration benefits are more than offset by the increased crowding of labor. What attracts workers to cities with better transportation are lower travel costs and the increased accessibility of locations with good amenities, not an expansion of economic activity.

Finally, we note a macroeconomic literature examining the effect of infrastructure expenditure on economic activity (e.g., Fernald 1999; Gramlich 1994; Leduc and Wilson 2013). This literature also does not suggest strong conclusions; however we refer the reader to the chapter by Ramey in this volume for an insightful review.

Following from Duranton and Turner (2011), there is also a literature relating capacity expansions to congestion. Redding and Turner (2015) survey the literature relating road expansions and traffic. This literature provides compelling evidence that a 1 percent expansion in a city's lane miles of highways causes a 1 percent increase in VMT over a fairly short horizon. Thus, as the history of Los Angeles clearly suggests, expanding road capacity to reduce traffic congestion is risky at best. A small recent literature examines the relationship between subway expansions and traffic—for example, Gendron-Carrier et al. (2018). This literature provides suggestive evidence that subways may have an effect on traffic congestion; however, this effect is likely fairly small. Duranton and Turner (2018) survey the literature evaluating various policy responses to traffic congestion and conclude that only policies to manage demand actually reduce traffic congestion.

To sum up, the evidence that infrastructure has important implications for how economic activity is organized is compelling. However, most of this evidence points to the importance of infrastructure as a determinant of where economic activity occurs. The evidence that infrastructure affects the

20. More precisely, the unit of observation in Duranton, Morrow, and Turner (2014) is a "commodity flow survey region." These regions are often somewhat larger than metropolitan areas but do not straddle state boundaries.

level of economic activity is mixed and is sensitive to econometric technique, and there is no clear basis for preferring one technique to another. Finally, the available evidence does not suggest that massive expansions of capacity are likely to provide a long-run solution to traffic congestion.

3.5 A Theory of Optimal Infrastructure Expenditure

We have now established the fundamentals of our ongoing allocation of resources to transportation infrastructure. We know the quantity and quality of three of the most important sorts of transportation infrastructure, particularly with regard to moving people.

It is not immediately obvious how we should think about the optimality of the observed program of expenditure. Can it possibly be rational to spend as much on buses as on the Interstate Highway system when the role of buses in national mobility seems so small relative to that of Interstate Highways? Does it make sense that subway cars are so old when subways seem to be attracting progressively more riders? In what follows we develop a simple framework in which to address these questions.

3.5.1 First Best

We consider the problem of a social planner providing transportation infrastructure by spending K_i where $i = H, B, S$ stands for Interstate Highways (to which we aggregate Interstate bridges), buses, and subways, respectively. For each mode of transportation i, infrastructure expenditure K_i, measured in monetary amount, is combined with traveler inputs L_i, measured in time, to provide transportation services Q_i, measured in units of person distance:

$$Q_i = F_i(K_i, L_i). \tag{3}$$

Simply put, dollars of infrastructure expenditure and person hours combine to produce miles of travel.[21] Importantly, the production function of transportation $F_i(.,.)$ is homogeneous of degree ν_i.

The social planner has the following social welfare (utility) function:

$$U = V\left(\sum_i Z_i Q_i\right) + C, \tag{4}$$

where the subutility $V(.)$ is increasing and concave and C is the consumption of other goods. We call the parameter Z_i the social weight of a mile traveled using mode i.

Our main objective is to recover the social weights in equation (4) from observable data about traveler inputs, infrastructure expenditure, and travel

21. Our framework is static. We implicitly view infrastructure expenditure as part of a steady state in a broader dynamic optimization. We leave this challenging extension to future work.

mileage by mode. This exercise allows us to assess the (relative) allocation of resources between modes. To assess the optimality of the (absolute) levels of expenditure, we would need to impose more structure on the demand for transportation and specify $V(.)$. Couture, Duranton, and Turner (2018) provide such a framework for a single mode of transportation.

Some further comments are in order. First, we consider a social planner weighting miles of travel differently across modes. There are several reasons why a social planner might do this. For instance, miles traveled with a subway in the central part of a large city may be economically more valuable than miles traveled on a highway in a rural area. A social planner may also have utilitarian motives and put a higher weight on bus miles, as buses are mainly used by the poor. Second, for simplicity and tractability, we treat travel distance as a good instead of an intermediate input that enables the earning of a labor income (though commute trips), the consumption of goods (through shopping trips), or various forms of leisure. See Couture, Duranton, and Turner (2018) or Duranton and Turner (2018) for further discussion of these issues. Third, we assume a quasi-linear social welfare function to avoid complications arising from income effects. Fourth, we also make the simplifying assumption that travel distances produced by different modes are perfect substitutes after accounting for their social weights. Fifth, we assume for simplicity that the returns to scale, measured by ν_i, are "decreasing enough" to ensure the existence of a unique interior optimum for the allocation of resources across modes by the planner.

Without loss of generality, we normalize the price of consumption to unity so that the budget constraint for income M is given by

$$C = M - \sum_i w_i^S L_i - \sum_i K_i, \tag{5}$$

where w_i^S is the social cost of traveler inputs for mode i. We allow this cost to differ as modes differ in monetary costs, speed of travel, and externalities.

We now consider the social planner's program, choosing both K_i and L_i for all modes to maximize social welfare in equation (4) subject to the household budget constraint (equation [5]), keeping in mind that travel distance is produced according to the travel technology described by equation (3). This situation corresponds to an unconstrained first best.

The first-order conditions imply that, for each input, the social value of the marginal product of infrastructure expenditure should be equalized across any two modes i and j:

$$Z_i \frac{\partial Q_i}{\partial K_i} = Z_j \frac{\partial Q_j}{\partial K_j} \text{ and } Z_i \frac{\partial Q_i}{\partial L_i} = Z_j \frac{\partial Q_j}{\partial L_j}. \tag{6}$$

The first-order conditions also imply that, for a given mode i, the last dollar spent on infrastructure should have returns equal to the last dollar spend on traveler inputs:

(7)
$$\frac{\partial Q_i}{\partial K_i} = \frac{1}{w_i^S}\frac{\partial Q_i}{\partial L_i}.$$

Then, recall that Euler's theorem for homogenous function implies

(8)
$$\frac{\partial Q_i}{\partial K_i}K_i + \frac{\partial Q_i}{\partial L_i}L_i = \nu_i Q_i.$$

After using this last expression to substitute for $\partial Q_i / \partial L_i$ in equation (7) and rearranging, we obtain $\partial Q_i / \partial K_i = \nu_i Q_i / (K_i + w_i^S L_i)$, which allows us to rewrite the first equality in equation (6) as

(9)
$$Z_i \frac{\nu_i Q_i}{K_i + w_i^S L_i} = Z_j \frac{\nu_j Q_j}{K_j + w_j^S L_j}.$$

This equation stipulates that, optimally, the amount of travel per dollar weighted by its social weight and the returns to scale should be equalized across modes.

3.5.2 Traveler Optimization and Decentralizing the First Best

There are several limitations to the analysis just set out. Foremost, we assume that the social planner chooses traveler inputs for each mode of transportation. In reality, the planner decides first on infrastructure expenditure for all modes before travelers individually choose their inputs by mode.

To model this, assume a representative traveler with utility,

(10)
$$u = V\left(\sum_i B_i q_i\right) + c,$$

where q_i and c are the traveler's travel distance and consumption of other goods, respectively. Summing travel and consumption across travelers recovers the aggregate quantities used above, Q_i and C.[22] The traveler's objective function is like that of the planner, except that travelers may apply different weights, B_i, for the mileage by mode relative to the weights used by the social planner, Z_i.

The budget constraint of the traveler is given by

(11)
$$c = m - \sum_i (w_i^T + t_i)\ell_i - r,$$

where t_i is a tax or subsidy for mode i, ℓ_i is traveler inputs, and r is a lump-sum monetary transfer that satisfies the balanced budget condition of the planner. With R, the aggregate monetary transfer, we have $\sum_i t_i L_i + R = \sum_i K_i$. For the traveler, the private cost of travel inputs w_i^T differs from its social cost w_i^S since travelers generate externalities, including in particular pollution and accidents for highway travel. Importantly, we do not consider

22. To simplify notations and without loss of generality we assume a unit population of travelers.

congestion costs in w_i^S as they appear through the production of travel, to which we now turn.

The representative traveler takes infrastructure investment and travel decisions by other travelers as given and faces constant returns to travel inputs. A traveler who devotes twice as much time to, say, highway travel will travel twice as far. More generally, travel distance is equal to the speed that a traveler experiences Q_i/L_i multiplied by travel inputs of this traveler, ℓ_i:

$$q_i = \frac{Q_i}{L_i}\ell_i. \tag{12}$$

Another way to think about equation (12) is to note that travelers receive the average and not the marginal return to their travel inputs, as they ignore the congestion they inflict upon other travelers.

The representative traveler maximizes the utility function (equation [10]) subject to the budget constraint (equation [11]) and the production of individual travel given by equation (12) for mode i. This yields

$$B_i\frac{Q_i}{L_i}V' = w_i^T + t_i. \tag{13}$$

We can first use this expression for mode i and the analogous expression for mode j to obtain the following:

$$\frac{B_iQ_i}{(w_i^T + t_i)L_i} = \frac{B_jQ_j}{(w_j^T + t_j)L_j}. \tag{14}$$

This equation indicates that the cost per mile faced by travelers weighted by the traveler's weight for that mode should be equalized across modes. As we show later, it is easy to compute the cost per mile faced by travelers for each mode and recover their relative weights. These weights can be compared to the social weights recovered from equation (9).

To reach the first best, the planner can set a tax (or subsidy) by mode t_i^* so that the decentralized equilibrium coincides with the first best. To compute this optimal tax, we can use equation (13), divide it by the corresponding first-order condition for the planner, use equations (7) and (8) to substitute the term in $\partial Q_i / \partial L_i$, and rearrange to obtain

$$t_i^* = \frac{B_i}{Z_i}\frac{K_i + w_i^S L_i}{\nu_i L_i} - w_i^T. \tag{15}$$

This expression shows that the optimal tax should correct for the three different wedges: (1) between the utility weights B_i used by travelers and those of the planner Z_i; (2) between the average cost in terms of travel input considered by the traveler and the marginal cost in the planner's calculation; (3) the private cost of travel inputs for travelers and the social cost of travel inputs. Finally, we note that, to decentralize the first best, the fiscal transfer r is also needed to provide the optimal level of infrastructure expenditure since the taxes on travel inputs are needed to induce travelers to travel optimally.

While this framework makes it possible to compare the allocation of infrastructure expenditure across modes, it does not allow us to assess what the optimal overall expenditure on transportation infrastructure would be. For this, we would need to know more about the demand for transportation than we currently do. Our approach sidesteps the demand side by considering that miles across modes are perfect substitutes, so that we only need information about costs.

3.5.3 How Far Are We from the First Best?

We can now attempt to evaluate whether the marginal products of infrastructure expenditure are equalized between modes of transportation as described in equation (9). While we do not know the Z_i, everything else can be observed from the data or inferred from the literature. Hence, we can ask what the social valuations of different modes would need to be to justify the difference we observe if we were in a first-best world. Evaluating equation (9) requires knowing about ν, Q, K, L, and w^s for each mode.

Starting with the returns to scale parameter in the production of travel, ν_i, Couture, Duranton, and Turner (2018) estimate a production function of travel by motorized vehicle for US metropolitan areas. While they restrict their estimation to a Cobb-Douglas case, they estimate slight decreasing returns to scale with $\nu_H = 0.96$ in their preferred regression. This implies about a 4 percent loss from congestion, consistent with the estimates reported by Parry, Walls, and Harrington (2007). Less is known about buses and subways. At the intensive margin, transit may enjoy increasing returns to scale as more traveler inputs in the form of more travelers can justify a greater transit frequency. Table 3.4 suggests that larger US transit districts provide transit services at a lower cost per rider. However, at the extensive margin, new transit lines are likely to serve less popular routes (Gendron-Carrier et al. 2018). To avoid biasing our calculations against transit, we assume $\nu_B = \nu_S = 1$. Obviously, knowing more about congestion and returns to scale in transit should be a priority for future research.

Turning to mileage by mode, Q_i, table 3.1 reports 243 billion vehicle miles traveled on rural Interstate Highways in 2008 and 476 billion on urban Interstate Highways for the same year. With 1.25 passengers per vehicle (Couture, Duranton, and Turner 2018), this corresponds to a total of 899 billion person miles. For transit, table 3.3 reports 21 billion person miles for buses in 2008 and 16.8 for subways in the same year.

For infrastructure expenditure K_i, section 3.3.1 reports an expenditure of \$22.5 billion dollars for the Interstate Highway System (inclusive of expenditure on bridges). For buses and subways in 2008, table 3.3 reports expenditure of \$21.4 billion and \$12.3 billion, respectively.

Obtaining measures of traveler inputs, L is more involved. Starting with traveler inputs, L, we measure a mean car speed of 25.5 miles per hour from the 2008 NHTS in table 3.2. This is arguably a lower bound since travel on Interstate Highways is typically faster than on other roads and Interstate

Highways represent only about 25 percent of aggregate mileage. If we focus more realistically on trips longer than 10 miles, car speed increases to 31.8 miles per hour. Given the person miles of highway travel reported above, a speed of 31.8 miles per hour implies 28.2 billion person hours.

For transit, from the 2008 NHTS we calculate a speed of 12.6 miles per hour for bus travel and 10.4 miles per hour for subway travel.[23] Given the mileage for these two modes, we obtain 1.66 billion passenger hours for bus travel and 1.61 billion passenger hours for subway travel.

Finally, evaluating equation (9) requires measures of the cost per hour, w^s. Like traveler inputs, hourly costs cannot be read directly from the data. To compute the hourly cost for these three modes, we first consider the value of time. Existing estimates of the value of time traveled generally center around 50 percent of an individual's hourly wage (Small and Verhoef 2007; Small 2012). Although time in transit is typically valued at a higher cost and travel time on highways is valued at a lower share of the hourly wage, we retain this figure of 50 percent for our baseline calculation. We take the mean wage for 2008 to be about \$23 per hour, as in Couture, Duranton, and Turner (2018). This implies a cost of time of \$11.50 per hour.

For buses and subways, we assume a fare of \$1.50 per trip. Given the ridership figures reported in table 3.3, we get a fare of \$4.90 per hour for buses and \$3.30 per hour for subway. These figures imply a fare box recovery rate of about 40 percent, slightly above the figures reported by the NTD of about 25 percent for these two transit modes. Adding \$11.50 per hour for the cost of time, the cost of travel w^S is thus \$16.48 per hour for buses and \$14.79 per hour for subways.

To compute the cost of car travel, we consider an operating cost of \$0.55 per vehicle mile, in line with federal guidelines for car travel reimbursement. At a speed of 31.8 miles per hour for 1.25 passengers, this implies a vehicle operating cost of \$14 per person hour. Adding \$11.50 per hour for the value of time of the travelers, we reach a total of \$25.50 per hour of highway travel. This calculation, so far, neglects the externalities associated with highway travel and represents only a private cost, not the social cost. Parry, Walls, and Harrington (2007) estimate the external costs associated with pollution, congestion, and accidents to be about \$0.10 per mile. This estimate is for all road travel. It is unclear what it implies for highway travel and for buses and subways. To be conservative, we can assume that highway travel has external costs of \$0.10 per vehicle mile due to worse accidents and more concentrated pollution for urban highways. This corresponds to about \$2.55 per hour. Hence, the social cost of travel, w^S, for cars is \$28.05 per person hour. Recall that congestion is taken into account through the scale parameter ν_i.

23. These travel speeds may seem low but the travel time in the denominator of this calculation includes the whole duration of the trips, including waiting times or walking to a station. There are nonetheless worries regarding the quality of the information reported by travelers when using travel diaries like the NHTS.

To evaluate equation (9), we must be careful to avoid the double counting of the gas tax, which is included in the vehicle user cost of \$0.55 per mile used earlier. With a federal gas tax of 18 cents per gallon and a state gas tax at an average of 36 cents per gallon and with fuel economy of 20 miles per gallon, \$19.4 billion of traveler costs goes toward paying for highway expenditure.

Putting all these numbers together, for the marginal value product of infrastructure investment, $\partial Q_i / \partial K_i = v_i Q_i / (K_i + w_i^S L_i)$, we find 1.09 miles per dollar for Interstate Highways, 0.43 miles per dollar for buses, and 0.47 miles per dollar for subways. Using equation (6), these figures imply that implicitly the social planner puts two and a half times as much value on a passenger bus mile relative to a passenger highway mile and about 10 percent more value relative to a subway passenger mile. Alternatively, equating the marginal mileage per dollar of expenditure across modes, which corresponds to $Z_i = Z_j$ in equation (6), would require multiplying highway infrastructure expenditure by a factor of more than 40.

We can also use equation (14) to recover the traveler's (relative) weights, B_i, for the different modes directly from travel behavior. After noting that the taxes and subsidies are already included in the private costs we computed earlier, we find that the cost per mile faced by travelers for highway travel is obtained by simply dividing 899 billion miles traveled by 28.2 billion hours valued at \$25.50 each. This is 1.25 miles per dollar. The same calculation implies 0.77 miles per dollar for buses and 0.97 miles per dollar for subways. In turn, this implies the weight put on bus miles by travelers is just over one and a half times the weight they put on highway miles and about 20 percent less than the weight they put on subway miles.

We think there are two main reasons why the cost per mile that travelers are willing to incur for buses and subways is higher than for Interstate Highways. The first is that we imposed the same time cost for all modes, ignoring the fact that the hourly wage of highway travelers (generally by car) may be higher than that of transit users. If, instead of \$23 per hour, we assume \$30 per hour for highway travel and \$15 for bus travel, the relative weights between bus and highway travel are down to 1.9 instead of 2.5 in our benchmark calculation. It is also possible that travelers put a higher value on travel by bus or subway because it is more likely to take place in more highly urban parts of the country relative to highway travel, which may be more urban. Pushing in the opposite direction, we note that transit travel may have a higher time cost relative to the hourly wage than highway travel (Small and Verhoef 2007; Small 2012). While we can explain why travelers put a higher weight on transit relative to highway travel, this does not explain the gap with the social planner.

To explain why the planner appears to put a higher relative weight than travelers on transit miles, we can think of two second-best explanations. The first is that the planner may be constrained in ability to redistribute income. The planner may then increase infrastructure expenditure on transit to redistribute income given that transit, and buses in particular, is used primarily by the poor. Another possibility is that the planner cannot tax or subsidize modes of transportation as required by the first best. For instance, the gas tax in the US represents only a few cents per mile, much less than the externalities caused by highway travel. By increasing expenditure on highways, the planner lowers the cost of travel for travelers, which in turn, leads to an increase in travel inputs. As shown by Duranton and Turner (2011), this demand response is large, and because travelers neglect congestion and other externalities, the planner will want to restrain infrastructure expenditure relative to another mode like buses or subways, for which the demand response is less and the wedge between the social and private cost of travel is also less.

3.6 Conclusion

3.6.1 Policy

Perhaps our main conclusion is that, on average, US transportation infrastructure does not seem to be in the dire state that politicians and pundits describe. We find that the quality of Interstate Highways has improved, the quality of bridges is stable, and the age of buses and subway cars is also about constant. With this said, we suspect that subway car age is not a good indicator of systemwide state of repair and that subway systems are actually depreciating.

We also report on the cost of infrastructure. Our results here are mixed. For buses and subways, cost per rider has been fairly steady over time, except for a jump in the cost per trip of small district bus trips around 2014. The bridge condition index has stayed about constant in the face of a tripling of expenditure, although an analysis of state-year variation does not indicate a big increase in the unit cost of improvements to bridge condition. The cost of the Interstate, however, has increased rapidly and monotonically from about 1970 through to 2008.

Both the Interstate and public transit buses absorb about $20 billion of public expenditure each year, while the Interstate provides about 35 times as many person miles of travel but also uses dramatically more private inputs than do buses. It is difficult to evaluate the reasonableness of such allocation decisions (and the others we describe) without recourse to theory. Using a simple model, we find that public funds for transportation are, on a passenger-mile basis, disproportionately allocated to buses and subways rather than highways. A partial explanation for this is that travelers themselves prefer to devote a greater amount per mile to bus and subway travel. However, this preference does not explain fully the imbalance in government infrastructure funding between modes, as some redistributive concerns may be at play to explain this imbalance.

The condition of infrastructure has, for the most part, improved over the past generation. However, highways and subways per person have decreased, even as travel per person has increased. Thus, while the condition of the infrastructure has improved or stayed constant, it is serving much more demand, and so the speed of travel has decreased and the experience of drivers and riders is worse. We speculate that the sentiment that infrastructure is deteriorating derives from the fact that users' experiences are deteriorating with increased congestion and that this deterioration is largely independent of physical condition. Relatedly, public perceptions of infrastructure quality may also reflect the highly publicized infrastructure report card generated by the American Society of Civil Engineers. As we have seen, these reports cards provide little information about objective measures of physical condition.

While we find little evidence to support common justifications for increases to infrastructure spending, we note the importance of demand management as a policy response to traffic congestion and also of axel-weight-based user fees for trucks.

We have restricted attention to the Interstate Highway System, bridges, and public transit. We have neglected railroads, pipelines, subway tracks, local roads, and water and sewer systems. All are important. Administrative data describing pipelines, railroads, and subway track may be available, and an examination of these data should be a high priority for researchers. Much less is known about local roads, and systematic data describing US water and sewer infrastructure seem not to exist. The creation and interrogation of such data should also be a high priority for research.

3.6.2 Research

Our panorama of US transportation infrastructure, albeit partial, raises a number of questions for future research. First, policy would benefit from more precise cost estimates than the rough aggregates we present in this chapter. Estimates of the full cost of trips in various locations, broken down into fixed and variable components, would help to guide allocation and pricing decisions. Such estimates could rely on in part on the administrative data we exploit, but could also combine them with innovative new data sources to measure congestion and reliability for both highways and transit—for example, Akbar et al. (2020). Related to congestion, most economists have a strong presumption that congestion pricing must be the main policy response to congestion. Congestion pricing nonetheless begs two important questions. The first is how to make it less unpopular. The second is about how best to implement congestion pricing on a road network with different types of roads, vehicles, and interrelated congestion and environmental externalities.

This chapter suggests, but does not address, a number of interesting and important questions for further research. Catastrophic bridge collapses are economically important events. Does the bridge condition index provide information that is useful for predicting such collapses? Are we gathering the right information about bridge conditions? What is the value of further data collection? Pavement quality, as measured by the international roughness index, is relatively little studied. How does pavement quality contribute to travel speed and congestion? How does pavement quality contribute to depreciation of the vehicle stock? Such questions are understudied but are central to any formulation of an optimal maintenance policy.

Two of the findings we document in this chapter do not have a clear explanation. The first is the increase in the cost of Interstate Highways. Although recent literature has ruled out a number of explanations, there is still too much uncertainty about the cause of this increase for a solution to be designed. We need to know whether increasing costs reflect improvements in the quality of highways and environmental protection, or poor project management. The decline of buses also requires further diagnosis. Bus travel, as it exists, is likely to be an economically inferior good for travelers. This said, bus travel is not a good with fixed characteristics. The demand for bus travel may be sensitive to various dimensions of quality, including comfort, reliability, and the design of routes and connections.

Finally, our review of the literature suggests that transportation improvements lead to a displacement of economic activity while net growth effects are limited. This finding needs to be buttressed and refined. The balance between displacement and net growth effects is likely to differ greatly across projects depending on mode, spatial scale, whether the project serves a corridor between cities or is a transit improvement within, and so on. A better understanding of this heterogeneity is also a high priority.

References

Ahlfeldt, Gabriel M., Stephen J. Redding, Daniel M. Sturm, and Nikolaus Wolf. 2015. "The Economics of Density: Evidence from the Berlin Wall." *Econometrica* 83 (6): 2127–89.

Akbar, Prottoy A., Victor Couture, Gilles Duranton, and Adam Storeygard. 2020. "Mobility and Congestion in Urban India." Working paper, University of Pennsylvania.

Allen, Treb, and Costas Arkolakis. 2014. "Trade and the Topography of the Spatial Economy." *Quarterly Journal of Economics* 129 (3): 1085–140.

Baum-Snow, Nathaniel. 2007. "Did Highways Cause Suburbanization?" *Quarterly Journal of Economics* 122 (2): 775–805.

———. 2019. "Urban Transport Expansions and Changes in the Spatial Structure of US Cities: Implications for Productivity and Welfare." *Review of Economics and Statistics* (forthcoming).

Baum-Snow, Nathaniel, Loren Brandt, J. Vernon Henderson, Matthew A. Turner, and Qinghua Zhang. 2017. "Roads, Railroads, and Decentralization of Chinese Cities." *Review of Economics and Statistics* 99 (3): 435–48.

Blumenberg, Evelyn, Michael Manville, and Brian D. Taylor. 2019. "Why Is Public Transit Use Declining? Evidence from California." Working paper, University of California, Los Angeles.
Brooks, Leah, and Zachary D. Liscow. 2019. "Infrastructure Costs." Working paper, George Washington University.
Chandra, Amitabh, and Eric Thompson. 2000. "Does Public Infrastructure Affect Economic Activity? Evidence from the Rural Interstate Highway System." *Regional Science and Urban Economics* 30 (4): 457–90.
Couture, Victor, Gilles Duranton, and Matthew A. Turner. 2018. "Speed." *Review of Economics and Statistics* 100 (4): 725–39.
Duranton, Gilles, Peter M. Morrow, and Matthew A. Turner. 2014. "Roads and Trade: Evidence from the US." *Review of Economic Studies* 81 (2): 681–724.
Duranton, Gilles, and Matthew A. Turner. 2011. "The Fundamental Law of Road Congestion: Evidence from US Cities." *American Economic Review* 101 (6): 2616–52.
———. 2012. "Urban Growth and Transportation. *Review of Economic Studies* 79 (4): 1407–40.
———. 2018. "Urban Form and Driving: Evidence from US Cities." *Journal of Urban Economics* 108 (0): 171–91.
Federal Highway Administration. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Technical report, Office of Engineering, Bridge Division, Bridge Management Branch, Washington, DC.
———. 2016. *Measuring and Specifying Pavement Roughness*. US Department of Transportation FHWA-HIF-16-032.
Fernald, John G. 1999. "Roads to Prosperity? Assessing the Link between Public Capital and Productivity." *American Economic Review* 89 (3): 619–38.
Garcia-López, Miquel-Àngel, Adelheid Holl, and Elisabet Viladecans-Marsal. 2015. "Suburbanization and Highways in Spain When the Romans and the Bourbons Still Shape Its Cities." *Journal of Urban Economics* 85 (0): 52–67.
Gendron-Carrier, Nicolas, Marco Gonzalez-Navarro, Stefano Polloni, and Matthew A. Turner. 2018. "Subways and Urban Air Pollution." Technical report. Cambridge, MA: National Bureau of Economic Research.
Gonzalez-Navarro, Marco, and Matthew A Turner. 2018. "Subways and Urban Growth: Evidence from Earth." *Journal of Urban Economics* 108: 85–106.
Gramlich, Edward M. 1994. "Infrastructure Investment: A Review Essay." *Journal of Economic Literature* 32 (3): 1176–96.
Heblich, Stephan, Stephen J. Redding, and Daniel M. Sturm. 2018. "The Making of the Modern Metropolis: Evidence from London." Working paper, London School of Economics.
Kreindler, Gabriel E. 2018. "The Welfare Effect of Road Congestion Pricing: Experimental Evidence and Equilibrium Implications." Working paper, Harvard University.
Leduc, Sylvain, and Daniel Wilson. 2013. "Roads to Prosperity or Bridges to Nowhere? Theory and Evidence on the Impact of Public Infrastructure Investment." *NBER Macroeconomics Annual 2012* 27: 89–142.
Mannering, Fred, Walter Kilareski, and Scott Washburn. 2007. *Principles of Highway Engineering and Traffic Analysis*. Hoboken, NJ: John Wiley & Sons.
Mehrotra, Neil, Juan Pablo Uribe, and Matthew A. Turner. 2020. "Does the US Have an Infrastructure Cost Problem? Evidence from the Interstate Highway System." Working paper, Brown University.
Meyer, John R., John F. Kain, and Martin Wohl. 1965. *The Urban Transportation Problem*. Cambridge, MA: Harvard University Press.
Office of Highway Policy Information. 2016. *Highway Performance Monitoring Sys-*

tem Field Manual. Office of Management & Budget (OMB) Control No. 2125-0028.
Parry, Ian W. H., Margaret Walls, and Winston Harrington. 2007. "Automobile Externalities and Policies." *Journal of Economic Literature* 45 (2): 1335–53.
Ramey, Valerie A. 2021. "The Macroeconomic Consequences of Infrastructure Investment." This volume.
Redding, Stephen J., and Matthew A. Turner. 2015. "Transportation Costs and the Spatial Organization of Economic Activity." In *Handbook of Regional and Urban Economics*, volume 5B, edited by Gilles Duranton, Vernon Henderson, and William C. Strange, 1339–98. Amsterdam: Elsevier.
Schwab, Klaus. 2019. *The Global Competitiveness Report*. Geneva: World Economic Forum.
Small, Kenneth A. 2012. "Valuation of Travel Time." *Economics of Transportation* 1 (1): 2–14.
Small, Kenneth A., and Erik T. Verhoef. 2007. *The Economics of Urban Transportation*. New York: Routledge.
Small, Kenneth A., Clifford Winston, and Carol A. Evans. 2012. *Road Work: A New Highway Pricing and Investment Policy*. Washington, DC: Brookings Institution.
Tsivanidis, Nick. 2019. "The Aggregate and Distributional Effects of Urban Transit Infrastructure: Evidence from Bogota's Transmilenio." Working paper, University of California, Berkeley.
Turner, Matthew A. 2019. "Local Transportation Policy and Economic Opportunity." Hamilton Project Policy Proposal 3. Washington, DC: Brookings Institution.
US Department of Transportation. 2013. *Status of the Nation's Highways, Bridges, and Transit: Condition and Performance, Report to Congress*. Washington, DC: US Department of Transportation.
US Federal Highway Administration. 1985. *Highway Statistics, 1984*. Washington, DC: Federal Highway Administration.
———. 1995. *Highway Statistics, 1995*. Washington, DC: Federal Highway Administration.
———. 2019. *Highway Statistics, 2018*. Washington, DC: Federal Highway Administration.

Comment Stephen J. Redding

One of the pieces of conventional wisdom about the US economy is its decaying infrastructure. On a recent report card, the American Society of Civil Engineers (ASCE) awarded US infrastructure a grade of D+. According to an article in the *New York Times* (John Holusha and Kenneth Chang,

Stephen J. Redding is the Harold T. Shapiro '64 Professor in Economics at Princeton University, a research fellow of the Centre for Economic Policy Research, and a research associate and director of the International Trade and Investment Program at the National Bureau of Economic Research.

I am grateful to Princeton University for research support. The usual disclaimer applies. For acknowledgments, sources of research support, and disclosure of the author's material financial relationships, if any, please see https://www.nber.org/books-and-chapters/economic-analysis-and-infrastructure-investment/comment-transportation-infrastructure-us-redding.