# **Transportation Infrastructure in the Us**\*

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*Abstract:* We document the quantity and quality of us roads, bridges, buses and subways in each year over the last 20 to 30 years. Next, we investigate total expenditure and the unit cost for each type of infrastructure over about the same time period. Third, we survey available estimates of the effects of infrastructure on various sorts of economic activity. 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. This analysis suggests that the marginal contribution to mobility is lower for us transit expenditure than for highway expenditure.

Key words: Transportation infrastructure.

JEL classification: R4, но

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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.

We investigate whether us investment in the interstate highway network, bridges of all types, public transit buses, and subways, is consistent with the importance that each type of infrastructure plays in the economy. We proceed in four stages. First, we document the quantity and quality of each type of infrastructure 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 activity. 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.

Over the past generation, the condition of the interstate highway network improved consistently and system extent increased modestly while traffic and expenditure about doubled. Over about the same time period, expenditure on bridges about tripled while bridge traffic increased modestly. Unlike an average interstate mile, however, an average bridge is in about the same condition as it was a generation ago. 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. Total expenditure on the public transit bus fleet is about the same as the sum of capital and maintenance expenditure on the interstate highway system. Subways carry about twice as many riders as they did a generation ago, at about the same expenditure per rider. The mean age of a subway car has stayed about the same over our study period, but at more than 20 years old, this average car is quote old.

These sorts of facts must form the foundation of any debate over infrastructure policy. 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 nearly a trillion miles of vehicle travel per year, must surely be central to formulating policy. To assess the optimality of the patterns we observe, we imagine a planner whose object is to provide trips and who accounts for the public cost of capital and user inputs. At what rate must such a planner be willing to trade bus trips for car trips in order to rationalize the patterns we observe?

Transportation policy is a topic of ongoing policy interest. Our results help to provide this debate with sounder empirical foundations. On average, except (probably) subways, most us

		Rural		Urban			
Highway statistics	Miles	Lane miles	VMT(10 <sup>9</sup> )	Miles	Lane miles	VMT(10 <sup>9</sup> )	
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	

Table 1: US roads and highways in 2008

*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.

infrastructure is not crumbling. In addition, the evidence that infrastructure creates economic growth is ambiguous. As for public transit, the preponderance of federal 'highway' expenditure goes to roads whose primary function is to serve local trips. Purely redistributive issues aside, the rationale for a federal preference for roads over transit is unclear.

In order to evaluate policy, we proceed in three steps. First, we describe our endowment of infrastructure and its cost. Second, we survey what is known about the economic consequences of infrastructure provision. Third, we provide a simple theoretical framework with which to aggregate this information into policy assessments. This process serves to highlight important areas for further research in the recent and active literature on transportation economics.

# 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.<sup>1</sup>

Table 1 gives a broad description of the US road network. In rural areas, the interstate highway system consists of about one percent of all mileage, about 2% of all lane miles and about one quarter 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 lane miles, but 30% of VMT in the federal aid highway system. The interstate highway system is similarly important in urbanized areas.

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

<sup>&</sup>lt;sup>1</sup> 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 transport tension in policy debates, we preserve the rural classification in table 1.





*Notes*: All panels 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. In each figure the solid line describes national total, the dashed line describes the urban portion of the interstate, and the dotted line describes the rural portion.

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 a 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. Mehrotra, Uribe, and Turner (2019) and Turner (2019) analyze these data and describe the evolution of usage, extent, and condition of the network from about 1980 until 2007.<sup>2</sup>

Figure 1 presents four figures based on data from Mehrotra et al. (2019). Average annual daily

<sup>&</sup>lt;sup>2</sup>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.

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 portion, however both parts of the network are following similar trends.<sup>3</sup>

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 reflects the expansion of existing urban interstate segments and the reclassification of rural segments to urban.

Finally, the HPMs also 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.<sup>4</sup> Figure 1 reports lane mile weighted IRI

<sup>&</sup>lt;sup>3</sup>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.

<sup>&</sup>lt;sup>4</sup>For more detail on and the measurement and reporting of IRI, see Federal Highway Administration (2016) and Office of Highway Policy Information (2016).

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.<sup>5</sup> The dashed and solid lines report IRI on urban and rural portions of the interstate. Rural highways are in better condition than urban highways. Both rural and urban highways exhibit the same trend in condition. Both improve dramatically over our study period.

For reference, the Federal Highway Administration considers roads to be in *good* or *acceptable* condition 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.

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 than in 1980.

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 five 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.

Rural portions of the interstate highway system are used less intensively than the urban portions and rural segments are in better condition than urban 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.

# 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

<sup>&</sup>lt;sup>5</sup>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.

Figure 2: Bridges: usage, stock, and condition



*Notes*: All panels are based on NBI data. In each panel, 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.

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.<sup>6</sup>

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 2 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 2 reports the evolution of

<sup>&</sup>lt;sup>6</sup>https://www.fhwa.dot.gov/bridge/mtguide.pdf

all bridges (solid line) and the evolution of the stock of interstate bridges (dashed line).7

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 m<sup>2</sup>) rather than in the count of spans. In panel (a), we see the deck area of us bridges increased from about 280 to 360 million square meters 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 bridge deck area. This suggests that the provision of 'crossings' has focussed on a decreasing number of bridges which were expanded to meet their more important role in the road network. Consistent with this, 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.<sup>8</sup> 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 2 reports the resulting measure of mean AADT. We see that AADT on an average lane of a bridge increases from about 2000 to about 2800, 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 o-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'.<sup>9</sup> Panel (d) reports the deck area weighted mean bridge condition index. While this measure exhibits some variance, its range seems small, about 0.25 of a point or one quarter of a category on any of the component condition measures. More 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 an 2010, before recovering to almost its

<sup>&</sup>lt;sup>7</sup>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.

<sup>&</sup>lt;sup>8</sup>See, for example, Highway Statistics 2008, table HM-33.

<sup>&</sup>lt;sup>9</sup>See https://www.fhwa.dot.gov/bridge/britab.cfm#def for more detail on NBI bridge condition reporting.

	Bus	Lt. Rail	Subway	Com. Rail	Van Pool	Dem. Resp.	
	2017						
Riders(10 <sup>6</sup> )	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	
Serv. Miles (10 <sup>6</sup> )	1,972.7	124.0	681.4	347.0	229.5	1186.1	
Pas. Miles (10 <sup>6</sup> )	16,843.3	2,690.3	17,555.5	12,250.7	1,254.6	933.2	
Exp.(10 <sup>6</sup> )	25,272.2	5,521.2	13,480.8	9 <i>,</i> 029.7	189.5	5,083.2	
# NTDs	1,148	40	14	25	107	1,894	
	2008						
Riders(10 <sup>6</sup> )	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	
Serv. Miles (10 <sup>6</sup> )	2,029.3	86.26	652.1	309.0	154.4	967.2	
Pas. Miles (10 <sup>6</sup> )	20,972.0	2,080.3	16,805.1	11,032.0	968.0	832.5	
Exp.(10 <sup>6</sup> )	21,396.4	4,344.4	12,107.9	6,919.8	137.3	3,168.4	
# NTD	500	28	14	22	59	466	

Table 2: Transit aggregate statistics by mode in 2008 and 2017 for the continental US

*Notes*: Riders and service miles are in millions. Expenditure is in millions of 2010 dollars and transit districts are counted only if they have a positive number of vehicles.

## 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.

# 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 2 reports on the numbers of riders, vehicles, service miles and total expenditure by mode for 2017 and 2008. Table 2 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,

	All modes	Bus				Subway			
	% Riders	Riders	%	Exp.	% Tot.	Riders	%	Exp.	% Tot.
					Exp.				Exp.
New York	40.3	722.9	15.4	2765.7	10.9	2699.5	70.9	7098.4	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	1390.9	9.7
Los Angeles	4.0	290.0	6.2	1254.0	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	4679.4	100.0	25412.0	100.0	3808.9	100.0	14266.7	100.0

Table 3: Buses and subways in five biggest transit districts, means over 2014-7

*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. Columns 3-7 describe buses. Columns 7-11 describe subways. Percentages describe the percentage of national totals in a city.

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 attention on these two modes of public transit in the continental us.

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 in some of our figure below.

Table 3 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.

The rest of table 3 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 3 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 3 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 300m people in the US, this implies about 15 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. 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 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.

Finally, 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 closer, although bigger districts generally have slightly older buses.

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.

## 2.3.2 Subways

Figure 4 replicates figure 3 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 4 tracks the New York subway, the dashed line, and all other subways, the dotted line, separately. Panel (a) of figure 4 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 than did ridership. Interestingly, 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.

The last panel of figure 4, 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.

The NTD does not report information about 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.<sup>10</sup> A more detailed examination of subway capital stocks remains an important topic for further research.

<sup>&</sup>lt;sup>10</sup>For example, 'How Politics and Bad Decisions Starved New York's Subways' New York Times Magazine, Nov 18, 2017.



Figure 3: Buses: usage, stock, and age of the fleet

*Notes*: All data from the National Transit Database. In panel (b), passenger miles traveled on buses are only for 'full reporter' transit districts. In all panels the solid line gives national totals, the dashed line gives total for the six transit districts listed in table 3, and the dotted line gives totals for the remaining transit districts.



# Figure 4: Subways: usage, stock, and age of the fleet

(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.

# 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.

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 Mehrotra *et al.* (2019). 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 2008 expenditure on roads and highways by all levels of government at 181.42 billion dollars.<sup>11</sup> Highway statistics does not report total expenditure by all levels of government for the federal aid system, but does report this number for all state-administered highways, broken out into capital expenditures, 62.57 billion dollars, and maintenance, at 20.00 billion dollars, or 83 billion dollars in total.<sup>12</sup> Highway statistics does report state and federal expenditure on capital and maintenance the federal aid highway system, respectively, 59.24 billion dollars and 9.58 billion, or 68.82 billion in total.<sup>13</sup> This system substantially overlaps the set of all state-administered highways.

By contrast, in 2008 total capital and maintenance expenditure by state and federal governments on the interstate highway system was 20.00 billion dollars and 2.5 billion, respectively, or 22.5 billion in total.

Thus, at least in 2008, the interstate highway system was capital intensive relative to the rest of the federal aid system. The interstate highway system accounts for about 28% of total federal aid system expenditure, and 12.5% of all government expenditure on roads. Comparing with table 1,

<sup>&</sup>lt;sup>11</sup>Highway Statistics Table HF-2, 2008.

<sup>&</sup>lt;sup>12</sup>Highway Statistics Table HF-2, 2008.

<sup>&</sup>lt;sup>13</sup>Highway Statistics Table HF-12b, 2008.



Figure 5: Total expenditure and construction cost per lane mile of interstate highway over time

*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 Mehrotra *et al.* (2019).

these are much 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 5 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% increase, 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.

Mehrotra *et al.* (2019) 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 of this paper is more recent, but shorter than that of Brooks and Liscow (2019). Like Brooks and Liscow (2019), Mehrotra *et al.* (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, Mehrotra *et al.* (2019) begin their analysis in 1984 a few years after the beginning of the HPMS.

Panel (b) of figure 5 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.<sup>14</sup> 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 5 is also reproduced from Mehrotra *et al.* (2019). 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 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, Mehrotra *et al.* (2019) 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.

<sup>&</sup>lt;sup>14</sup>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.

Figure 6: Expenditure and mean change in condition per dollar('000) over time.



*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 dollar spent by year, weighted by bridge deck area.

# 3.2 Bridges

Panel (a) of figure 6 reports annual aggregate maintenance expenditure on interstate bridges from highway statistics.<sup>15</sup> 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 bridges increased only slightly from a base of about 350,000 over this period, this means that expenditure on an average 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 2(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  $\Delta_{st}$ BCI denote changes in the state mean bridge condition index between *t* – 1 and *t*. Finally, let *y*<sub>st</sub> 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,

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

Figure 6 (b) plots the resulting  $\beta_t$  values together with 95% confidence intervals. These estimates reflect the change in state mean BCI resulting from 1000 dollars of expenditure. This figure is

<sup>&</sup>lt;sup>15</sup>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.

essentially flat, though a few years are estimated very imprecisely. Experimenting with different variants of the bridge condition index or with expenditure per square meter of bridge area, leads to similar results. This seems not to be very informative, and highlights the usefulness of focusing attention on construction and maintenance of the interstate highway system as a way to learn about the evolution of construction and maintenance costs, as is done in Brooks and Liscow (2019) and Mehrotra *et al.* (2019).

#### 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 7 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. We should note that 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,

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



Figure 7: Total expenditure and unit cost for us bus service over time

(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 small 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 smaller 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.

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  $\beta$ 's indicate transit district weighted annual means of total expenditure per rider.

Figure 7 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 estimates for smaller 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 in the small districts, about what we would guess from table 2. There is a clear step up in the last few years for the smaller districts, 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 7 reports density of mean cost per rider from 2014 to 2017, by district. The dashed line in this figure gives the density of total expenditure per rider. The mode of this density is about 8 dollars per rider, but there is considerable variation around this mode. Similarly, 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 modal district in our sample serves a rider for about 9 dollars over the period 2014-7. Again, there is considerable variation around the mode. 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 8 replicates figure 7 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 3, 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 smaller subway districts and the cost per rider for the New York system. These estimates suggest that cost per rider has been trending up slowly in smaller systems even as they fall in New York. Costs per rider have increased from about 5.50 dollars to about 7 dollars in smaller systems 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.





(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 smaller districts. Dashed line is mean annual cost for New York. Dotted line is mean annual cost per rider for smaller 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.

# 4. Transportation infrastructure and economic activity

We here provide a brief survey of what is know 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 Miquel-Ángel, 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 (2018). 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 employment 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.<sup>16</sup>

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) estimate structural models of the effects of subways on Berlin and

<sup>&</sup>lt;sup>16</sup>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 across states.

London and find large effects.

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).

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.

# 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. We refer to highways, buses, and subways as modes of transportation. For each mode 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.<sup>17</sup> Simply put, dollars of infrastructure expenditure and person hours combine to produce person miles of travel. For tractability reasons, we assume that the production function for transportation services for each mode is constant elasticity of substitution:

$$Q_{i} = A_{i} \left( \theta_{i} K_{i}^{\rho_{i}} + (1 - \theta_{i}) L_{i}^{\rho_{i}} \right)^{\frac{\nu_{i}}{\rho_{i}}} .$$
(3)

Although this functional form is restrictive, we allow the shares,  $\theta_i$ , the elasticities of substitution  $\sigma_i = \frac{1}{1-\rho_i}$ , returns to scale  $\nu_i$ , and the productivity shifters  $A_i$  to vary across modes.

<sup>&</sup>lt;sup>17</sup>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.

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

$$W = V^S(\sum_i Z_i Q_i) + C.$$
(4)

where the sub-utility  $V^{S}(.)$  of the social planner is increasing and concave and *C* is the consumption of other goods. We call the parameter  $Z_i$  the social weight of a person mile traveled using mode *i*.

Some comments are in order. First, our main objective is to recover the social weights from observable data about traveler inputs, infrastructure expenditure, and travel mileage by mode. There are several reasons why social weights may differ across modes. First, if we only take into account the private cost of inputs and ignore the externalities associated with the different modes of transportation, the social weights embedded in equation (4) may reflect differences in the social desirability of transportation modes and the externalities attached to them. For instance, the social planner may assign a higher weight to a less polluting mode of transportation. Even, if we account for all external costs appropriately, there might be other reasons why social weights differ across modes. For instance miles traveled with a subway in the central part of a large city may be more valuable than miles traveled on a highway in a rural area.

Second, for simplicity and tractability, we treat travel distance as a good instead of an intermediate input that enables the consumption of goods (through shopping trips) or various forms of leisure. See Couture, Duranton, and Turner (2018) or Duranton and Turner (2018) for further discussions of these issues. Third, we assume a quasi-linear social welfare function to avoid complications arising from income effects. To a large extent, we are preoccupied with the efficiency of infrastructure expenditure across modes where such effects are unlikely to matter. Fourth, we also make the simplifying assumption that travel distances produced by different modes are perfect substitutes after accounting for their social weights. In spite of the linearity of the argument of  $V_S$ , decreasing returns to scale in the production of travel, e.g., from congestion and the construction of progressively more marginal transit routes ensure a unique interior optimum.

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

$$C = I - \sum_{i} (w_i + t_i) L_i = M - \sum_{i} (w_i L_i) - \sum_{i} K_i,$$
(5)

where  $w_i$  is the cost of traveler inputs for mode *i* and  $t_i$  is a tax (or subsidy if negative). We allow this cost to differ as modes differ in monetary costs and speed of travel. The second equality in equation (5) arises because the government's budget is balanced:  $\sum_i (t_i L_i) = \sum_i K_i$ . We note that the social planner should use the full social cost of traveler inputs  $w_i^S$  in equation (5).<sup>18</sup>

<sup>&</sup>lt;sup>18</sup>Below, we use estimates from past literature to compute the external cost of travel inputs. However, we do not make any correction for external costs associated with infrastructure expenditure. For instance, we ignore the external costs associated with co2 emissions when resurfacing highways. While it would be straightforward to add them to our framework, we lack detailed empirical estimates for them. This said, they are arguably smaller than the external costs associated with traveler inputs for highway travel.

We first consider a simple maximisation program by the social planner choosing both  $K_i$  and  $L_i$  for all modes to maximize social welfare (4) subject to the household budget constraint (5), keeping in mind that travel distance is produced according to equation (3). This situation corresponds to an unconstrained first-best. While this not realistic since the planner directly chooses traveler inputs, we show below how this optimum can be decentralized using taxes, subsidies, and transfers. Further below, we also discuss more constrained situations where the first-best cannot be implemented.

The first-order condition for social welfare maximization with respect to infrastructure investment for mode *i* is:

$$Z_i \frac{\mathrm{d}Q_i}{\mathrm{d}K_i} (V^S)' = 1, \qquad (6)$$

and the first-order condition with respect to traveler inputs is:

$$Z_i \frac{\mathrm{d}Q_i}{\mathrm{d}L_i} (V^S)' = w_i^S \,. \tag{7}$$

Equation (6) implies that the social value of the marginal product of infrastructure expenditure should be equalized across any two modes *i* and *j*:

$$Z_i \frac{\mathrm{d}Q_i}{\mathrm{d}K_i} = Z_j \frac{\mathrm{d}Q_j}{\mathrm{d}K_j} \,. \tag{8}$$

Because the marginal welfare from an extra person mile traveled is the same for all modes conditional on their social weight, equation (8) implies that the last dollar invested in mode *i* produces  $\frac{dQ_i}{dK_i}$  more passenger distance traveled, which is valued at its weight  $Z_i$  in the social welfare function. The product  $Z_i \frac{dQ_i}{dK_i}$  must be equalized with the equivalent product for mode *j*. Using equation (7), a similar set of conditions occur for traveler inputs  $L_i$ :

$$Z_i \frac{\mathrm{d}Q_i}{\mathrm{d}L_i} = Z_j \frac{\mathrm{d}Q_j}{\mathrm{d}L_j} \,. \tag{9}$$

Equations (6) and (7) also imply that, for a given mode *i*, the last dollar spend on infrastructure should have returns equal to the last dollar spend on traveler inputs:

$$\frac{\mathrm{d}Q_i}{\mathrm{d}K_i} = \frac{1}{w_i^S} \frac{\mathrm{d}Q_i}{\mathrm{d}L_i} \,. \tag{10}$$

Using the production function of travel (3), it is easy to show that:

$$\frac{\mathrm{d}Q_i}{\mathrm{d}K_i}K_i = \nu_i Q_i \frac{\theta_i K_i^{\rho_i}}{\theta_i K_i^{\rho_i} + (1 - \theta_i) L_i^{\rho_i}},\tag{11}$$

with a corresponding condition for  $\frac{dQ_i}{dL_i}$ . Summing these two conditions and substituting  $\frac{dQ_i}{dL_i}$  using equation (10) yields:

$$\frac{\mathrm{d}Q_i}{\mathrm{d}K_i} = \frac{\nu_i \, Q_i}{K_i + w_i^S \, L_i} \,. \tag{12}$$

We can now write again equation (8) using equation (12):

$$Z_{i} \frac{\nu_{i} Q_{i}}{K_{i} + w_{i}^{S} L_{i}} = Z_{j} \frac{\nu_{j} Q_{j}}{K_{j} + w_{j}^{S} L_{j}}.$$
(13)

This equation stipulates that, optimally, the cost per person mile 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 the traveler inputs for each mode. In fact, travelers make choose mode and the resources they devote to travel. A more realistic problem would be to have the planner decide first on infrastructure expenditure for all modes of transportation, and then to have atomistic travelers choose modes and inputs.

In this section, we show that the first best can be decentralized using mode-specific taxes and subsidies and direct fiscal transfers even if travelers using different weights for travel modes. We also show that traveler optimization also allows us to compare the weights put by travelers and the social planner on different travel modes.

A prerequisite of an analysis of traveler behavior is a description of the representative traveler. We assume such a traveler has utility,

$$U = V^T (\sum_i B_i q_i) + c , \qquad (14)$$

where  $q_i$  and c are the traveler's travel distance and consumption of other goods, respectively. Summing travel and consumption across consumers recovers the aggregate quantities used above,  $Q_i$  and C. The traveler's objective function differs from the planner's in two ways. While we keep a quasi-linear form, we allow for the transportation sub-utility of the representation traveler  $V^T(.)$ to differ from that of the social planner  $V^S(.)$ . Consumer may also 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 consumer is given by:

$$c = m - \sum_{i} \left( w_i^T + t_i \right) \ell_i - r , \qquad (15)$$

where *r* is a lump-sum monetary transfer that satisfies the balanced budget condition of the planner. Noting *R*, the aggregate monetary transfer, we have  $\sum_i t_i L_i + R = \sum_i K_i$ . We note a third difference with the planner's program. For the traveler, the cost of travel inputs  $w_i^T$  differs from the cost used by the planner  $w_i^S$  since travelers generate externalities, including in particular pollution and accidents for highway travel. The last difference with the planner's command solution is that travelers receive the average and not the marginal return to their travel inputs, as they ignore the congestion they inflict upon other travelers. Put differently, individual travelers

take travel decisions from other travelers as given. Their travel distance is equal to the speed that they experience  $\frac{Q_i}{L_i}$  multiplied by their individual travel inputs,  $\ell_i$ :

$$q_i = \frac{Q_i}{L_i} \,\ell_i \,. \tag{16}$$

We maximize the utility function (14) subject to the budget constraint (15) and the production of individual travel given by equation (16) for mode i to obtain:

$$B_i \frac{Q_i}{L_i} (V^T)' = w_i^T + t_i \,. \tag{17}$$

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

$$\frac{B_i Q_i}{(w_i^T + t_i) L_i} = \frac{B_j Q_j}{(w_j^T + t_j) L_j}.$$
(18)

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 for equation (13).

We can also use equation (17) and divide it by the corresponding first-order condition for the planner. After rearranging, we obtain:

$$t_{i} = \frac{B_{i}}{Z_{i}} \frac{(V^{T})'}{(V^{S})'} \frac{\frac{Q_{i}}{L_{i}}}{\frac{\mathrm{d}Q_{i}}{\mathrm{d}L_{i}}} w_{i}^{S} - w_{i}^{T}.$$
(19)

This expression shows that the tax that the planner should use will correct for the four differences between the traveler's and the planner's programs: (i) the weights  $B_i$  vs.  $Z_i$ ; (ii) the marginal utilities  $(V^T)'$  and  $(V^S)'$ ; (iii) the wedge between marginal and average cost, and (iv) the existence of other externalities in the use of travel inputs,  $w_i^T$  and  $w_i^S$ .

Assuming that the planner has the same utility function as the representative traveler and applies the same weights, expression (19) can be simplified as follow after using equations (10) and (12)

$$t_{i} = \frac{K_{i} + w_{i}^{S}L_{i}}{\nu_{i}L_{i}} - w_{i}^{T}.$$
 (20)

This corresponds to a standard Pigouvian tax where we take into account the wedge between average and marginal cost and other externalities associated with travel inputs. The first term on the right-hand side of equation (20) can be interpreted as the social cost of a unit of traveler input. Finally, we note that, to decentralize the first best, the fiscal transfer *m* 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.

# 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 (13). 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.

Starting with the returns to scale parameter in the production of travel,  $v_i$ , 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 instead of the more general constant elasticity of substitution of equation (3), they cannot reject constant returns despite the precision of their estimates. We thus assume  $v_H = 1$ . 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. Indeed, table 3 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, Gonzalez-Navarro, Polloni, and Turner, 2018). To avoid biasing our calculations against transit, we assume  $v_B = v_S = 1$ .

Turning to mileage by mode, 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 2 reports 21.0 billion person miles for buses 2008 and 16.8 for subways in the same year.

For infrastructure expenditure, section 3.1 reports an expenditure 22.5 billion dollars for the interstate highway system. For buses and subways in 2008, table 2 reports expenditure of 21.4 and 12.3 billions dollars, respectively.

Obtaining measures of  $w^T$ , the private cost per hour, and *L*, traveler inputs is more involved. Starting with traveler inputs, we measure a mean car speed of 31.6 miles per hour from the 2009 NHTS by dividing the sum of all trip distance by the sum of all trip times. 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 6 miles (or 10 kilometers), car speed increases to 39.5 miles per hour. Given the person miles of highway travel reported above, a speed of 39.5 miles per hour implies 22.8 billion person hours.

For transit, from the 2009 NHTS we calculate a speed of 10.4 miles per hour for bus travel and 11.7 miles per hour for subway travel.<sup>19</sup> Given the mileage for these two modes, we obtain 2.03 billion passenger hours for bus travel and 1.43 billion passenger hours for subway travel.

<sup>&</sup>lt;sup>19</sup>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.

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 car travel, we consider an operating cost of 0.55 dollar per mile, in line with federal guidelines for car travel reimbursement.<sup>20</sup> At a speed of 39.5 miles per hour for 1.25 passengers, this implies a vehicle operating cost of 17.4 dollars per person hour. Adding 11.5 dollars per hour for the value of time of the travelers, we reach a total of  $w_H^T = 28.9$  dollars per hour for the private cost of highway travel.

For buses and subways, we assume a fare of 1.5 dollars per trip. Given the ridership figures reported in table 2, we get a fare of 4.1 dollars per hour for buses and 3.7 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.

Putting all these numbers together, to quantify equation (12), we find that the marginal product of infrastructure investment is 1.32 miles per dollar for interstate highways, 0.40 miles per dollar for buses and 0.49 miles per dollar for subways. Using equation (9), these figures imply that implicitly the social planner puts more than three times as much value on a passenger bus mile relative to a passenger highway mile and about 20% more relative to a subway passenger mile. Alternatively, equating the marginal mileage per dollar of expenditure across modes would require multiplying highway infrastructure expenditure by a factor of 70.

This calculation, so far, neglects the externalities associated with travel, in particular highway travel. Parry, Walls, and Harrington (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 0.15 dollar per mile due to worse accidents and congestion while the other two modes have no external costs. Even with these conservative assumptions, we find that considering external costs has only a modest effect on our calculation. We find that the marginal product of infrastructure expenditure on highways is 1.14 miles per dollar instead of 1.32 without accounting for these externalities. This is still close to three times as much as with buses and more than twice as much as subways.

We can also use equation (18) 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 22.8 billion hours

<sup>&</sup>lt;sup>20</sup>With a federal as tax of 18 cents per gallon and a state gas tax with an average of 34 cents per gallon and fuel economy of 20 miles per gallon, we double count 2.6 cents per gallon. This makes a negligible difference to our results.

valued at 28.9 dollars each. This is 0.73 dollar per mile. The same calculation implies costs per mile of 1.51 dollars for buses and 1.30 dollar for subways. In turn, this implies the weight put on bus miles by travellers is just above twice the weight they put on highway miles and only about 15% higher 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 50 dollars per hour for highway travel and 15 for bus travel, the relative weights between bus and highway travel are about equalized. While this threefold difference may seem large, it corresponds to the interquartile ratio for the distribution of individual income in the us. 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 travellers 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. The World Economic Forum (?) also argues that the us lags behind many countries regarding the quality of its infrastructure. While casual observation agrees with these comparisons, this does necessarily not mean that world leaders in infrastructure have invested their resources wisely nor that it would be worth emulating them.

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.

These findings raise two questions. First, why is there such a diversion between objective measurement and public sentiment? Second, what does this suggest for infrastructure policy?

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 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 seem reflect annual infrastructure report card generated by the American Society of Civil Engineers.<sup>21</sup> These estimates are not founded in economic theory, and it is natural to suspect that they partly reflect the interests of the society that produces them.

This complicates the already difficult problem of infrastructure policy. While our efforts are clearly preliminary, we have tried to demonstrate here that calculating the user cost of infrastructure is a tractable problem. In this, we contribute to a large literature evaluating various costs associated with travel and infrastructure, e.g., the cost of pavement damage caused by trucks (Small, Winston, and Evans, 2012), the cost of congestion (Couture *et al.*, 2018, Kreindler, 2018)

<sup>&</sup>lt;sup>21</sup>The criteria on which these report cards are based are described here: https://www.infrastructurereportcard. org/making-the-grade/what-makes-a-grade/

and other auto related externalities (Parry and Small, 2005). On the other hand, as the conflict between our findings and the prevailing policy debate illustrates, an assessment of the optimality of the quantities of various infrastructure stocks appears to be difficult. This suggests that a natural pathway to improving infrastructure provision is an increased reliance on user fees and Pigouvian taxes, like congestion pricing and axle weight based user fees for trucks (Small *et al.*, 2012), and a decreased reliance on subsidies from general revenue for operating and capital expenditure. We could reasonably hope that an institutional framework in which infrastructure provision was more closely tied to its cost would direct resources toward higher value uses. In contrast, at present, user fees cover only a fraction of the cost of highways, subways and buses, while congestion is almost universally unpriced.

## 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. Storeygard, Akbar, Couture, Duranton *et al.* (2018). 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 a 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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