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TRANSPORTATION INFRASTRUCTURE IN THE US

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ABSTRACT

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. In fact, most US transportation infrastructure is not deteriorating and the existing scientific literature does not show that infrastructure creates growth or reduces congestion. However, current annual expenditure on public transit buses exceeds that on interstate construction and maintenance. A careful examination of how funding is allocated across modes is suggested by the evidence. Massive new expenditures are not.

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1. Introduction

'*...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.

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 last 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 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% 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. Expendi-

ture 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 2 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 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 seems 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 reiterate longstanding recommendations of transport economists for demand management as an alternative to capacity expansion for congested roads, and for 'per axel weight' fees for trucks to incentivize the use of trucks that are less damaging to the highways and roads.

2. Usage, stock, and condition of highways, bridges, and public transit

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 strictly contains the interstate highway system. Table 1 provides some basic facts about the road system in the United States (US) in 2008.[1] In rural areas, the interstate highway system accounts for about one percent of all mileage, about 2% of all lane miles, but about 24% of all vehicle miles traveled (VMT). Importantly, rural interstate highways are also important compared to the rest of the rural federal aid highway system. They account for less than one tenth of rural federal aid lane miles, but 30% 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.

[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 rural roads vs. urban public transportation tension in policy debates, we preserve the rural classification in table 1.

Table 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

Notes: 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.

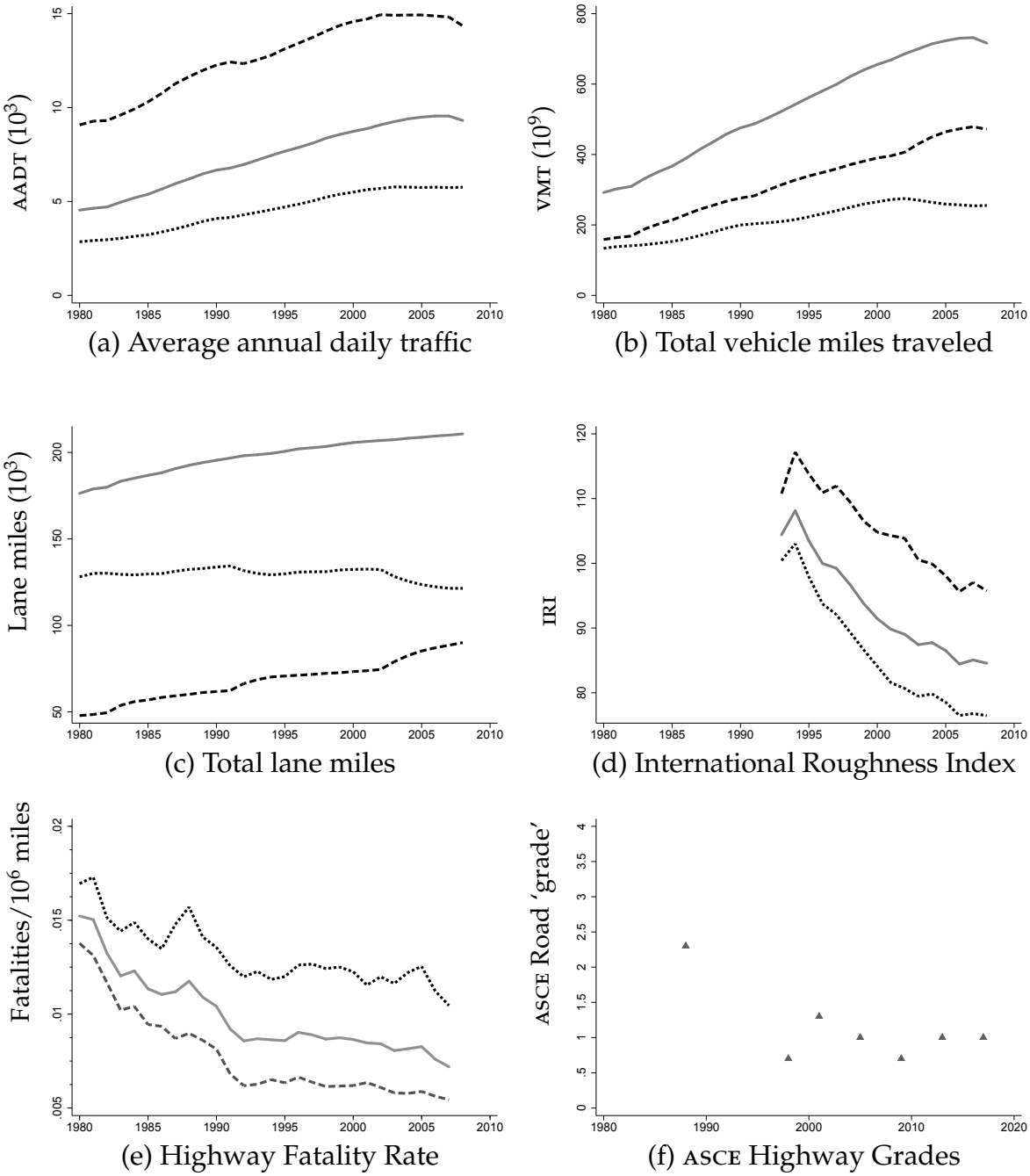
In what follows, we focus attention on the interstate highway system for three reasons. First, data availability is better. Second, it is more extensively studied and so more is known about it. Third, it is an important part of the network. With this said, the remainder of the network is understudied,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

The federal government funds most interstate highway construction and maintenance, and keeps a careful inventory of the roadways for which it assumes financial responsibility. This inventory results in an annual database called the 'Highway Performance Monitoring System' (HPMS). HPMS data are collected by various state highway authorities under the direction of the Federal Highway Administration, and they describe the interstate highway network in detail. **?** 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 1 presents four figures based on data from **?**. 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 figure 1(a) 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 more than doubled to about 10,000 vehicles per day by 2010. Thus, AADT on the interstate highway network increased by about 3.0% per year. The dashed and dotted lines in figure 1a 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

[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 to earlier years.

Figure 1: Interstate highways: usage, stock, and condition



(a) Average annual daily traffic

(b) Total vehicle miles traveled

(c) Total lane miles

(d) International Roughness Index

(e) Highway Fatality Rate

(f) ASCE Highway Grades

Notes: Panels (a-e) are based on HPMS data. In panel (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) ASCE grades for US road infrastructure by year. In (a)-(e) the solid line describes national total, the dashed line describes the urban portion of the interstate, and the dotted line describes the rural portion.

portion, however both parts of the network are following similar trends.[3]

Panel (b) of figure 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 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% 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 1 reports lane miles of interstate highways in operation by year from 1980 until 2007. We see that lane miles increased from about 175,000 to about 210,000 over this period, an increase of about 20%, or 0.7% 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 accomplish this, it 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 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

[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 1 do not reflect constant samples of roads.

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

[5]HPMS has only required IRI reporting for the universe of interstate segments from 1992 onward, so this measure begins later than those reported in other panels of figure 1.

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 as 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 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 reflects problems with initial reporting of IRI rather than actual deterioration of the network.

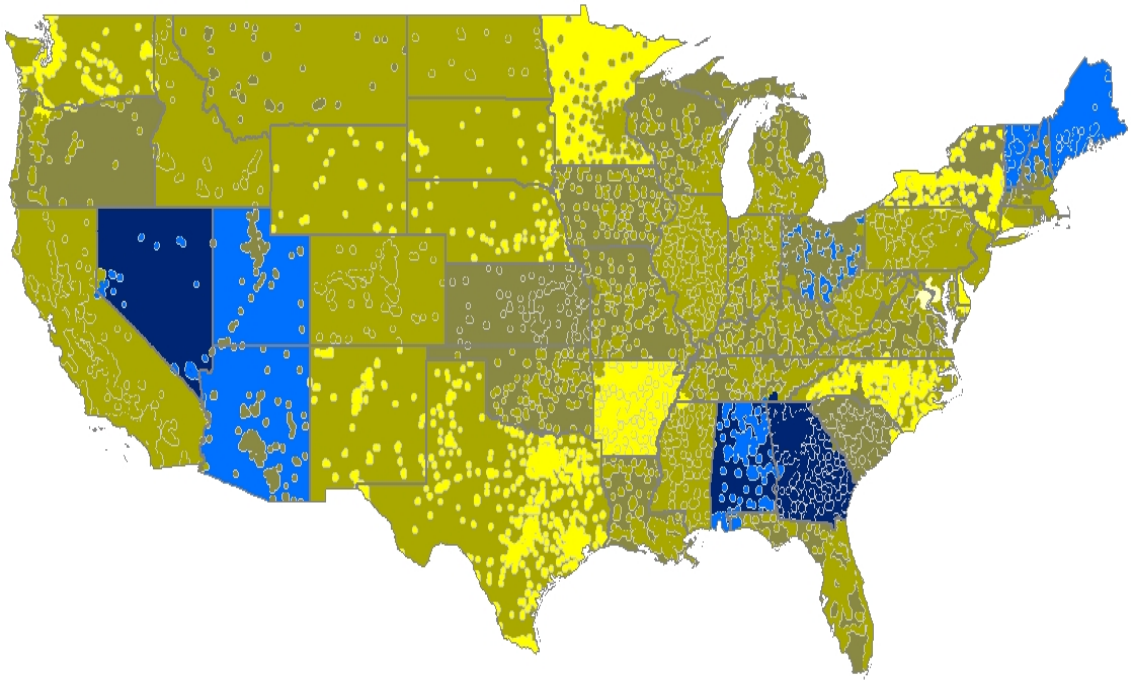
The two panels of figure 2 provide more detail about how IRI varies across the country. To make these figures we divide each state into its rural an urbanized portions, adding the entirely urban District of Columbia, to get to 97 regions. We next construct mean IRI for the rural and urban portions of 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 the top panel of figure 2, we assign each bin a color ranging from light yellow for the lowest and best bin to dark blue for the highest and worst bin. For legibility, we exaggerate the size of the urbanized areas in each state.

Recalling FHA quality definitions, the good/acceptable threshold occurs at 95 inches, in the dark green regions, while the acceptable/poor threshold occurs at 170 inches, in the blue regions. Therefore, while this figure reveals considerable heterogeneity in road quality, it overwhelmingly indicates that in the 1992-5 period, the interstate was in pretty good shape, at least as indicated by the FHA's standards. Indeed, only in Nevada, Alabama, and Georgia have Interstate conditions anywhere near the acceptable/poor threshold, and in Alabama and Georgia, it is only the rural portions of the interstate that approach this threshold.

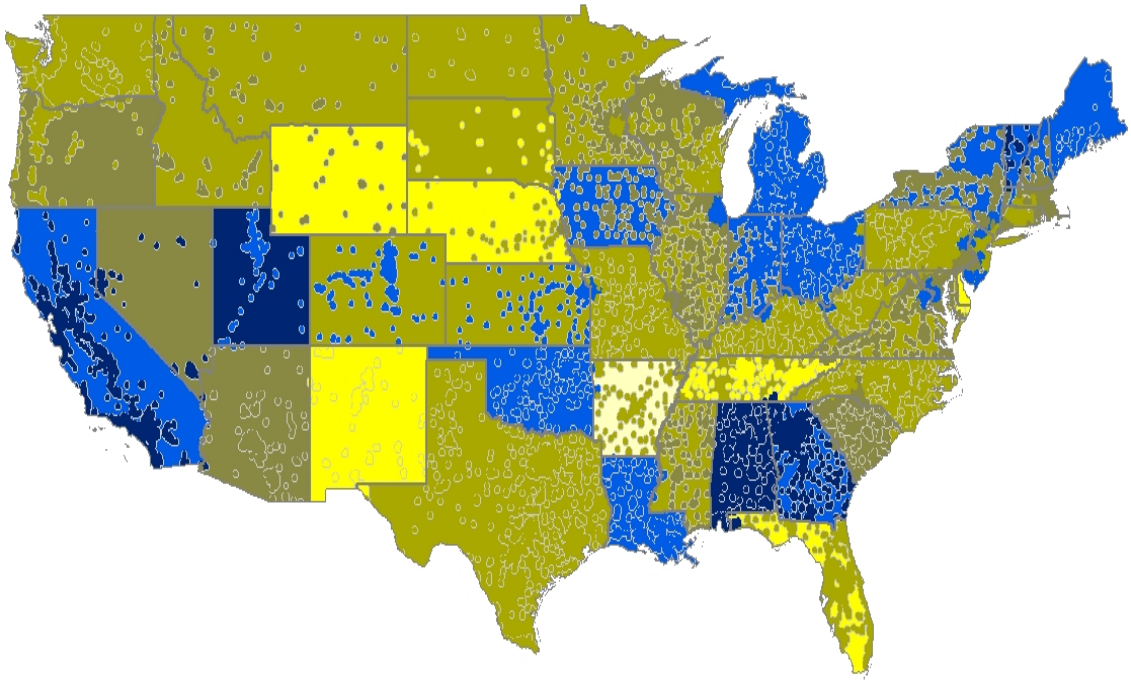
The bottom panel of figure 2 is similar, but reports on changes in IRI between the initial three year period, 1993-5, and the final three year period, 2005-7. The range of within region change in IRI over this period was - 77 to 20 inches per mile. We divide this region in six bins, each 17 inches wide. Recalling that decreases in IRI are good, in the bottom panel of figure 2, we assign each bin a color ranging from light yellow for the largest decrease, to dark blue for the largest increase.

Importantly, medium blue describes the bin ranging from - 9 to 8 inches, that is, the bin where mean regional IRI stays about constant. We assign dark blue to the bin containing

Figure 2: Urban and rural IRI in 1993-5 and changes in IRI from 1993-5 to 2005-7.



(a) International roughness index, 1993-5



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

Notes: Panel (a): State mean IRI for rural and urban interstate highways averaged over 1993-5. Panel (a): State mean change in IRI for rural and urban interstate highways from 1993-5 to 2005-7.

all regions where mean interstate IRI increased between 9 and 20 inches over our about 12 year period. From the figure, we see that only a handful of regions of the country saw 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 was relatively poor and their deterioration relatively rapid.

Returning our attention to figure 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 1 reports the American Society of Civil Engineers (ASCE) annual grades for US road infrastructure, converted from letter grades to a four point scale with A=4.0, B=3.0, C=2.0 and D=1.0.[7] These 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 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 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 seems consistent

[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 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

Notes: 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.

with the dramatic increase in VMT that we see in figure 1, again with the caveat that figure 1 describes the interstate, while table 2 describes trips on all roads.

We note that the different waves of the NHTS on which table 2 is based define speed slightly differently. This complicates 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, 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 smart-phones to measure travel behavior (e.g. Kreindler, 2018, Akbar, Couture, Duranton, and Storeygard, 2020), this suggests that phasing out the NHTS in favor of smart-phone 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 in 1980. This increase in the intensity of use occurs in spite of an about 20% increase in the extent of the network over this period. The increases to network extent, together with increased AADT means 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, US population increased from about 226 million in 1980 to about 309 million in 2010, an increase of about 37%, or about 1.0% per year. Thus, the lane miles of interstate highways grew at just above two thirds the rate for population (about 0.7 vs. about 1.0%), 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 2 maps initial IRI and changes over our study period and does not reveal obvious patterns. Interstates in the rust belt and California deteriorate. They 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.

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.

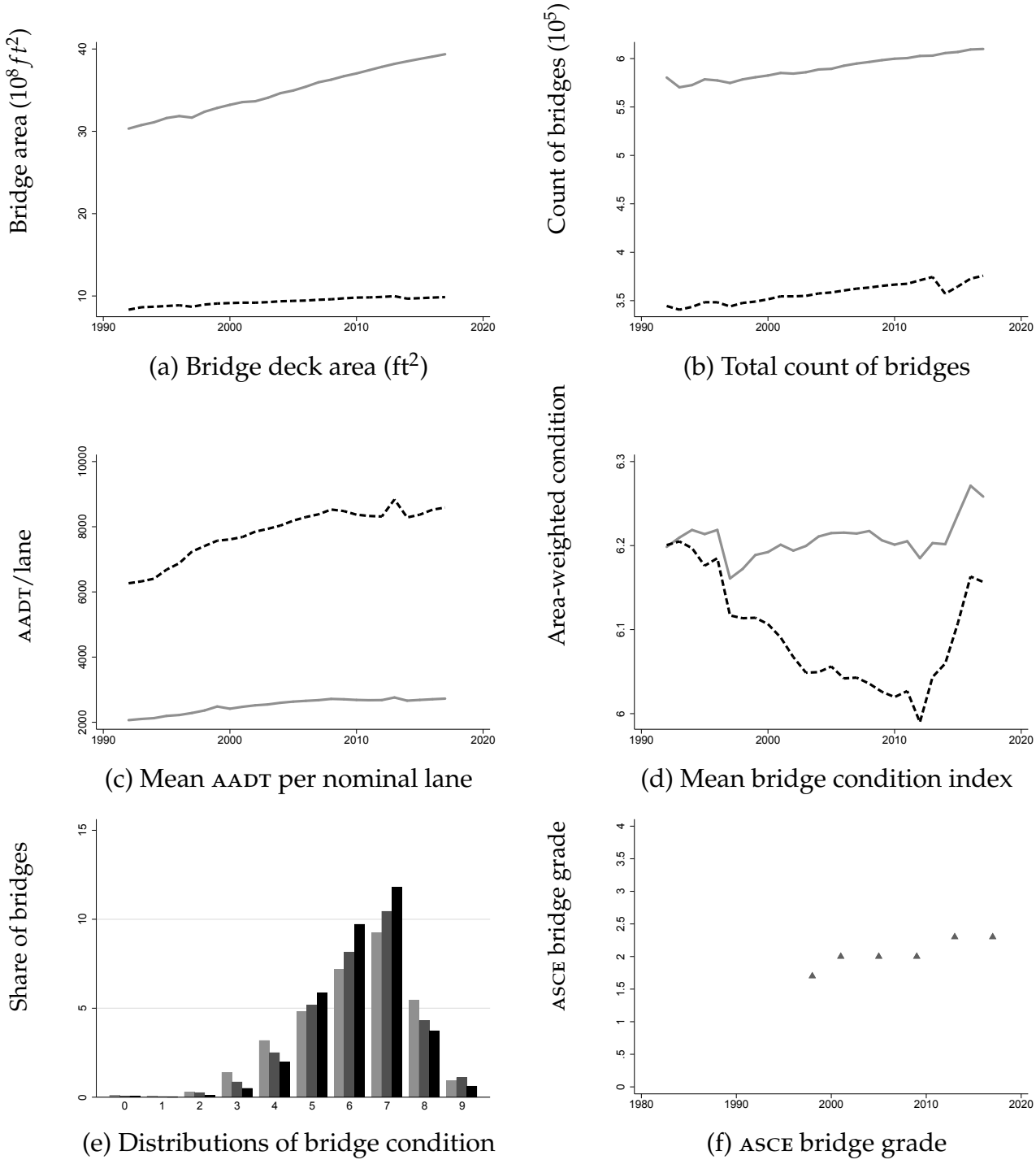
For the purposes of the NBI, a bridge is defined as

> *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 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 reports

Figure 3: Bridges: usage, stock, and condition



(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

Notes: 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. (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.

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 ft^2) 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%. Over the 27 year span of NBI data, this is about 0.9% 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% increase, or about 0.25% 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 to what we report in figure 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 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%, or about 1.25% per year. This is rapid compared to the increase in the number of bridges, but it 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 0-9, 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) reports the deck area weighted mean bridge condition index. While this measure exhibits some variance, its range seems small, about

[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.

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

0.25 of a point or one quarter of a category on any of the component condition measures. More importantly, 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, rather, 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' *failed condition*, out of service; '1' *imminent failure condition*, bridge closed; '2' *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 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 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). 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) reports the ASCE grades for US bridge infrastructure. These data are similar to those presented in figure 1 for highways and are the result of a similar process. Like the ASCE road condition index, they are available about every four years, but 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

[11] More precise definitions for these codes and codes 3-9 are provided in Federal Highway Administration (1995)

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 indicate pervasive disrepair, at least as measured by the National Bridge Inventory.

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 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' reflects three NTD modes, motor buses (MB), trolley buses (TB) and bus rapid transit (RB). Our data on light rail reflects two NTD modes, light rail (LR) and street car rail (SR). Subways report the NTD 'heavy rail' (HR) data. Commuter rail is the NTD mode CR. Demand response aggregates both demand response buses 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% 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 below.

Table 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% of all transit rides in the entire country. Chicago is second, with 6%, followed by DC, Los Angeles, Boston and Philadelphia. In total, these six districts account for about 60% of all transit rides in the country. Public transit usage is highly concentrated in a few large cities, particularly New York.

Table 3: Transit aggregate statistics by mode in 2008 and 2017 for the continental US

	Bus	Light Rail	Subway	Com. Rail	Van Pool	Dem. Resp.
			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

Notes: 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.

Table 4: Buses and subways in five biggest transit districts, means over 2014-7

	All modes	Bus				Subway			
	% Riders	Riders	%	Exp.	% Tot. Exp.	Riders	%	Exp.	% Tot. Exp.
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

Notes: 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.

The rest of table 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 New York subway system carries about 71% of all subway riders and about 31% of all public transit riders in the whole country.

The remaining five of the top six transit districts account for another 20% of all subway riders, with the residual 9% distributed across 8 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 it provides only 15% of the national total. The top six transit cities provide only about 36% 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% of all subway rides but accounts for only about 50% of expenditure. This suggests that this system is relatively efficient. A caveat applies. Our data on expenditure reflects 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 to ridership shares suggests that these large transit districts are providing public transit at a lower cost than smaller districts.

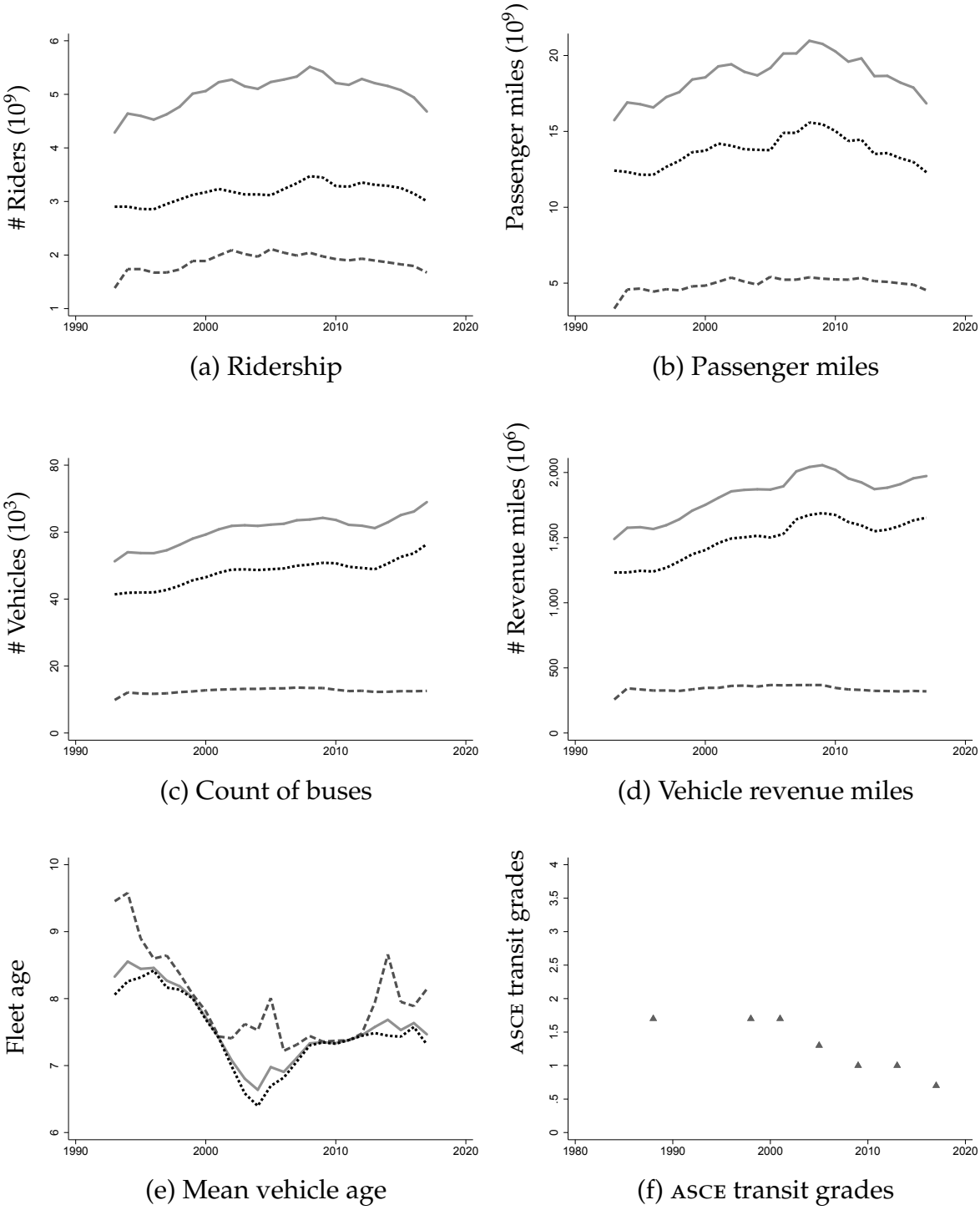
2.3.1 Buses

Figure 4 panel (a) 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 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. Rather it 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, about 2,300 miles per person per year.[12] Panel (b) 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% over our study period, while ridership increases and then decreases by only about

[12]Note that we here report vehicle miles travelled. On average, each a car in the US carries about 1.25 people (Couture, Duranton, and Turner, 2018), so person miles travelled is about 25% larger.

Figure 4: Buses: usage, stock, and age of the fleet



(a) Ridership

(b) Passenger miles

(c) Count of buses

(d) Vehicle revenue miles

(e) Mean vehicle age

(f) ASCE transit grades

Notes: Panels (a-e) 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 total for the six transit districts listed in table 4, and the dotted line gives totals for the remaining transit districts.

20%. Both the large and small transit districts follow about the same path, although more of the national variation in passenger miles comes from small transit districts.

Panel (c) 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% or about 1.4% 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, or about 33%. This is about 1.2% 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 increased dramatically in small districts.

Panel (e) 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 to 2017. Vehicle age in large and small districts track each other closely, although bigger districts generally have slightly older buses.

Table 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 the second 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 reflects change in the composition of bus trips, toward more congested places, it seem likely that decline at least partly reflects a decline in the speed of bus travel holding routes constant, and that this decline largely reflects the dramatic increases in AADT that we note in figure 1.

For reference, panel (f) 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, but also because the ASCE index aggregates information about all transit, not just buses. With that said, and recalling from table 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 1935-63. 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 post war years, to 6.4 billion in 1960 and further to 5.8 billion in 1963 when their data end. For comparison, in table 3 we see that bus ridership was about 5.5 billion in 2008 and 4.7 billion by 2017. For comparison, 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 post-war years than it is now. In part, this decline is attributable to the rising motorization of the poor (Blumenberg, Manville, and Taylor, 2019).

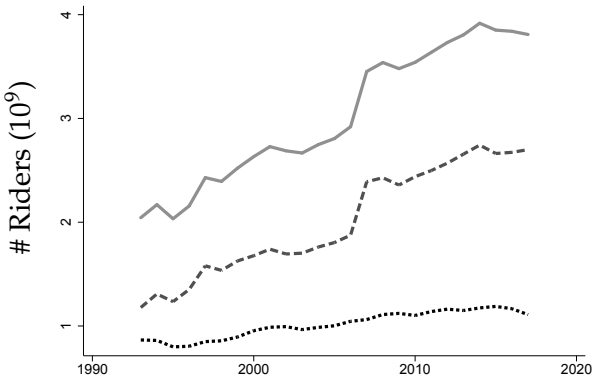
2.3.2 Subways

Figure 5 replicates figure 4 for subways. Panel (a) 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%, or about 2.8% per year. Panel (b) reports increases in passenger miles served by subways. This increases from about 10 to about 16 billion miles per year, an increase of about 60%. 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% per year, the growth rate in subway ridership is close to the 3.2% growth rate of VMT on the interstate highway system and significantly larger than the 1.2% growth rate of population.

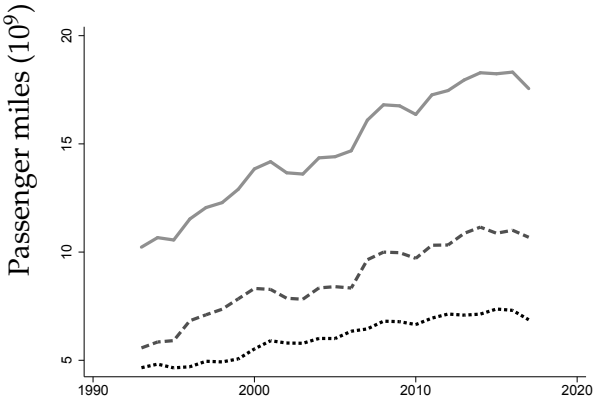
Given the importance of the New York subway system, figure 5 reports on the New York subway, the dashed line, and all other subways, the dotted line, separately. Panel (a) of figure 5 shows that almost all of the national increase in subway ridership over our study period reflects increases in ridership on the New York subway.

Panel (c) 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% increase or 0.6% 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 700 million, an increase of about 40%. This is also much smaller than the increase in ridership. Since the number of subway cars increased by about 15% 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

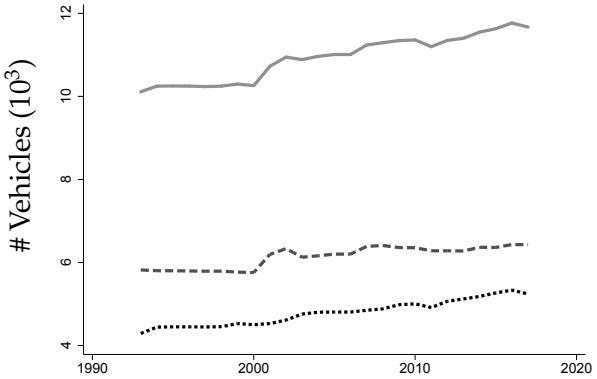
Figure 5: Subways: usage, stock, and age of the fleet



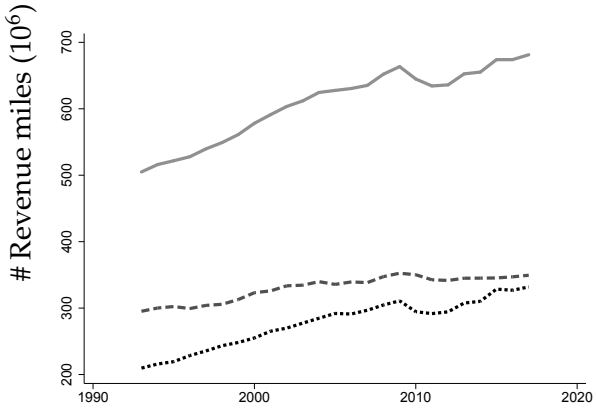
(a) Ridership



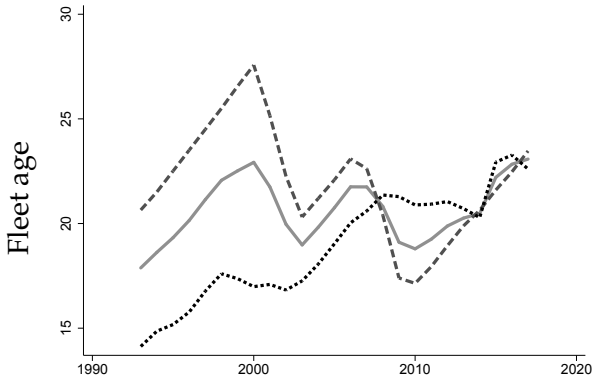
(b) Passenger miles



(c) Count of subway cars



(d) Vehicle revenue miles



(e) Mean age of subway car fleet

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

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 2 that the average speed of travel by subway is declining over our sample period.

Meyer *et al.* (1965) report on subway ridership during the period between 1935 and 1963. Curiously, subway ridership was fairly stable throughout this period, at about 2 billion riders per year. Comparing to panel (a) of figure 5 we see that this 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.

The last panel of figure 5, panel (e) shows the mean age of the fleet of subway cars. We see that the mean age of the subway car fleet shows 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 4 we see that the ASCE transit grades declined from a 'C-' to a 'D-' over the period 1988 to 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. 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, and for highways and bridges, goods. We now turn attention to the cost of these capital stocks.

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

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 we discuss above, 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 described above.

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 **?**. Before we discuss their findings, it makes sense to be explicit about what, exactly, they are describing.

As we saw in table 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 dollars 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% of all government expenditure on roads. Comparing with table 1, this is larger than the interstate highway system's share of lane miles, and not far off from its share of all VMT.

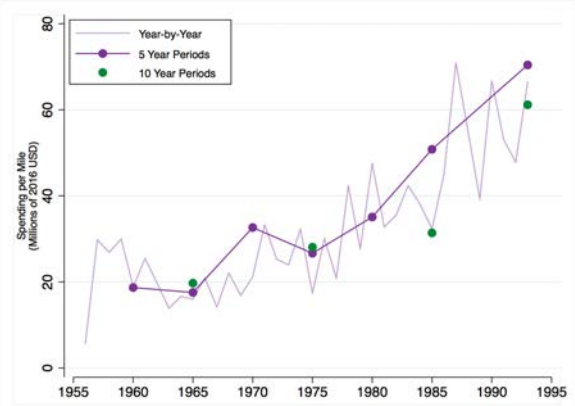
Brooks and Liscow (2019) estimate the cost of building a mile of interstate highway in every year from 1956 through to 1993. To accomplish this, they rely on 'PR511 data' to document the construction of interstate mileage by state and year. These data, which also formed the basis for Baum-Snow (2007), 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 (e.g., US Federal Highway Administration, 1985) which is available from about 1956 through to the present.

Panel (a) of figure 6 reproduces figure 2 from Brooks and Liscow (2019). It shows the ratio of total expenditure on the interstate highway system to total miles constructed in five year bins from 1960 to 1995. The figure shows a dramatic increase, from about 20 million dollars (2016) per mile, to about 70 million dollars per mile. This is about a 250%

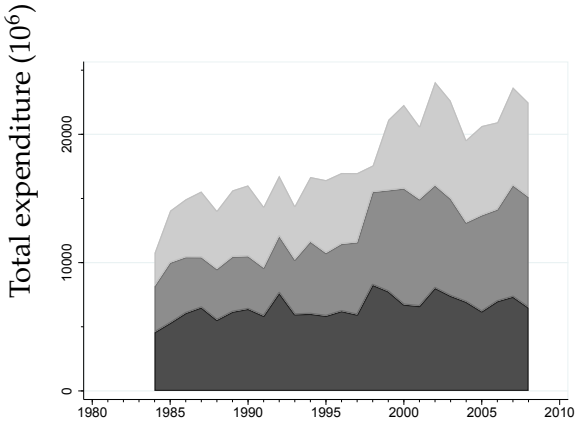
[14] Highway Statistics Table HF-2, 2008.

[15] The larger federal aid highway system received 68.8 billion dollars, including 59.2 billion for capital expenditure and 9.6 billion for maintenance (Highway Statistics Table HF-12b, 2008).

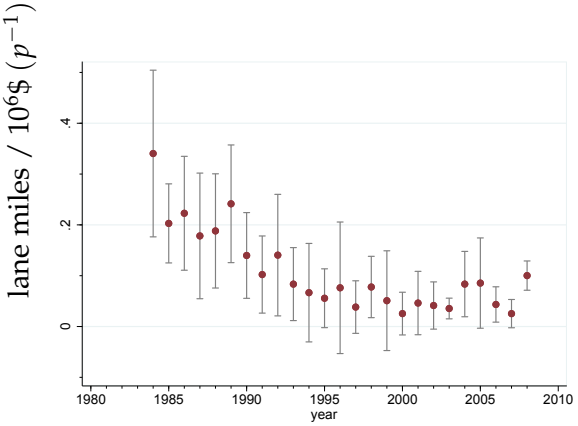
Figure 6: Total expenditure and construction cost per lane mile of interstate highway over time



(a) Construction cost per mile



(b) Total expenditure



(c) New lanes miles per million

Notes: (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 give 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. Figure (a) is reproduced from Brooks and Liscow (2019), figures (b) and (c) are from **?**.

increase in real terms, or about 7% per year. Brooks and Liscow (2019) show that this increase probably does not reflect increases in input and labor costs nor changes in the location or terrain where highways were built.

? 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 to 2007, and so the study period in **?** is more recent and shorter than that of Brooks and Liscow (2019). Like Brooks and Liscow (2019), **?** 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, **?** begin their analysis in 1984, a few years after the beginning of the HPMS.

Panel (b) of figure 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 and 7 billion dollars (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 and 10 billion dollars 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, e.g., snow removal, signage and minor maintenance.[16] This amount trends up from about 3 billion to about 7 billion dollars 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 dollars per year.

Panel (c) of figure 6 is also reproduced from **?**. Like panel (a) it 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 the millions of dollars *per lane mile* rather than *per mile* of highway. Examining panel (c) we see that in 1984-90, one million dollars of expenditure purchased about 0.2 lane miles. This fell to about 0.05 lane miles per million dollars in 2002-7. 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, **?** 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 single heavily loaded five axel combination truck, i.e., a typical tractor trailer rig (see, e.g., 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 *et al.*, 2012). On the basis of calculations available in Mannering *et al.* (2007), and recalling that a single lane of interstate highway can carry about 2200 cars per hour, a single combination truck causes

[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 below.

about as much damage to a highway as about 2.1 commute hours of automobile traffic.[17]

This has two implications. First, as pointed out by Small *et al.* (2012), if user fees are to target the vehicles that cause damage to the roads, they must target trucks, and in particular, trucks carrying heavy loads on a small number of axels. The HPMS reports crude measures of truck traffic. e.g., 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.

3.2 Bridges

Panel (a) of figure 7 reports annual aggregate maintenance expenditure on interstate bridges from highway statistics.[18] Total expenditure on interstate bridges increased from about 1 to about 3.5 billion dollars between 1984 to 2008. This is about a 9% 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 to 8.4 million dollars per year over this period. Thus, the approximately constant mean bridge condition that we see in figure 3(c) 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 $\mathbb{1}_{st}(\tau = t)$ an indicator that takes the value one if $\tau = t$ and zero otherwise.

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

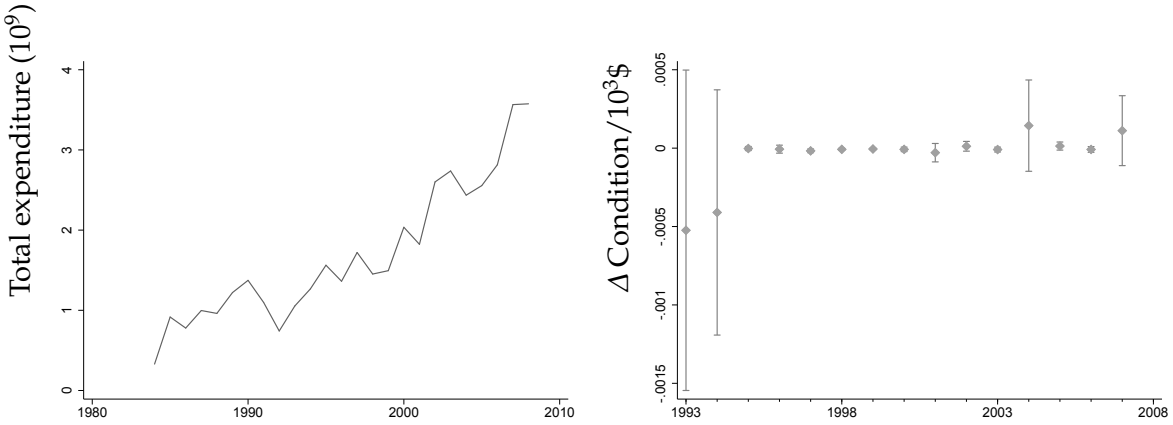
$$\frac{\Delta_{st}\text{BCI}}{y_{st}} = \sum_{\tau=1994}^{2016} \beta_\tau \mathbb{1}_{st}(\tau = t) + \epsilon_{st}. \tag{1}$$

Figure 7 (b) plots the resulting β_t values together with 95% confidence intervals. These estimates reflect the change in state mean bridge condition index resulting from 1000 dollars of expenditure. This figure is essentially flat, though a few years are estimated

[17] See Mannering *et al.* (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, in our discussion of the interstate highway system, we counted bridge expenditure as part of maintenance.

Figure 7: Expenditure and mean change in condition per dollar over time.



(a) Expenditure (b) Change in condition per dollar

Notes: (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.

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 is puzzling. The more so when we compare figure 7 (a) to figure 3 (d). 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 figure 7 (b) 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 figure 7 (b) 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, we expect the bridge condition to reflect maintenance expenditure very poorly. This is just what we see in figure 7 (b). This 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 **?**.

3.3 Public transit

Like the NBI, the NTD reports information about the costs of providing public transit. In particular, by transit district, year and mode, the NTD reports operating and capital costs. 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.

3.3.1 Buses

The solid line in figure 8 panel (a) 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 dollars over this period. This is an increase of 73% or about 2.8% 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 dollars, 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 5.

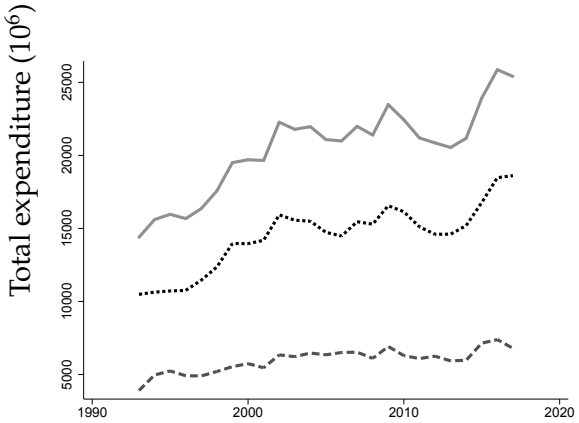
To investigate trends in the cost of bus based transit over time we estimate a regression similar to the one we conducted for bridges (1). More specifically, we estimate the following regression separately for the six large transit districts and the remaining smaller districts,

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

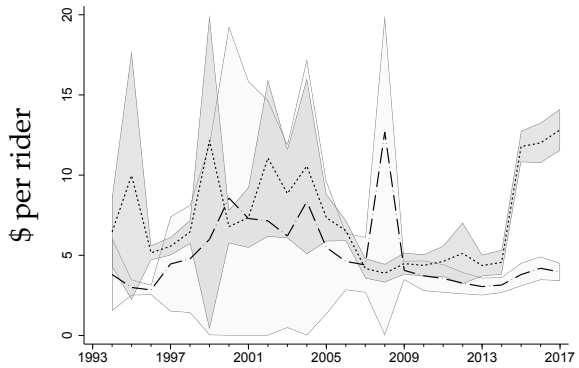
Here, i,s,t index transit districts, states, and years. c denotes total expenditure on buses and y indicates a measure of output, here riders. Thus, this is a regression of district year level expenditure per trip on year indicators. The magnitudes of the β's indicate transit district weighted annual means of total expenditure per rider.

Figure 8 panel (b) reports these fixed effects, along with confidence 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 grey area describes associated pointwise confidence bounds. The dotted line and medium grey shading provide the corresponding

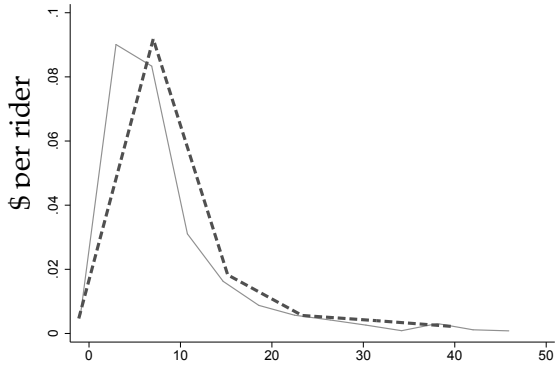
Figure 8: Total expenditure and unit cost for US bus service over time



(a) Expenditure



(b) Expenditure per rider



(c) Density of expenditure

Notes: (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 grey shading describes pointwise confidence bounds. Dotted line is mean annual cost per rider for all districts and medium grey shading describes pointwise confidence bounds. (c) Probability density function of district mean cost per rider from 2014-7. Dashed line gives the probability density function of total expenditure per rider. Solid line gives the probability density function of operating costs per rider.

estimates for all districts. Several of the year means are estimated imprecisely. We suspect this is partly due to the changes in accounting rules mentioned above. 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. There is a clear step up in the average during the last few years, to about 12 dollars 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 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 dollars 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.

3.3.2 Subways

Figure 9 replicates figure 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) we report total expenditure on subways by year. This amount rises from 8 billion dollars to about 16 billion 2010 dollars from 1992 to 2017, an increase of about 100%.

This is striking for two reasons. First, this is close to the amount of public expenditure on the interstate highway system. Second, it is about proportional to the increase in ridership over this time.

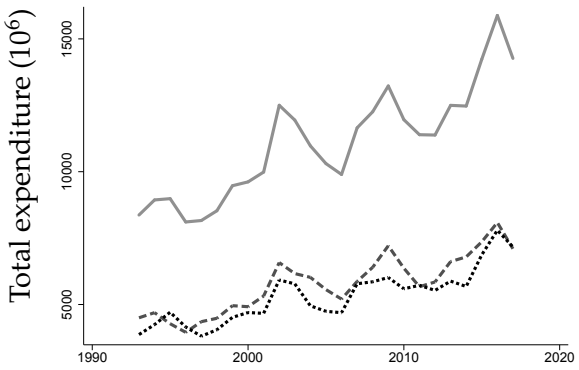
In table 4, we saw that New York accounted for about half of all subway expenditure from 2014-2017. In panel (a) we see that this relationship has been about constant over the course of our study period. New York has accounted for about half of all US expenditure on subways, even as expenditure has doubled.

Panel (b) 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 cost per rider has been trending up slowly on average even as they fall in New York. Costs per rider have increased from about 5.50 dollars to about 7 dollars on average and decreased from about 4 dollars to about 3 dollars in New York. As we mentioned above, our measure of total expenditure does not reflect capital depreciation or augmentation, so these estimates should be regarded with some caution.

4. Transportation infrastructure and economic activity

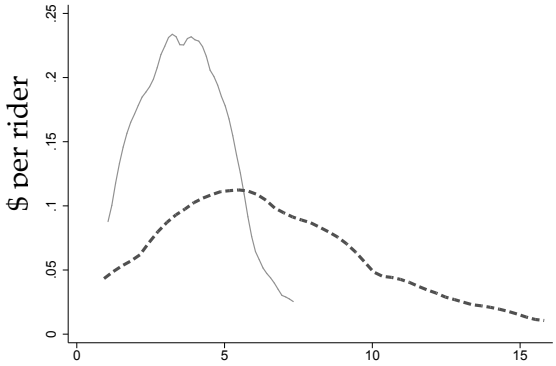
Over the past generation we have seen US highways, bridges and subways (but not buses) used much more intensively. In spite of this, objective measures of condition improved or stayed constant (although our data for subways only measure subway cars and may thus be too partial to be really useful). This has been achieved as a consequence of increases

Figure 9: Total expenditure and unit cost for US subway service over time



(a) Expenditure

(b) Expenditure per rider



(c) Density of expenditure

Notes: (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 grey shading describes pointwise confidence bounds. (c) Probability density function of district mean cost per rider from 2014-7. Dashed line gives PDF of total expenditure per rider. Solid line gives PDF of operating costs per rider.

in expenditure on all four classes of infrastructure. This expenditure has allowed at least modest expansions of capacity and maintenance that at least matches depreciation. Massive increases in infrastructure are not required reverse the decline of US transportation infrastructure. Not only is this infrastructure, for the most part, not deteriorating, much of it is in good condition or improving.[19]

[19]We are aware that international comparisons suggest US transportation infrastructure lags behind that of a number of other developed countries (e.g. 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.

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 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) examines 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, e.g., Baum-Snow (2019), Baum-Snow, Brandt, Henderson, Turner, and Zhang (2017) or Garcia-López, Holl, and Viladecans-Marsal (2015). A smaller literature finds qualitatively similar effects for public transit, e.g., Gonzalez-Navarro and Turner (2018), Heblich, Redding, and Sturm (2018) or 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 changes in metropolitan area employment between 1983 and 2003, and the initial stock of interstate lane miles. They find that a 10% increase in the stock of roads causes about 1.5% increase in employment over their study period. This effect is of about twice as large as the effect of a one standard deviation increase 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%. 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) compares 1990 to 2010 changes in employ-

ment and economic output in large Chinese cities to changes in their stock of highway lane miles and finds 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, while the latter regresses changes on levels. In a similar vein, Duranton, Morrow, and Turner (2014) finds 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 citywide lights at night' light intensity. On the other hand, Ahlfeldt, Redding, Sturm, and Wolf (2015) and Heblich *et al.* (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. For example, Leduc and Wilson (2013), Gramlich (1994) or Fernald (1999). 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 (Ramey, 2020).

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% expansion in a city's lane miles of highways causes a 1% 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, e.g., Gendron-Carrier, Gonzalez-Navarro, Polloni, and Turner (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.

[20]More precisely, the unit of observation in Duranton *et al.* (2014) is a 'commodity flow survey region'. These regions are often somewhat larger than metropolitan areas but do not straddle state boundaries.

To sum up, the evidence that infrastructure has important implications on 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 level of economic activity is mixed, 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.

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.

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:

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

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:

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

[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.

where the sub-utility $V(.)$ 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 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 *et al.* (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 *et al.* (2018) or Duranton and Turner (2018) for further discussions 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 (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:

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

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:

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

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

$$\frac{\partial Q_i}{\partial K_i} K_i + \frac{\partial Q_i}{\partial L_i} L_i = \nu_i \, Q_i \,, \tag{8}$$

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

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

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

5.2 Traveler optimization and decentralizing the first-best

There are several limitations to the analysis above. 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,

$$u = V(\sum_i B_i \, q_i) + c \,, \tag{10}$$

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:

$$c = m - \sum_i \left(w_i^T + t_i \right) \ell_i - r \,, \tag{11}$$

where t_i is a tax or subsidy for mode i, ℓ_i is traveller inputs, and r is a lump-sum monetary transfer that satisfies the balanced budget condition of the planner. With R, the aggregate

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

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 congestions 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 $\frac{Q_i}{L_i}$ 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 travelers maximizes the utility function (10) subject to the budget constraint (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:

$$\frac{B_i Q_i}{(w_i^T + t_i) L_i} = \frac{B_j Q_j}{(w_j^T + t_j) L_j} \,. \tag{14}$$

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 below, its is easy 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 the use equation (13), divide it by the corresponding first-order condition for the planner, use equations (7) and (8) to substitute the term in $\frac{\partial Q_i}{\partial L_i}$, 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: (i) between the utility weights B_i used by travelers and those of the planner Z_i ; between the average cost in terms of travel input considered by the traveler and the marginal cost

in the planner's calculation ; (iii) 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.

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 *et al.* (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% 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 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 1 reports 243 billion vehicle miles traveled on rural interstate highways in 2008 and 476 on urban interstate highways for the same year. With 1.25 passengers per vehicle (Couture *et al.*, 2018), this corresponds to a total of 899 billion person miles. For transit, table 3 reports 21.0 billion person miles for buses 2008 and 16.8 for subways in the same year.

For infrastructure expenditure K_i, section 3.1 reports an expenditure 22.5 billion dollars for the interstate highway system (inclusive of expenditure on bridges). For buses and subways in 2008, table 3 reports expenditure of 21.4 and 12.3 billions dollars, 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 2 above. 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% 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 for 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% 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% for our baseline calculation. We take the mean wage for 2008 to be about 23 dollars per hour as in Couture *et al.* (2018). This implies a cost of time of 11.5 dollars per hour.

For buses and subways, we assume a fare of 1.5 dollars per trip. Given the ridership figures reported in table 3, we get a fare of 4.9 dollars per hour for buses and 3.3 dollars per hour for subway. These figures imply a fare box recovery rate of about 40%, slightly above the figures reported by the NTD of about 25% for these two transit modes. Adding 11.5 dollars per hour for the cost of time, the cost of travel w^S is thus 16.48 dollars per hour for buses and 14.79 dollars per hour for subways.

To compute the cost of car travel, we consider an operating cost of 0.55 dollar 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 14.0 dollars per person hour. Adding 11.5 dollars per hour for the value of time of the travelers, we reach a total of 25.5 dollars per hour of highway travel. This calculation, so far, neglects the externalities associated with highway travel and only represents a private cost not

[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.

the social cost. Parry *et al.* (2007) estimate the external costs associated with pollution, congestion, and accidents to be about 0.10 dollar 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 dollar per vehicle mile due to worse accidents and more concentrated pollution for urban highways. This corresponds to about 2.55 dollars per hour. Hence, the social cost of travel, w^S for cars is 28.05 dollars per person hour. Recall that congestion is taken into account through the scale parameter ν_i above.

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 dollar per mile used above. With a federal as tax of 18 cents per gallon and a state gas tax at an average of 36 cents per gallon and fuel economy of 20 miles per gallon, 19.4 billions dollars of traveler costs goes towards paying for highways expenditure.

Putting all these numbers together, for the marginal value product of infrastructure investment, $\frac{\partial Q_i}{\partial K_i} = \frac{\nu_i Q_i}{K_i + w_i^S L_i}$, 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% more 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 above, 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 25.5 dollars 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 above one and a half times the weight they put on highway miles and about 20% 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 which ignores the fact that the hourly wage of highway travelers (generally by car) may be higher than that of transit users. If, instead of 23 dollars per hour, we assume 30 dollars 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 its ability to redistribute income. The planner may then increase infrastructure expenditure on transit to redistribute income given that transit, and buses in particular are 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.

6. Conclusion

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 dollars 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. Related to this, 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 water and sewer. 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 seems not to exist. The creation and interrogation of such data should also be a high priority for research.

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 above. 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, e.g. 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 inter-related congestion and environmental externalities.

This paper 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 international roughness index is relatively little studied. How does it contribute to travel speed and congestion? How does it is 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 above do not have a clear explanation. The first is the increase in the cost of interstate highways. While 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 above 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, and whether the project serves a corridor between cities or is a transit improvement within, etc. A better understanding of this heterogeneity is also a high priority.

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