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

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Abstract: Between 1990 and 2008 the cost to construct a lane mile of interstate increased five-fold while the cost of resurfacing doubled. We consider four explanations for these increases: composition; changes in pavement durability; the institutional and regulatory environment; and input prices. Only changes in input prices explain the increase in resurfacing costs. None of the explanations explains the increase in the cost of new construction, though hard to observe changes in how highways are built seem responsible. A calibrated model of highway investment suggests that the gas tax revenues may cover the relevant user cost of capital for the US interstate.

Key words: *Interstate highways, Infrastructure costs, construction productivity.*

JEL classification: H54, R42, R53, E22

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1 Introduction

We estimate the costs of building and maintaining the US interstate highway system. We find that the price to improve pavement quality with resurfacing increased by almost a factor of two between 1990 and 2008 while the price to build a new lane mile of interstate increased more than five-fold between 1984 and 2008. We also develop and calibrate a model describing the optimal investment in the length and durability of highway system. We find that, despite sizable increases in the price of new lane miles and the price of improving pavement quality, the user cost of capital does not exhibit an upward trend and gas tax revenues may be sufficient to cover the cost of capital for the interstate system. In all, our evidence provides at most, limited support for the idea that US infrastructure spending is subject to some sort of 'cost disease'.

We consider four main classes of explanations for the increases in the price of new lane miles and improvements to pavement quality: 1) a composition effect reflecting a shift of resurfacing or new construction towards more difficult, e.g., urban, segments; 2) resurfacing or construction process has become more difficult, e.g., requiring application of more paving material; 3) changes in the institutional or regulatory environment that has decreased the productivity; 4) lastly, that input prices have risen.

For pavement quality, the data support only one of these explanations. The price of asphalt increased dramatically over the course of our study period. The product of this price change and the quantity of asphalt used in resurfacing can almost entirely explain the observed increase in the price of pavement smoothness. There is also evidence for decreasing marginal returns to effort: over time the interstate has become progressively smoother, with resurfacing resulting in slightly smaller improvements as the initial condition improves. Our efforts to explain the increase in the price of construction for new lane miles are less conclusive. We find suggestive evidence that the price increase for new construction reflects changes in pavement material and thickness, but increased materials costs play only a small role.

Together with Brooks & Liscow (2020), our results suggest the following stylized description of the evolution of the cost of the interstate highway system. First, the price of resurfacing about doubled between 1990 and 2008. About 70% of this increase is explained by increases in materials costs. Decreasing returns to effort also plays a role. Second, Brooks & Liscow (2020) finds that the price of new construction roughly quadrupled between 1970 and 1993, with suggestive evidence that this price increase reflects the rise of "citizens' voice". Our results suggest a similar increase between 1984 and 2008 and we also find suggestive evidence that highway characteristics changed in hard to observe ways and that the role of materials costs is likely small relative to the total. Third, over our study period, expenditure on other maintenance was about constant on a per lane mile basis.

We can divide the approximately 19b (2010 USD) 2008 annual expenditure on the interstate system into three components; resurfacing at 8.6b, new construction at 6.5b, and other maintenance at 3.8b. In light of the results above, this means that for the 45.6% of the budget used for resurfacing, we can explain price increases as a reflection of input prices. For the 20% directed to other maintenance, prices are not obviously rising. Finally, for the 34.4% of expenditure used for new construction, prices are rising rapidly and we lack a conclusive explanation, although we can eliminate some possibilities and have suggestive evidence for the role of citizen's voice from Brooks & Liscow (2020) and our results suggest a role for difficult to observe changes in how roads are built.

Though we document sizable increases in the cost of investing in highway length and smoothness, utilization and quality have improved over our study period and interest rates have fallen. To ascertain whether the user cost of capital has risen, we specify the planner's optimal investment problem. The planner makes an investment decision in extent and quality taking as given a user fee charged per vehicle mile traveled (gas tax) and the demand for highway driving. We derive equilibrium conditions that determine the optimal path of investment in highway extent and smoothness as a function of the interest rates and the price of investment in new lane miles and smoothness. Despite the rise in the cost of new construction and resurfacing, we find no clear upward trend in the user cost of capital and, more surprisingly, that the gas tax (low and about constant in nominal terms since 1993) may nevertheless be near optimal. Falling interest rates and rising utilization work against the rising price of new investment. Moreover, the increasing cost of constructing new lane miles in the future implies user costs are lower today.

These results are of interest for a number of reasons. First, infrastructure policy is the subject of active policy debates. Aging transportation infrastructure, low interest rates, and concerns over climate change have increased the prospect of larger federal investments in infrastructure. Because the interstate highway system is constructed to similar standards across locations and over time, it provides a useful special case for examining changes in the cost of infrastructure construction. The collection of detailed data on the physical characteristics and expenditures on the interstate highway system facilitates the measurement of costs over time.

Second, infrastructure is an important asset class and there has been speculation that US productivity in infrastructure construction has been stagnant or declining over the past generation.[1] Our investigation sheds light on this issue. To the extent that highways in the US are subject to

[1] Recent examples of exorbitantly expensive and delayed transportation infrastructure abound: the Boston Central Artery/Tunnel Project ("Big Dig"), New York City's Second Avenue Subway, San Francisco-Oakland Bay Bridge replacement, Seattle's Alaskan Way viaduct replacement, Maryland/Washington DC Purple Line project, etc.

a 'cost disease', it affects at most the 35% of highway expenditure devoted to new construction. Moreover, the US interstate network provides twice as much travel in areas that are on average more densely populated. We cannot reject the possibility that the progressive increases in the cost of new construction could represent welfare improving, if costly, design changes and not declining productivity.

Third, the benefits of the interstate highway system have been the subject of much recent research. However, investigations of its cost have been rudimentary. To the extent that welfare analysis of the Interstate requires an evaluation of costs and benefits, our results improve such welfare analyses by improving the precision with which we calculate costs.

2 Literature

The interstate highway system has been studied extensively. This includes estimates of its costs. These estimates range from periodic running totals of the total expenditure on the system, e.g., Lewis (1982) and Bennett et al. (2019), to efforts involving considerable econometric or economic sophistication. Among the latter, Brooks & Liscow (2020) is most closely related to this paper and performs an analysis similar to our estimate of the costs of new construction. Like us, they match a state-year inventory of new interstate construction to expenditure data from the Highway Statistics series. They use these data to estimate a regression that is similar to our construction cost regression.

With this said, the Brooks & Liscow (2020) investigation differs from ours in a number of ways. First, where we rely on the Highway Performance Monitoring System (HPMS) data to describe the highway system, they rely on the PR511 data. The PR511 data run from about 1950 until 1993 and track procurement contracts. Practically, they are similar to the HPMS, but are older and report less information. Unlike us, Brooks & Liscow (2020) focus entirely on the construction of new roadway miles, while we also consider expansion lanes and resurfacing. Partly this reflects limitations of their data, but partly it reflects the fact that they study the interstate when it was newer and maintenance was less important.[2]

Brooks & Liscow (2020) estimate that the cost of a mile of interstate construction increased by about a factor of four between 1970 and 1993. They find that proximity to wetlands, population density and slope each has some ability to explain the level of prices, but not its trend. Rather, they

[2] Figure 9 in the supplemental material compares mileage in the PR511 and HPMS data. They match closely. Lane miles, however, grow more quickly than does mileage during our study period. A comparison of the Brooks & Liscow (2020) expenditure data to ours indicates greater divergence. This is in part due the fact that they base their analysis on federal expenditure while we rely on state expenditure, which includes federal expenditure. We are grateful to Leah Brooks and Zachary Liscow for sharing their data for the purpose of this comparison.

find that trends in the price of housing near interstates explains the trends in the price of interstate construction. On the basis of this finding and some supplementary evidence, they argue that the increase in highway construction costs reflects increased citizen participation (and obstruction) in the planning process, a hypothesis the call 'citizen's voice'. While our data and methods are not exactly comparable to those of Brooks & Liscow (2020), our results seem to be consistent with theirs. We also find some evidence that changes in pavement thickness and materials choice play a role in the increase in the price of new construction. Input prices play a role, although it is likely small.

With this said, we find definitive evidence for the importance of input prices for the price of roughness. Therefore, while we cannot reject the "citizen's voice" hypothesis for new construction, we can do so for resurfacing. Most of the increase in the cost of resurfacing can be explained by increases in the cost of paving material.

Both Allen & Arkolakis (2014) and Duranton & Turner (2012) are primarily interested in the benefits of the interstate system, but provide basic estimates of its costs as well. On the basis of a 1982 estimate of 560 billion USD2007 of total construction cost in Lewis (1982), and 65 billion of annual maintenance, Allen & Arkolakis (2014) estimate that the total annual cost of the interstate system is about 100 billion USD2007 per year. From figure 1 (a), the extent of the network in 1982 was about 170,000 lane miles. Dividing, we have a total annual cost per lane mile of about 0.6 million. On the basis of 2006 construction cost estimates reported in Ng & Small (2012), Duranton & Turner (2012) conclude that construction costs between 27 and 89 million USD2007 per mile. Using an estimate of maintenance costs similar to that of Allen & Arkolakis (2014) and annualizing construction costs, leads Duranton & Turner (2012) to estimate total annual costs per lane mile of between 2 and 5.2 million USD2007 per lane mile. Compared to and Allen & Arkolakis (2014) and Duranton & Turner (2012), our analysis considers many years rather than one and explicitly treats resurfacing.

Our attention to resurfacing is nearly unique. We know of only one other paper to investigate the topic. Small & Winston (1988) provide a model of optimal pavement thickness for roads subject to periodic resurfacing, and calibrate this model. Their results are noteworthy for two reasons. First, they rely on an older, subjective, measure of pavement quality (Present Serviceability Rating) that predates the more modern 'International Roughness Index' around which our analysis revolves. Second, they provide the only evidence on the cost of resurfacing that we have seen, at 200,000 USD2010 per lane mile for urban interstates.[3] This is considerably higher than our estimates, which range from about 35,000 USD2010 per lane mile in 1990 to about 75,000 USD2010 in 2008 for an

[3] Small & Winston (1988) find that the cost to resurface a lane mile is 113,000 USD1984 per lane mile for urban roads, converting to 2010USD using the PPIACO, we have 200,000.

average (not urban) lane mile.

Finally, Smith et al. (1997) and Smith et al. (1999) investigate factors that affect highway construction costs. Smith et al. (1997) is based on a 1996 survey of state transportation departments. This survey asked respondents to evaluate the effect that various types of federal regulation had on the costs of highway construction. These surveys suggest that wetlands, historic sites, endangered species and hazardous waste sites were all associated with higher costs. Smith et al. (1999) assembles highway statistics data from 1990-4 describing construction expenditure and lane miles of public roads (not just interstates). Using a research design similar to our construction regression and Brooks & Liscow (2020), they investigate how expenditure responds to the count of endangered species in the state-year, to the number of environmental impact statements performed in the state-year, to the number of superfund candidate sites in the state and to the count of national historic register places in the state. They find suggestive evidence that environmental regulation drove up construction costs.[4]

In order to evaluate trends in the total user cost of capital, we develop an optimal capital stock model for the interstate highway system. While this exercise seems to have few precedents, Keeler & Small (1977) resembles it conceptually. Keeler & Small (1977) calibrate an older theoretical model developed by Mohring (1970) to estimate the optimal level of highway provision in a fully dynamic model. Keeler & Small (1977) is more general than our model in that it more completely specifies the value of the highway network. On the other hand, it provides estimates of construction and maintenance costs on the basis of nine California counties between 1947 and 1972, whereas we use national data from 1984 until 2008 and distinguish between resurfacing and other maintenance.

3 Data

Our estimation requires data describing the extent and condition of the highway network; the quantity and timing of investment; and road characteristics that may affect construction and resurfacing costs. This section describes how we construct such data. An appendix provides technical details.

3.1 Lane miles and roughness

As the primary source of funding for the interstate highway system, the US federal government requires state highway authorities to keep segment level annual inventories of the system and report them to the Federal Highway Administration. The resulting data are the Highway Performance

[4] For clarity, we note that Smith et al. (1999) rely on highway statistics Table SF12 to measure construction costs. As we discuss below, this table aggregates the SF12a data that we rely on to measure construction and resurfacing.

and Monitoring System maintained by the US Office of Highway Policy Information.[5]

The HPMS consists of two annual data sets, the 'Universe' and 'Sample' data sets. Both Universe and Sample data are available from 1980 until 2008, with 2009 available for a subset of states. Since only about half of the states report any HPMS data in 2009, we end our study period in 2008.[6] The HPMS went through three revisions between 1980 and 2009. These revisions preserved the basic structure of both data sets, although not all variables are common to all years.

Data collection for the HPMS is a huge undertaking and it is completed imperfectly. Counties or states occasionally fail to report part or all of the data required for either the Universe of Sample data and states sometimes take a few years to comply with changes in reporting requirements. Reporting for the Sample data is somewhat less complete than for the Universe data.

As its name suggests, the Sample data provides a detailed description of a carefully constructed representative sample of interstate segments (Office of Highway Policy Information, 2016). Each segment is identified by a unique segment-ID and we are able to track these IDs over time. The Sample data periodically updates its sampling frame and recreates the set of segments and segment-IDs from which it samples. This creates two problems. First, it sometimes disrupts our ability to track particular segments. Second, it means that new segment-ID's can reflect either new construction or a revision of the sampling frame. We rely on the Sample data to describe resurfacing, However, because of the periodic recreation of segment identifiers in the sample data, we rely on the Universe data to track the construction of new lane miles.

Beginning in 1988, the Sample data reports the International Roughness Index (IRI), the Federal Highway Administration's main measure of pavement condition. IRI reporting is substantially incomplete until 1990 and so we begin our analysis of IRI in this year.

IRI is calculated in two steps. First, a vehicle tows or carries an instrument along a lane of interstate, usually the right lane. The instrument creates a precise profile of elevation changes along the path it traverses. Second, this elevation profile is used to estimate the number of inches of suspension travel a typical vehicle would experience while traveling along this road. This number, denominated in inches per mile, is IRI (Federal Highway Administration, 2016). A newly resurfaced interstate segment rarely has an IRI below 50. 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 inches (US Department of Transportation, 2013). Summing over lane miles within a year gives an estimate of

[5]See, for example, https://www.fhwa.dot.gov/policyinformation/hpms/shapefiles.cfm. Our HPMS data came to us on a CD produced by personnel from the Office of Highway Policy Information.

[6]During 2009-10, the Federal Highway Administration converted the HPMS from its original tabular form to a GIS based data model. As a consequence of this conversion, data for 2010 is not available, and post-2010 HPMS data is not directly comparable to the older data.

the total inches of suspension travel to required traverse the entire network.[7]

We will generally think of the quality of the Interstate as being measured in inches, with more inches being worse and conversely. This allows a transparent mapping of IRI onto standard theoretical notions of depreciation and investment. Depreciation is an *increase* in system-wide inches. Investment results in a *decrease*. The price of investment is the price of reducing inches of roughness. This last definition seems particularly intuitive, it is the price of repairing a pothole.

The HPMS Sample data does not report expenditures on highways. However, for each segment-ID and year, the sample data reports a categorical variable indicating whether a segment was resurfaced during the year. The definition of this indicator in the HPMS, probably not by accident, matches closely to the definition of '3R' expenditure in the Highway Statistics data described below.[8] We use this variable to identify years when a segment is resurfaced.

We rely on the Universe data to construct our measures of total interstate lane miles. As the name suggests, the Universe data reports on every segment of the Interstate in every year. While the Universe data reports less detail than the Sample data, they allow us to calculate lane-miles of interstate by state-year precisely.[9] We measure new construction of lane miles as year-over-year increases in state lane miles.

Both Universe and Sample data report Average Annual Daily Traffic (AADT) for each segment. This is the count of vehicles traversing the segment on an average day during the year, a measure of how much service each segment provides. Multiplying by segment length, number of lanes and 365 days per year, we can use AADT to calculate Vehicle Miles Travelled (VMT) on the segment. Summing over segments allows us to calculate the total amount of service provided by the Interstate Highway system for any geography or time period.

3.2 Investment

The federal government finances much of the interstate system. Financing occurs in three stages. States are awarded *appropriations* by the Federal Government. States incur *obligations* to contractors for specific investments in the system. Finally, when the contracts are satisfied, the federal government transfers money to the states in order to discharge the contracts. These are *expenditures*. Leduc & Wilson (2013) provide a detailed description of this process.

The Federal Highway Statistics series is an annual report on appropriation, obligations, and

[7] Prior to 1988, the FHA relied on a more subjective measure of pavement condition, the Present Serviceability Rating(PSR). These data are available from 1980 onward, though states gradually stop reporting them with the 1988 requirement to report IRI. PSR and IRI are not directly comparable.

[8] See, for example, *Archive Highway Performance Monitoring System (*HPMS*) Data Item Descriptions: 1993 - 1998* item 50 and the footnote on table SF12a for Highway Statistics 1991.

[9] We note that the Universe data reports IRI, but reporting begins about four years later than the Sample data.

expenditures for the national highway system. These reports are available from the Federal Highway administration during our 1980-2008 study period.[10] We are primarily interested in expenditures and note that Highway Statistics reports the total of state and federal expenditures.

We rely primarily on two tables in Highway Statistics, SF12 and SF12a. Table SF12 reports total interstate expenditure under two main headings, 'capital outlay' and 'maintenance'. These categories do not correspond neatly to new construction and resurfacing, but their sum gives total expenditure by state-year. Table SF12a provides a more detailed description of expenditure. In particular, Table SF12a reports expenditure on 'Right of Way and Engineering', 'New Construction' and 'Major Widening'. We sum these three categories for our measure of construction expenditure. Table SF12a also reports expenditure on 'Reconstruction' and 'Rehabilitation, Restoration and Resurfacing'(3R). We sum these two categories for our measure of resurfacing expenditure. Table SF12a also reports expenditure on 'Bridge Work'. Our measure of maintenance expenditure is the difference between the sum of resurfacing and construction expenditure, and total expenditure net of expenditure on bridges. In this way, we use the categories reported in tables SF12 and SF12a to classify expenditure to correspond with the new construction and resurfacing that we observe in the HPMS as closely as possible.[11] By construction, our calculation of maintenance expenditure will not match maintenance expenditure reported in table SF12.

The exact categories of expenditure reported in Highway Statistics vary slightly over time. Later years tend to disaggregate categories reported in earlier years. We also note that Highway Statistics only reports the detailed expenditure breakdown of table SF12a beginning in 1984. This is well before the start of IRI reporting in the Sample data, but four years after the 1980 start of the Universe data. In consequence, we begin our analysis of new construction in 1984.

3.3 Segment and network characteristics

Much of our data on segment attributes derives directly from the HPMS. Both Sample and Universe data report whether each segment is urban or rural on the basis of whether a segment lies in an urbanized area or not.[12] Thus, we can also calculate the state-year shares of urban lane miles. Our data on AADT is also available at the segment-year level. The Sample data permits the calculation of the mean grade of each segment it describes. Therefore, even though the Universe data does

[10] In fact, the Highway Statistics series is available almost continuously from 1946 until the present at https://www.fhwa.dot.gov/policyinformation/statistics.cfm and https://www.fhwa.dot.gov/policyinformation/hsspubsarc.cfm

[11] For more detail on bridge expenditure and maintenance, see Duranton et al. (2020). In most years, the HPMS does not indicate whether particular segments are bridges or contain bridges.

[12] The Federal Highway Administration maps of urbanized area are based on the corresponding census maps, but are slightly adjusted (Federal Highway Administration, 2013).

not report grade, sampling weights in the Sample data allow the calculation of lane-mile weighted mean grade by state-year.

We do not observe whether segments are new construction in the Universe or Sample data. However, the Universe data allows us to calculate total miles, total lane miles and lane-mile weighted mean lanes by state and year. Taken together, this allows us to estimate the fraction of all new lane miles that are new mileage as opposed to expansions of existing segments.[13]

The Sample data also describes each sample segment in detail, e.g., shoulder width, subsurface drainage. We experiment widely with these data, but focus on two characteristics. First, the Sample data reports whether each segment is 'rigid', 'composite', or 'flexible'. A 'rigid' road is one that consists primarily of concrete slabs. A flexible road is one that consists primarily of asphaltic concrete, i.e., blacktop. A composite road consists of a combination of such layers, for example, a layer of asphaltic concrete over a concrete or gravel base. The Sample data also describe variation within these classes, although we abstract from this additional detail.

Second, the Sample data reports the 'structural number' for each fexible or composite segment. Structural Number is an index used by highway engineers to measure durability of a road (Mannering et al., 2007, Ch. 4). It is a weighted sum of the thicknesses of the various layers of gravel, concrete and asphaltic concrete that make up each segment.[14] For example, each inch of asphaltic concrete contributes about 0.41 to a segment's structural number, depending slightly on quality. Given this formula, we can sometimes use the level or change in structural number to estimate the volume of paving material used in a construction or resurfacing project. Structural number and surface type are reported only in the sample data. However, the Sample data sampling weights permit estimates of state-year values.

We also calculate some mean state network attributes from GIS data. Starting from the 2005 NHPN planning map of the interstate (Federal Highway Administration, 2005), we create a buffer extending 2.5 miles on either side the interstate. We use this buffer to calculate the attributes of land within the buffer from three GIS based data layers. First, from the 2001 NLCD (United States Geological Survey, 2011), we calculate the share of land within the buffer that is classified as urban. Second, also from the 2001 NLCD, we calculate the share of land within the buffer that is water or wetlands. Third, using a digital elevation map (United States Geological Survey, 2010), we calculate the mean elevation of the interstate within a state, as of 2005. Note that these measures vary only at the state level. We also experiment with GIS based measures of climate derived from

[13]The Universe data allows us to calculate total *segment* length (the total length of the interstate) and the average number of lanes, by state and year. If we assume that new segment miles have the same number of lanes as an average segment in the year before, this lets us estimate the share of new lane miles in a state-year that are expansions of an existing segment and the corresponding share due to the construction of new mileage.

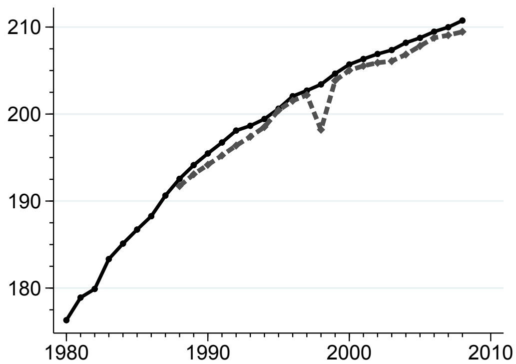
[14]Structural number is simply the thickness of concrete in inches for rigid roads.

the PRISM gridded climate data (PRISM Climate Group at Oregon State University, 2012), although we do not report the results.

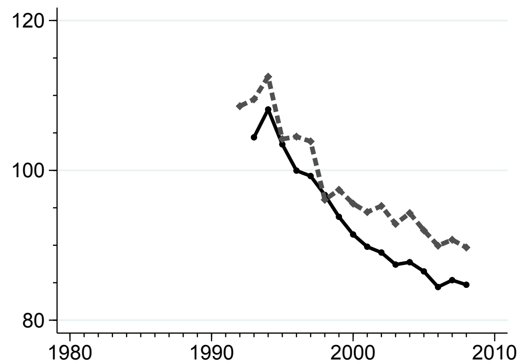
We measure the price of asphaltic or bituminous concrete by combining three data sources. The (Federal Highway Administration, 1987) reports annual average prices per ton for bituminous concrete used in federal highway construction from 1975 through 2006 (in 1987 dollars) while U.S. Bureau of Labor Statistics (2020) reports an index of the price of asphalt paving material from 2004 to the present, normalized to 2004. We combine these two and use the PPIACO series to convert all prices to the 2010 dollars we use as numeraire. We note that this is a national, not a state level, time series. Finally, to investigate the role of exposure to unionized labor markets, we rely on the Current Population Survey's report of the share of the labor force that is in a union by state and year.[15]

[15] Data constructed by Hirsch & MacPherson (2003) updated annually at unionstats.com.

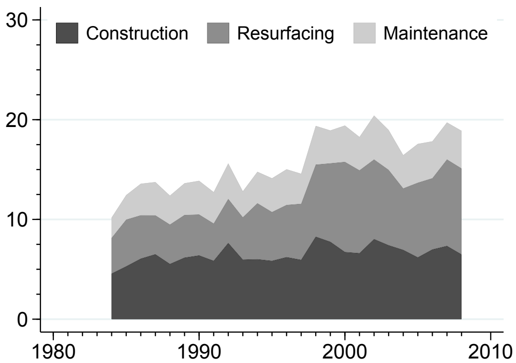
Figure 1: Trends in the state of the interstate highway system



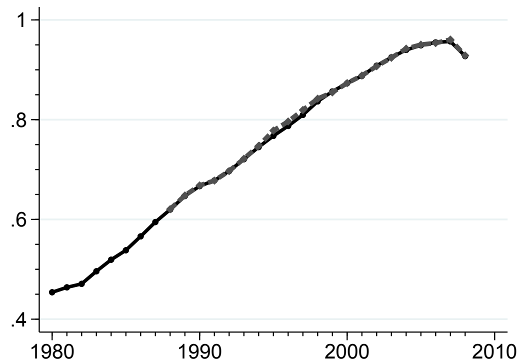
(a) Lane miles/1,000



(b) IRI



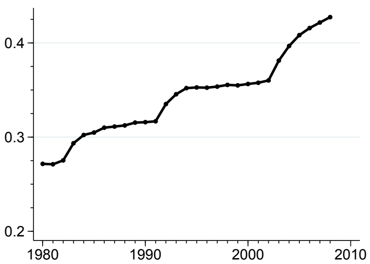
(c)Expenditure



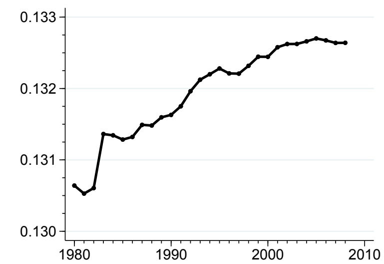
(d) AADT/10,000

Note: (a) Total Interstate Lane Miles by year ('000 miles). (b) Lane mile weighted IRI for the whole Interstate by year, (inches per mile). (c) Total Interstate expenditure by year and category. Dark gray is construction, medium gray is resurfacing, light gray is maintenance (10^9 2010USD). (d) Lane mile weighted AADT for the whole Interstate by year (vehicles/day). In each of (a,b,d) the dashed line gives an estimate from the Sample data, while the solid line is based on the Universe data.

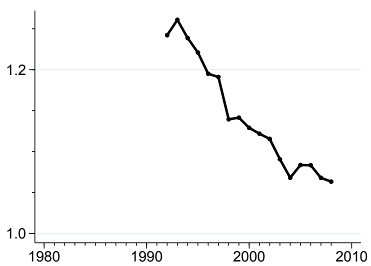
Figure 2: Lane mile weighted means of network characteristics, 1980-2008.



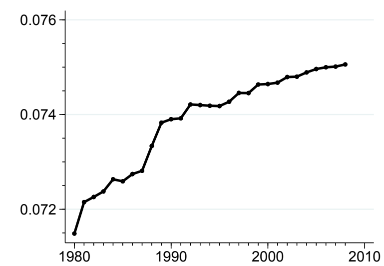
(a) Urban HPMS



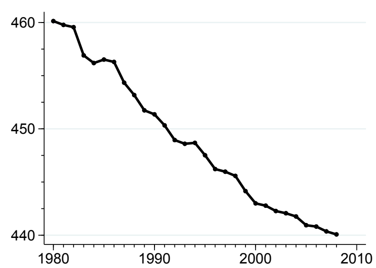
(b) Urban NLCD 2008



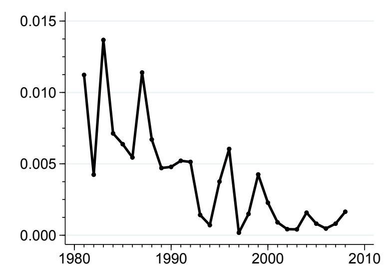
(c) HPMS Grade



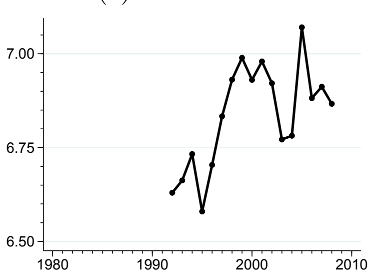
(d) NLCD Water



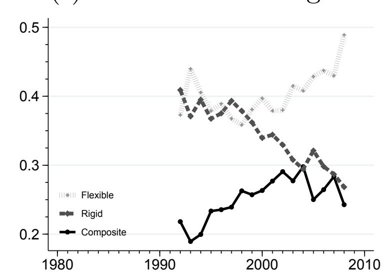
(e) Elevation



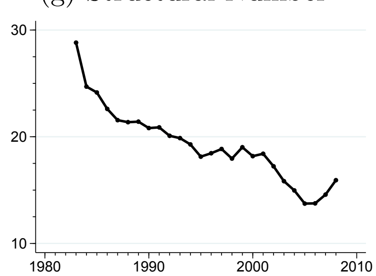
(f) Share New mileage



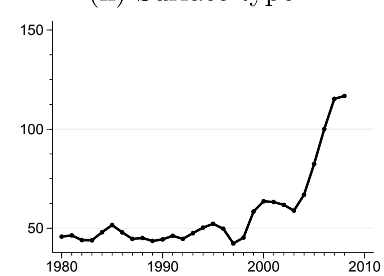
(g) Structural Number



(h) Surface type



(i) Unionization



(j) Asphalt price

4 Description

4.1 Lane miles, iri, Expenditure and aadt

Figure 1 describes trends in the evolution of the interstate highway system over our study period. In panel (a), we see that the interstate consisted of about 175,000 lane miles in 1980 and that this increased to about 210,000 by 2008. Figure 1 (a) reports two measures of lane miles. The solid line reports lane miles from the Universe data, while the dashed line reports estimates from the Sample data.[16]

In panel (b) we report the lane mile weighted average of IRI. Two features of this graph are noteworthy. First, mean IRI declines from about 110 inches per mile to about 85 inches per mile between 1990 and 2008, from just above the good-acceptable threshold to just below. Second, estimates based on the sample data track the Universe data closely, confirming the validity of sampling weights in the Sample data.

Figure 1 (c) shows total expenditure on the interstate system by year, across the three classes of expenditure we describe above, new construction, resurfacing and maintenance. The bottom dark region of figure 1 (c) indicates expenditure on construction in millions of 2010USD. The height of the intermediate region indicates expenditure on resurfacing and the height of the upper region indicates expenditure on maintenance. Thus, the upper envelope of the figure indicates total expenditure.[17]

Over the 1984-2008 period when this disaggregated expenditure data is available, total annual expenditure on the interstate increases from 10.2 b to 18.9 b. Total expenditure on construction increases more slowly than does expenditure on resurfacing. This seems like a natural consequence of an aging system. Maintenance expenditure is about constant. Since the extent of the system increases, this means that expenditure per mile on maintenance decreases over our study period. In 2008, expenditures on maintenance, resurfacing and new construction were 3.8 b, 8.6 b, and 6.5 b, respectively. Thus maintenance accounts for 20% of total highway expenditure, resurfacing for 45.6%, and new construction for the remaining 34.4% in 2008.

In panel (d) of figure 1 we report the lane mile weighted mean of AADT. AADT increased from about 4500 vehicles per day, to nearly 9000 vehicles per day, for an average lane mile of interstate. As in the other figures, estimates based on Sample data closely track those based on the Universe

[16] We note that the data on which figure 1 is based differs slightly from what we use in our regressions. In our regression samples we drop a small number of state-years which report zero maintenance (or construction) expenditure and non-zero resurfacing (or construction), or conversely, and similarly for construction. Figure 1 describes all available state-years. The same comment applies to figures 2 and 2.

[17] Between 1998 and 2008, our data (not shown) report expenditure on right of way separately. During this period, right of way expenditures are only 10-15% of construction expenditures and do not show an obvious trend.

data.

In short, the extent of the interstate has increased, its condition has improved, and the number of vehicles served per lane mile has about doubled. Total expenditure also about doubled.

4.2 Attributes of the interstate network

Figure 2 shows time series variation in the data described in section 3. There are ten panels in all. Each describes the lane mile weighted mean of an attribute of the stock of interstate lane miles by year.

Panel (a) is constructed from the HPMS Universe data. Over time, the share of lane miles in urbanized areas increases from 0.27 to about 0.44. This is a large change and reflects both the expansion of urbanized areas and the expansion of the network in initial urbanized areas. Like the corresponding NLCD based measure in panel (b), the HPMS based urbanization measure increases consistently over the whole study period.

Panels (b), (d) and (e) are based on time invariant state level indexes constructed from gridded digital elevations maps or remotely sensed land cover data as described in section 3. Variation in these figures reflects annual changes in the proportions of the network that lie in each state. These figures show that over time progressively larger fractions of interstate lane miles lay in states that had more urban cover in a buffer near the 2005 interstate, that had more water or wetlands in this buffer, and where the route of the 2005 interstate was at a lower elevation. In particular, in 1980, the 2.5 mile buffer strip on either side of an average lane mile of interstate was about 13.05% in urban cover and 7.1% water and wetlands cover in 1980, and these shares increased slightly but steadily to 13.25% and 7.5% by 2008. The elevation of a similarly average strip fell by about 40 feet over this time.

Panel (c) reports the network mean grade calculated from Sample data. This figure shows a clear decrease in mean grade of lane mile of the interstate. Panel (f) shows the share of new lane miles that were new mileage rather than expansions of existing segments.[18] This share is tiny throughout our study period and trending down. Taken together, panel (c), (e) and (f) suggest that during our study period interstate construction consisted primarily of expansions of existing segments in lower and flatter areas.

Panels (g) and (h) both present lane mile weighted network means based on the sample data. Panel (g) shows the share of all lane miles in each of three main surface categories, flexible (doted grey), rigid (dashed dark grey), and composite (solid black). Over the course of our study, we see

[18]We note that this share is an estimate. Construct these shares, we assume that all new mileage has the same number of lanes as an average segment in the preceding year, and use this value to calculate the share of all new lane miles that are part of new segments.

an increase in the share of flexible roads and composite roads at the expense of rigid roads. Some of this change reflects the conversion of rigid roads to composite by the addition of an asphaltic concrete layer. Panel (h) shows the lane mile weighted mean of Structural Number. Over the period during which we observe these data, 1990 to 2008, structural number trends up, unevenly, from about 6.6 to about 6.9. This increase is consistent with the construction of progressively more durable roads or the accumulation of paving material on the roads as a consequence of ongoing resurfacing. Recalling our earlier discussion, a one inch layer of asphaltic concrete will contribute about 0.4 to the structural number of a road, so trends in structural number are consistent with an average interstate lane mile consisting of an extra 0.75 inches of asphaltic concrete in 2008 than in 1990.

Panel (i) is based on state-year level unionization data describing the percentage of the work force that is unionized in each state-year. Thus, variation in this figure reflects both changes in unionization within states over time and changes to how the network is distributed across states. Panel (h) shows the price per ton of asphaltic concrete. This series is flat from 1980 until the early 1990s, and then increases from about 50 to about 125 dollars per ton. Note that our IRI data runs from 1990 to 2008, the period during which the price of asphaltic concrete is increasing rapidly.

Summing up, over the course of our study period, the network shifted towards areas that were flatter, lower, wetter and more urban. The interstate's exposure to unionized workers decreased and the price of paving material increased dramatically. New construction became even more focused on expansion lanes rather than new mileage, the structural number of an average lane mile increased and the type of surface shifted from rigid toward flexible pavements.

5 Econometric model

We are interested in measuring trends in the price of roughness and new construction. In addition, we would like to establish whether such trends are related to road or state attributes that suggest an explanation for the trend. This requires that we develop two regression specifications for each of roughness and construction; one to measure trends in prices and a second to investigate whether the average trend can be attributed to segments with particular attributes.

Our data are organized by road segment, state and year; $j \in J$, $s \in \{1, ..., 48\}$ and t. Let L_{jst} indicate total lane miles of interstate highway for segment j in state s and year t and let L_{st} indicate lane miles of interstate highway in state s and year t. Omitting subscripts for legibility, let Q indicate the quality of a length of interstate. Quality is measured in inches of suspension travel, so Q indicates the inches of suspension travel required to traverse a length of road. Define $q = Q/L$ to be inches of suspension travel per mile traveled along this road, that is, IRI. Here and throughout, we adopt the convention of using lower case letters to indicate per mile interstate attributes and uppercase to indicate aggregate attributes.

Let I indicate total expenditure. We are interested in three subclasses of expenditure, I^L, I^Q, and I^M, where $I = I^L + I^Q + I^M$. These are; expenditure on new lane miles, expenditure on resurfacing, and expenditure on maintenance that does not directly impact resurfacing or new construction.

Let Δ indicate first differences. Thus, $\Delta L_{st} = L_{st} - L_{st-1}$ is change in lane miles. Let x denote other attributes of a given section of roadway. For example, whether it is urban, lies in a wet region or is hilly.

We would like to estimate the price of a lane mile of interstate, p^L, and the price to reduce the roughness of the interstate by one inch, p^Q. We begin with the price of roughness and then turn to the price of new lane miles.

5.1 Resurfacing regressions

We estimate the price of an inch of roughness using the segment-by-year Sample data. The sample data reports an indicator for whether a segment was resurfaced in each year. Denote this indicator by $\mathbb{1}_{jst}(q)$ and define it to take the value one if the segment j in state s is resurfaced in year t, and zero otherwise.

We can now estimate the effect of resurfacing on roughness,

$$\Delta q_{jst} = C_0 + C_1 \mathbb{1}_{jst}(q) + C_2[\mathbb{1}_{jst}(q)t] + \text{Controls}_{jst} + \epsilon_{jst}. \tag{5.1}$$

Here, C_1 gives us the conditional mean difference in roughness between resurfaced and unresurfaced segments when $t = 0$ (1990) and C_2 gives us the rate at which this difference changes over time. We present results using different permutations of the following controls; state indicators, year indicators, state-year indicators and segment indicators.

In equation (5.1), C_1 and C_2 measure the change in roughness from resurfacing in inches per mile. We would like to know the price per inch to reduce roughness. To produce such an estimate, first let L^Q_{st} denote lane miles of interstate resurfaced in a state-year. We can then calculate resurfacing expenditure per resurfaced mile as,

$$\imath^Q_{st} \equiv \frac{I^Q_{st}}{L^Q_{st}},$$

in millions of dollars per lane mile. We next regress change in roughness on the interaction of resurfacing expenditure per mile and the resurfacing indicator,

$$\Delta q_{jst} = A_0 + A_1 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}\right] + A_2 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}t\right] + \text{Controls}_{jst} + \epsilon_{jst}. \tag{5.2}$$

Because the left hand side is denominated in inches per mile and the units of $\mathbb{1}_{jst}(Q)\imath^Q_{st}$ are millions of dollars per resurfaced lane mile, the units of A_1 are inches per million dollars. A_2 is the same as A_1, but it measures the rate at which A_1 changes, i.e., inches per million dollars per year. Thus, $A_1 = 1/p^Q_{1990}$ and $A_1 + A_2t = 1/p^Q_{1990+t}$, We consider the same set of controls in this regression as in 5.1.

Much of the variation in expenditure reflects state-year level expenditures reported in Highway Statistics. Given this, we cluster standard errors at the state-year level in all resurfacing regressions.[19]

We experimented with other parameterizations of the trend in the price of roughness. The data do not allow us to determine whether the rate of change is different in different parts of our 1990 to 2008 period of analysis. Given this, we discuss only the simple linear specification.

We suspect that HPMS occasionally reports construction or resurfacing in a different year than the associated expenditure is recorded in Highway Statistics. We drop the small number of state-years where resurfacing expenditure is positive in Highway Statistics and the HPMS reports no resurfacing, and conversely.

Our data will indicate an increase in the price of roughness. In order to attribute this increase to potential causes, we allow the trend in the inverse price of roughness to vary with segment or state characteristics. For a given segment or state attribute x_{ist}, this leads to the following generalization of (5.2),

$$\begin{aligned}\Delta q_{jst} = {} & A_0 + A_1 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}\right] + A_2 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}t\right] + A_3t \\ & + B_1 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}x_{jst}\right] + B_2 \left[\mathbb{1}_{jst}(Q)\imath^Q_{st}x_{jst}t\right] + B_3x_{jst} \\ & + \text{Controls}_{jst} + \epsilon_{jst}.\end{aligned} \tag{5.3}$$

In this regressions, we interpret A_1 and A_2 as we did in equation (5.2) when $x = 0$. As x varies, B_1 measures the mean change in base year price and B_2 measures the 'cross-partial' term, the rate at which the trend in price changes with changes in x. For example, we generally find that if x is a measure of how urban is the state or segment, then $B_1 > 0$ and $B_2 < 0$. This means that, all else

[19]It is natural to think of equation (5.2) as an equation of motion for segment quality. This suggests that we think carefully about the depreciation process. In particular, this suggests including a measure of AADT on the right hand side of equation (5.2). We experimented with such specifications and concluded that our measures of AADT were too noisy to be informative about pavement depreciation rates.

equal, one million dollars reduces roughness by a smaller amount on more urban roads in 1990, but that this urban penalty decreases over time.

5.2 State-year construction regressions

We would also like to estimate the cost of construction for new lane miles, p^L. We proceed much as we did for our segment level resurfacing regressions, adjusting for the fact that our data on lane miles is at the state-year level.

In particular, we estimate,

$$\Delta L_{st} = A_0 + A_1 I^L_{st} + A_2[I^L_{st}t] + A_3 t + \epsilon_{st}. \tag{5.4}$$

This equation relates state-year change in lane miles to state-year construction expenditure. We denominate expenditure on lane miles in millions of dollars per year. Because the dependent variable is measured in lane miles, A_1 gives lane miles per million dollars of expenditure when $t = 0$ (1984). A_2 gives the rate at which this inverse price changes over time. As for our resurfacing regression, this is an inverse price, $A_1 = 1/p^L_{1984}$ and $A_1 + A_2 t = 1/p^L_{1984+t}$. Increases in A_1 indicate that a million dollars of construction expenditure buys more, so the price is lower. A_2 is typically negative, which means that with each successive year, one million dollars buys fewer lane miles, and hence that the price of lane miles is increasing.

The data show that the price of new lane miles has increased over our 1984 to 2008 study period. It does not provide strong evidence that this rate of increase is faster or slower in different parts of our study period. Given this, as for our roughness regressions, we present only the linear specification. Because these data are relatively coarse, our ability to include control variables is limited, however, in some specifications we include state indicator variables.

We are concerned about measurement error and we respond two ways. First, and as in our resurfacing regression, we drop a small number of state-years with impossible combinations of construction and expenditure, one quantity positive and the other zero. Second, we conduct an instrumental variables estimate. Specifically, we exploit variation is the four year lag of total state interstate appropriations. The rationale for this instrument is similar to that given in Leduc & Wilson (2013). Instrument validity requires that lagged appropriations predict the expenditure, but not be related to measurement error. In fact, lagged appropriations strongly predict expenditure, and it seems reasonable to suppose that they do not anticipate mismeasurement of expenditure.[20]

Much as in our analysis of roughness, we would like to understand the extent to which the

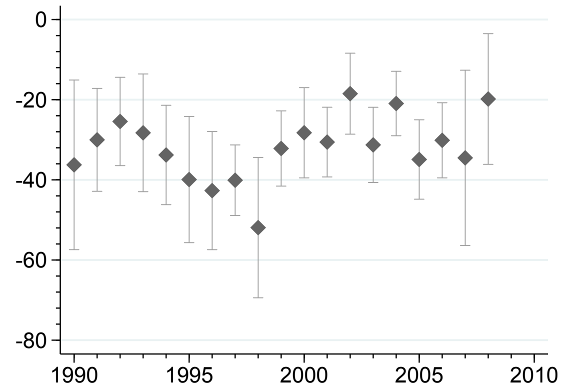
[20] We do not conduct these IV regressions for our investigation of roughness because first stage predictive ability is too low.

increase in the price of new construction is related to state or road attributes that suggest explanations for the observed price increase. To accomplish this, we include an interaction term, much as we did in equation (5.3). Letting x_{st} denote the state level attribute of interest, we estimate,

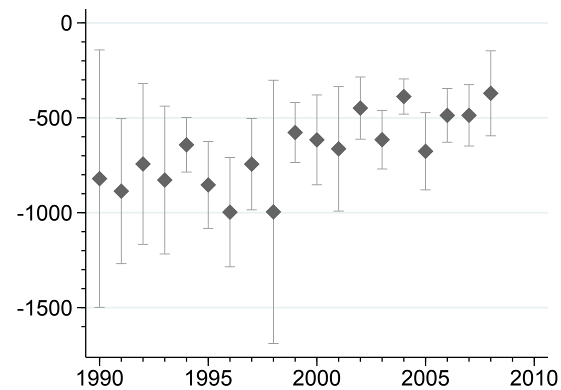
$$\begin{aligned}\Delta L_{st} &= A_0 + A_1 I^L_{st} + A_2[I^L_{st} t] + A_3 t \\ &\quad + B_1[I^L_{st} x_{st}] + B_2[I^L_{st} x_{st} t] + B_3 x_{st} + \epsilon_{st}.\end{aligned} \tag{5.5}$$

In this regression, the interpretation of A_1 and A_2 are about the same as in (5.4). B_1 and B_2 measure how the price level varies with x, and B_2 is a 'cross-partial' term that measures how the difference in price between 'high x' and 'low x' roads evolves over time.

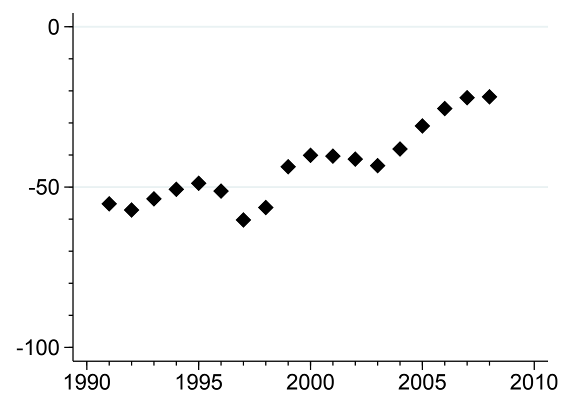
Figure 3: Effect of resurfacing and resurfacing expenditure on IRI by year



(a)



(b)



(c)

Note: (a) x-axis is years, y-axis is inches. This figure shows the effect of resurfacing on the roughness of resurfaced segments. (b) x-axis is years, y-axis is inches per resurfaced mile from one million dollars per resurfaced mile of resurfacing expenditure. (c) Minus one times lane miles worth of asphaltic concrete per million USD2010 of expenditure, assuming a one inch thick resurfacing layer. We see a clear trend in panel (b). Spending results in smaller reductions in roughness over time. Panel (a) does not show a strong trend. Panel (c) tracks the pattern in panel (b) closely.

Table 1: Resurfacing and IRI

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{ist}(Q)$	-32.83***	-32.21***	-34.32***	-37.91***	-38.10***	-41.10***
	(1.90)	(1.86)	(2.08)	(3.61)	(3.62)	(4.08)
t				-0.09	-0.07	-0.04
				(0.08)	(0.08)	(0.09)
$\mathbb{1}_{ist}(Q)t$				0.58+	0.56	0.66+
				(0.35)	(0.35)	(0.38)
State FE	No	No	No	No	Yes	No
State-Year FE	No	Yes	Yes	No	No	No
Segment id FE	No	No	Yes	No	No	Yes
N	206,404	206,403	204,253	206,404	206,404	204,254

Standard Errors in Parentheses Clustered at the State-Year Level.
$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6 Results

6.1 Resurfacing

The first panel of figure 3 illustrates the evolution of the effect of resurfacing on IRI. To construct this figure, we estimate the regression

$$\Delta q_{jst} = \sum_{\tau=1990}^{2008} A_\tau \left[\mathbb{1}_{jst}(\tau = t)\mathbb{1}_{jst}(q)\right] + \epsilon_{jst}.$$

Because the indicator variable $\mathbb{1}_{jst}(q)$ is zero for any segment year where the segment is not resurfaced, this coefficients A_τ give the mean change in roughness for resurfaced segments by year. Figure 3 (a) plots these coefficients and 95% CIs based on errors clustered by state-year.

Although we see some variation in point estimates, for the most part, confidence intervals for the different years overlap. For almost all years a resurfacing event reduces the roughness of a segment by between 20 and 40 inches per mile. This figure shows at most a small positive trend so that resurfacing events in 1990 were not much different than in 2008.

Panel (b) is similar to panel (a), but weights each resurfacing event by state-year resurfacing expenditure per resurfaced lane mile. In particular, it reports the coefficients of the following regression,

$$\Delta q_{jst} = \sum_{\tau=1990}^{2008} A_\tau \left[\mathbb{1}_{jst}(\tau = t)\mathbb{1}_{jst}(q)\imath_{st}^{Q}\right] + \epsilon_{jst}. \tag{6.1}$$

Confidence intervals are based on standard errors clustered at the state-year level. The units of IRI

Table 2: Resurfacing expenditure and IRI

	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}$	-637.07***	-626.39***	-663.84***	-916.64***	-918.50***	-978.23***
	(38.67)	(37.92)	(41.84)	(90.85)	(90.05)	(93.45)
t				-0.07	-0.05	-0.02
				(0.08)	(0.08)	(0.09)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q} \times t$				27.15***	27.03***	29.10***
				(6.96)	(6.85)	(7.00)
State FE	No	No	No	No	Yes	No
State-Year FE	No	Yes	Yes	No	No	No
Segment id FE	No	No	Yes	No	No	Yes
N	206,404	206,403	204,253	206,404	206,404	204,254

Standard Errors in Parentheses Clustered at the State-Year Level.
$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

and $\imath_{st}^{Q}$ are inches per mile and millions of dollars per resurfaced mile. It follows that the units for the A_τ are inches per million dollars. As in our main resurfacing regression (5.2) these regression coefficients are inverse prices.

Although estimates for earlier years are somewhat imprecise, panel (b) shows a clear upward trend. In the early 1990s, one million dollars of expenditure reduced roughness by about 900 inches. By the end of our sample, the same million dollar expenditure reduced roughness by about 450 inches. Thus, the raw data suggests that the price of reducing roughness about doubles between 1990 and 2008. Comparing panels (a) and (b) of figure 3 suggests that most of this price increase reflects increases in the cost of resurfacing, not a decrease in the effect of a resurfacing project.

Table 1 presents estimates of variants of equation 5.1. Column 1 of Table 1 presents a regression of segment-year change in IRI on an indicator for whether the segment was resurfaced, a simplified version of (5.1) omitting terms involving time. On average, resurfacing reduces IRI by about 33 inches. Column 2 refines Column 1 by including state-year indicator variables. Column 3 repeats column 1, but includes segment and state-year indicators. Although the identifying variation in each of these regressions is quite different, the estimated effect of resurfacing is not.

Column 4 estimates equation (5.1) including the terms involving time. There is a small positive change in the effect of resurfacing expenditure that is barely distinguishable from zero. Column 5 replicates the regression of Column 4 while including state indicators. Column 6 replicates column 4 while including segment indicators. Consistent with the barely visible trend that we see in figure 3 (a), these regressions indicate a barely detectable trend in the effect of resurfacing expenditure. In column 6, given the point estimate of about 0.66 on the interaction of time and the resurfacing indicator, the effect of resurfacing decreases from 41.10 inches in 1990 to 29.22 inches in 2008.

Table 3: Composition effects in resurfacing

	AADT	HPMS Urban	NLCD Urban	Rigid surface	Structural Number	Unionization
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}$	-1146.82***	-1101.79***	-1704.86***	-883.01***	-356.29*	-1429.21***
	(118.45)	(121.44)	(193.36)	(86.10)	(169.96)	(269.99)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}t$	33.60***	32.76***	59.70***	23.18***	-7.57	63.38***
	(8.33)	(8.53)	(14.07)	(6.41)	(12.79)	(19.04)
t	0.01	-0.02	-0.02	0.02	-0.02	-0.11
	(0.09)	(0.09)	(0.09)	(0.08)	(0.09)	(0.13)
x	-0.32			3.04*	0.36	-0.34
	(0.21)			(1.39)	(0.30)	(0.42)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}x$	43.09**	299.02*	4,848.13***	-408.83**	-91.24***	26.25+
	(14.02)	(148.15)	(953.60)	(126.55)	(25.88)	(14.53)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}tx$	-1.54	-10.08	-197.55**	24.29*	5.37**	-2.07+
	(0.95)	(11.06)	(76.27)	(10.24)	(1.86)	(1.09)
Segment id FE	Yes	Yes	Yes	Yes	Yes	Yes
N	204,254	204,254	204,254	204,086	204,254	204,254

Standard Errors in Parentheses Clustered at the State-Year Level.

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2 estimates the effect of one million dollars per resurfaced mile of expenditure on roughness, that is, equation 5.2. Interpreting these results requires careful attention. Decreases in roughness are good, so if the price of resurfacing goes up, the coefficient A_1 of $\mathbb{1}_{ist}(Q)\imath_{st}^{Q}$ will increase to become a negative number with smaller magnitude. Second, the units for A_1 are inches per mile per million dollars of expenditure per lane mile. This is an inverse price, so as A_1 increases in magnitude the price of roughness falls. Similar comments apply to interpreting the coefficient of $\mathbb{1}_{ist}(Q)\imath_{st}^{Q}t$.

In column 1, we estimate that one million dollars per lane mile of resurfacing expenditure reduces roughness by about 637 inches. This magnitude does not vary as we add state-year indicators in column 2, or segment and state-year indicators in column 3.

In column 4, we allow for a trend and an interaction between the trend and expenditure. That the coefficient on the interaction is 27 means that one million dollars of expenditure eliminates 27 fewer inches in each successive year. Thus, in 1990 one million dollars eliminates about 900 inches of roughness. By 2008, this falls to about 400 inches. These estimates are almost unchanged in columns 5 and 6 where we add state and segment indicators.

Table 4: Importance of changes in network composition for resurfacing price change

	AADT	HPMS Urban	NLCD Urban	Rigid surface	Structural Number	Unionization
x_{1992}	3.96	0.49	0.13	0.46	7.00	15.81
x_{2008}	5.04	0.55	0.12	0.26	7.18	11.72
Δx	1.08	0.06	-0.02	-0.20	0.19	-4.09
$x \times \mathbb{1}_{ist}(Q)\imath^Q_{st}$	43.09	299.02	4848.13	-408.83	-91.24	26.25
$x \times \mathbb{1}_{ist}(Q)\imath^Q_{st} \times t$	-1.54	-10.08	-197.55	24.29	5.37	-2.07
$\Delta p^Q(x,t)$	-78.12	-77.45	-514.46	238.78	668.55	-620.26

Note: Top three rows give state weighted means and change of composition variables for the variable indicated at the top of each column. Rows four and five reproduce regression coefficients from table 6. The final row calculates the total change in IRI due to changes in x and t on the basis of the previous rows.

Having established an upward trend in the price of roughness, we now investigate possible explanations for this increase. It is well known that road construction is more expensive in urban areas (Ng & Small, 2012). Moreover, in figure 2 we see that the average lane mile of interstate is more heavily used, more likely to be designated urban, and is in a state where the area near the 2005 interstate had a higher fraction of urban cover in 2001. Thus, by whatever measure, the network seems to be getting 'more urban'. Putting these two facts together, it is natural (but incorrect) to conjecture that the price of roughness is rising because we are resurfacing more expensive urban roads.

To investigate this possibility, table 3 presents three estimates of equation 5.3 in which the extra segment attribute is, from column 1 to 3, segment-year level AADT, the HPMS segment-year urban indicator, and the NLCD state level impermeable cover measure. We include segment indicators as controls in all of the results we present in table 2.[21] In unreported results, we replicate each of the specifications in table 3 for the combinations of fixed effects that we use in table 3. Parameter estimates are stable across specifications.

Beginning with column 1, we see that AADT has two effects. First, as expected, the level effect of AADT on inches per million dollars is positive. Increasing AADT by 1, here 10,000 vehicles per average day, decreases the amount of roughness repaired by one million dollars by about 43 inches.

[21] The NLCD based urban measure varies only at the state level by construction. Likewise, the HPMS sampling frame requires that segment-id change when urban status changes so HPMS urban status also does not vary within segment. Consequently, we omit the levels of these variables in columns 2 and 3 of table 3 because they are colinear with segment fixed-effects.

To the extent that busier roads are more urban, this confirms our prior that urban construction is more expensive. Second, the mean annual change in this AADT premium is small, -1.54 inches, and not distinguishable from zero. Notice that the signs on the two terms involving AADT are opposite. Over time the premium for smoothing high AADT segments is (weakly) decreasing.

In total, this suggests the following. It is more costly to keep roads with large AADT values smooth, although this premium is weakly decreasing over time. During the study period there has been an increase in AADT for an average resurfaced segment. The trends up in mean AADT and down in the premium on high AADT segments work against each other. Comparing with column 7 of table 2 we see that the trend in the effect of expenditure on roughness is barely changed by the addition of the two terms involving AADT. This suggests that the trend down in the AADT premium about offsets the trend up in AADT.

Column 1 of table 4 refines this intuition. The table reports the sample mean values of AADT in 1990 and 2008, along with coefficients of the two terms involving AADT from column 1 of table 3. Given these values, it calculates the implied mean change in roughness per million dollar that results from the realized change in mean AADT and the passage of 18 years.[22] The result, given in the bottom row of table 4, is -78 inches. Trends related to AADT lead to a greater decrease in roughness per million of expenditure at the end of the sample than the beginning. Therefore, while AADT is unambiguously important for determining the price of smoothness, it is not important for explaining the trend in this price.

The next two columns of table 3 consider the HPMS and NLCD based measures of how urban is a segment. By either measure, one million dollars repairs fewer inches of roughness as segments are more urban (the different magnitudes reflect the different magnitudes of the underlying measures, see figure 2.) Both urban measures trend up over the study period and the premium for urban segments is decreasing over time. Unlike what we see for AADT, the decrease in the urban premium is distinguishable from zero for the NLCD based measure of urbanization.

Summing up, the first three columns of table 3 confirm our prior that urban resurfacing is more expensive. However, they also reveal that the urban premium is decreasing over time. This second trend works against the trend toward a more urban interstate system, and almost entirely cancels it out. Therefore, while urban status is unambiguously important for determining the price of smoothness, it does not seem to explain the trend in the price of roughness.

A second candidate explanation for the increase in the price of roughness involves increased

[22] Let B_1 denote the estimated coefficient of $x \times \mathbb{1}_{ist}(Q)\imath_{st}^{Q}$ and B_2 the coefficient for $x \times \mathbb{1}_{ist}(Q)\imath_{st}^{Q} \times t$ from table 3. We can evaluate the change in IRI per million dollars that results from changes in x and changes in the importance of x as $\Delta\text{IRI} = B_1 \times \Delta x + B_2 \times (x + \frac{\Delta x}{2}) \times 18$. The bottom row of table 4 presents this calculation for each of the composition variables considered in table 3.

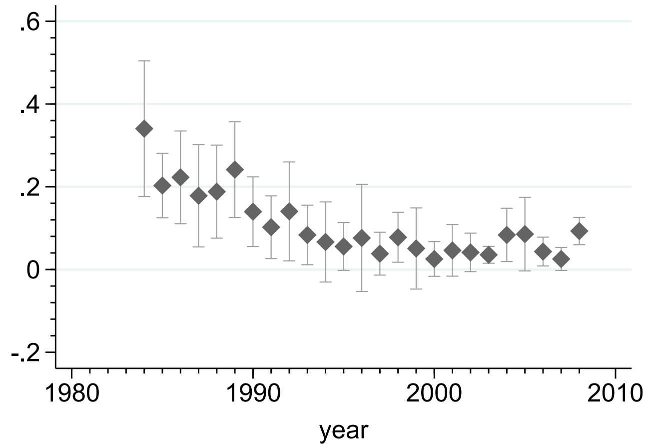
exposure to union labor. In fact, we see in figure 2 that the average lane mile is in a state where union share of employment is lower at the end of our study period than the beginning. Therefore, if union exposure is to explain the increase in the price of roughness, the union premium must increase over time. To investigate this possibility, the last column of table 3 considers the effect of state-year union share of all employment. The pattern of coefficient estimates is that same as we saw for AADT and the two urban measures. The price of smoothness is higher in state-years with higher union shares and this premium is declining over time. Curiously, the coefficient on the trend in column 6 about doubles relative to column 7 of table 3. This suggests that the price of roughness increased faster for segments in states with lower union exposure. That is, the presence of unions worked against the increase in the price of roughness.

Columns 5 and 6 consider the physical characteristics of segments. Column 5 considers an indicator that is one if the segment is rigid, i.e., a concrete slab. We see that it is less expensive to make such segments smooth, and this discount decreases over time. Column 6 considers the role of structural number. These results are both more dramatic and more intuitive than the results in column 5. Increasing structural number by one means that one million dollars reduces roughness by an extra 91.24 inches. This discount decreases over time by 5.37 inches per year. From figure 2 we see that on average, structural number increases over our study period. Alone of the composition variables, the structural number specification is the only one in which there is no trend in the price of roughness once we allow the trend to vary with structural number. Looking at table 4 we see that the total effect of changes in time and structural number are about 668 inches, close to the sample average change of 524 inches.

Columns 5 and 6 together suggest that something about the physical characteristics of the segment may be behind the increase in the price of roughness. Structural number seems particularly deserving of further investigation and we will return to it in the next section.

Appendix table 8 presents three further regressions of the same form as those in table 3, but that investigate the role of proximity to water, average grade and elevation. Neither average grade nor elevation is important for either the level or trend in the price of roughness. We are analyzing resurfacing, a construction project that takes place on an interstate highway. Given the uniformity of the interstate, that resurfacing costs are not sensitive to the range of grade and elevation that exists within the system, this finding seems intuitive. Proximity to water is more interesting because it helps to shed light on the role of environmental regulation on costs. Enacted in 1972, the clean water act is one of the Nation's more important pieces of environmental regulation. Intended to protect the quality of surface water, it requires permits for storm water discharges from construction activities that disturb one or more and management of non-point source run-off from roads. If the

Figure 4: Lane miles per million of construction expenditure over time



Note: Plot of lane miles constructed per million dollars of construction expenditure by year. 95%CI's based on robust standard errors.

clean water act were responsible for the increase in highway construction costs, we would expect prices to rise faster for roads in wetter areas. Table 8, does not support this hypothesis. While the price of roughness is clearly higher in wetter areas, proximity to water or wetlands does not explain the trend in this price. While this is not conclusive, it does not support the hypothesis the trend the price of roughness is due to environmental regulation. We note that positive effect of proximity to water on price is similar to the finding in Smith et al. (1999).

6.2 Construction

To describe the increase in construction costs define $\mathbb{1}_{st}(\tau)$ to be one in year τ and zero otherwise. Then conduct the following regression,

$$\Delta L_{st} = \sum_{\tau=1984}^{2008} A_\tau \left[\mathbb{1}_{st}(\tau) I_{st}^L\right] + \epsilon_{st} \tag{6.2}$$

In this regression, the A_τ are the mean number of lane miles per million of expenditure on new construction by year. Figure 4 plots these inverse prices by year, together with the 95% CIs implied by robust standard errors. This figure shows a decline in the number of lane miles purchased by one million dollars of expenditure. Around 1984 one million dollars would buy about 0.2 lane miles. By 2008 this had declined by almost a factor of 10.

Table 5 presents regressions based on equation 5.4. Column 1 presents a regression of ΔL_{st} on I_{st}^L. Column 2 adds state fixed effects. The dramatic change in the coefficient of expenditure

Table 5: Equation of motion for system length

	OLS				2SLS	
	(1)	(2)	(3)	(4)	(5)	(6)
Y^L	0.0472*	-0.0008	0.1135**	0.0643*	0.1031***	0.1584***
	(0.0230)	(0.0134)	(0.0328)	(0.0256)	(0.0213)	(0.0309)
t			-0.6487*	-0.6585*		-0.8271***
			(0.2910)	(0.2649)		(0.2266)
Y^L t			-0.0045***	-0.0040**		-0.0037*
			(0.0012)	(0.0012)		(0.0018)
State FE	No	Yes	No	Yes	No	No
N	1,171	1,171	1,171	1,171	1,171	1,171
F					37.39	56.51

Standard errors clustered by state in parenthesis.

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

confirms the importance of state level variation in construction costs documented in Brooks & Liscow (2020). In column 3, we add a trend (year-1984) and an interaction of the trend with expenditure. As suggested by figure 4, one million dollars buys fewer lane miles in each successive year. Column 4 repeats column 3 with state fixed effects. This has a negligible effect on our estimate of the trend downward in lane miles per million dollars of expenditure. Columns 5 and 6 repeat 1 and 3, but instrument terms involving expenditure with corresponding terms involving the four year lag of total interstate appropriations. This change in estimating technique has little impact on our estimates of the trend in prices, although the level coefficient is larger in column 5 than column 1.[23]

Table 6 parallels table 3 and examines the role of composition in the increasing price of new lane miles. We estimate the effect of changes in the following variables on the change in construction costs; grade, elevation, proximity to water, proximity to urban land cover, urban classification, unionization, AADT, share of new mileage in construction, mean structural number and, finally, the share of rigid pavement.

Only a handful of the estimated interaction effects are different from zero. Construction is more costly as the share of lane miles classified as urban increases. Mean share of nearby urban cover also increases costs, but is measured less precisely. Construction is more expensive as the road network is busier. Just as we saw for resurfacing, construction costs are higher in busier, more urban places. Also as we saw in our resurfacing regressions, the trends in the urban cost premium mean that this premium decreases over time. States with greater exposure to unions or higher

[23]Our instrument is weak if we include state fixed-effects as controls. Therefore, we do not report IV regressions corresponding to columns 2 and 4 of table 5. Appendix table 5 reports first stage results.

Table 6: Composition Effects in Construction Costs

	HPMS-Grade	Elevation	NLCD-Water	NLCD-Urban	HPMS-Urban	Unionization	AADT	New-miles	Structural Number	Share rigid
Y^L	0.167	0.049	0.024	0.156^{+}	0.201^{*}	0.121	0.207^{+}	0.047^{*}	-0.120	0.009
	(0.108)	(0.032)	(0.046)	(0.092)	(0.089)	(0.074)	(0.105)	(0.022)	(0.167)	(0.028)
$Y^L t$	-0.006	-0.003^{*}	-0.003	-0.010^{*}	-0.013^{**}	-0.009^{**}	-0.012^{*}	-0.003^{**}	0.011	-0.000
	(0.004)	(0.002)	(0.002)	(0.004)	(0.004)	(0.003)	(0.005)	(0.001)	(0.007)	(0.002)
t	0.041	-0.602^{*}	-0.690^{*}	-0.525^{+}	-0.276	-0.560	0.371	-0.729^{*}	-0.367	-0.168
	(0.289)	(0.284)	(0.272)	(0.266)	(0.337)	(0.334)	(0.430)	(0.313)	(0.310)	(0.265)
x	2.470				-44.410	0.279	-0.138^{+}	-0.272	2.177	31.373
	(6.976)				(49.636)	(1.326)	(0.081)	(0.268)	(3.403)	(23.323)
$Y^L\ x$	-0.060	0.000	0.304	-0.483	-0.289^{*}	-0.004	-0.000^{+}	0.017	0.028	0.165
	(0.057)	(0.000)	(0.300)	(0.371)	(0.138)	(0.004)	(0.000)	(0.017)	(0.027)	(0.118)
$Y^L tx$	-0.000	-0.000	-0.010	0.029^{+}	0.019^{**}	0.000^{+}	0.000^{+}	-0.000	-0.002^{+}	-0.011^{+}
	(0.003)	(0.000)	(0.011)	(0.016)	(0.007)	(0.000)	(0.000)	(0.001)	(0.001)	(0.006)
State FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	799	1,171	1,171	1,171	1,171	1,171	1,171	1,006	988	988

Standard Errors in Parentheses Clustered at the State Level

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

mean structural number do not have measurably different costs. However, there are trends in these costs. States where union share declines faster see slightly faster cost increases, and states where structural number increases faster see more rapid cost increases.

The estimations in table 6 are qualitatively similar to those in Brooks & Liscow (2020), but differ in a number of particular ways. First, we study a more recent time period, 1984 to 2008 versus 1960 to 1993. Second, our construction expenditure data exploits the extra detail that is available in the more recent Highway Statistics volume to exclude expenditure on the interstate that is not explicitly related to new construction. Third, the details of our specification and the source data for our variables differ in a number of ways that seem minor. Finally, our data does not include a measure of housing prices, while Brooks & Liscow (2020) do not observe construction materials or quantities.

With this said, the results in table 6 seem qualitatively similar to those in Brooks & Liscow (2020). Like Brooks & Liscow (2020), table 6 seems more informative about things that are not causing the increase in the price of interstate construction than about things that are causing it. Whether we measure urban status with the HPMS indicator, proximity to impermeable cover or business, a million dollars buys fewer miles as the location is more urban. However, the trend in this premium is opposite the level effect, so that the urban premium declines with time. Comparing, for example, the 'HPMS Urban' column of table 6 to column 4 of table 5, we see that the unconditional trend in table 5 is smaller at -0.004 than the corresponding value from table 6, -0.009. While these estimates are imprecise, on average the price of non-urban roads increases more rapidly than an average road, and consequently, the rate of price increase for an average urban road is less rapid than average. The shift toward more urban construction does not seem to explain the trend up in the price of new construction.

For all of HPMS Grade, elevation, water proximity, and share of new-miles, we see that the coefficient on I_t^L is very close to the estimate for an average road, -0.0044, that we see in table 5. By a similar logic to what we used above, and again noting the low precision of the estimates, this means that the rate of price increase on an average road is the same as the rate of increase for a segment without the particular attribute in question. Alternatively, we see that the coefficient on the interaction term $I^L tx$ is indistinguishable from zero for all four variables. Changes in union share have essentially no effect on the rate of increase in the price of new construction.

The last two columns of table 6 investigate the role of structural number and share rigid. These two construction variables are the only ones for which the interaction term, $I^L tx$, is distinguishable from zero and the unconditional trend, $I_t^L t$, is not. That is, in a purely statistical sense, and again noting the relatively low precision of the results, trends in these variables explain the trends in the price of new construction. In addition, structural number is the only variable for which the sign on $I^L t$ is positive. That is, over time a million dollars buys progressively more miles of low structural number highway and less of high structural number highway. The precision of this term is such that it not distinguishable from zero at conventional levels, but is is distinguishable from the corresponding trend for an average segment, -0.0044, that we estimate in table 5.

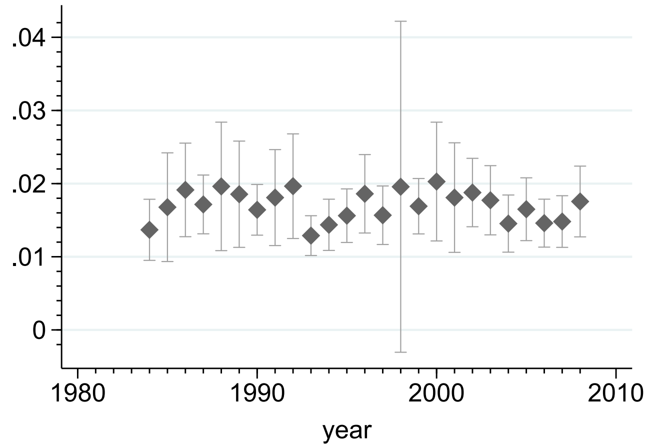
Summing up, the results of table 6 are mainly negative. Terrain, urban share, union exposure and the share of new miles do not seem to explain the increase in the price of new construction. Our estimates for the effect of share rigid and structural number are imprecise, but suggest that these variables, structural number in particular, may be related to the increase in the price of new construction.

6.3 Maintenance

In order to evaluate the total cost of operating the interstate, it remains to document the level and changes in expenditure on maintenance, $\imath^M$. For completeness, we here briefly analyze maintenance expenditure.

Figure 5 shows the results of a regression that is similar to equation 6.2, but which predicts

Figure 5: Millions of dollars per mile of Interstate maintenance expenditure by year.



Note: Plot of maintenance expenditure per lane mile over time, $\frac{I^M_{st}}{L_{st}}$.

annual maintenance expenditure as a function of year indicators. From the figure, maintenance costs are about 0.01×10^6 or about 10,000$ per lane mile. These costs have been steady or declining over time.

7 The price of asphaltic concrete and the price of smoothness

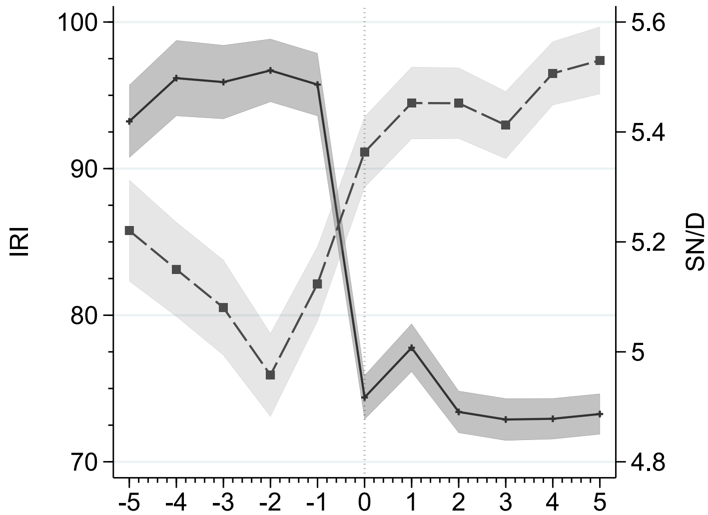
Table 3 establishes that, at least in a purely statistical sense, structural number alone can explain the change in the price of roughness.

The relationship between structural number and the price of roughness has two likely explanations. First, that the cost of materials used for resurfacing rose dramatically over our study period. This could reflect either an increase in the price of paving material, in the quantity used per mile, or a combination of the two. Second, that some unobserved variable correlated with changes in structural number is an important determinant of the trend in the price of roughness.

For the purpose of this discussion it will be helpful to explicitly distinguish between the price to resurface a lane mile of interstate, and the price to reduce an inch of roughness on the interstate. Up until now we have focused attention on the price of roughness, however, the price of resurfacing and the price of roughness are mechanically related. We can convert one price into the other if we know the change in inches of roughness that result from resurfacing. This is precisely the quantity we estimate in table 1.

We develop two estimates of the change in the price to resurface a lane mile of interstate. One we derive from our regression results, our 'regression based estimate'. The other is an 'engineering

Figure 6: Event Study of Structural Number and IRI



Note: Changes in IRI and structural number around resurfacing events for all segments with flexible pavement.

estimate' that derives from what we know about the price and quantity of paving material required for resurfacing. These two estimates agree closely and suggest increases in the price of asphaltic concrete can account for most of the increase in the price of resurfacing.

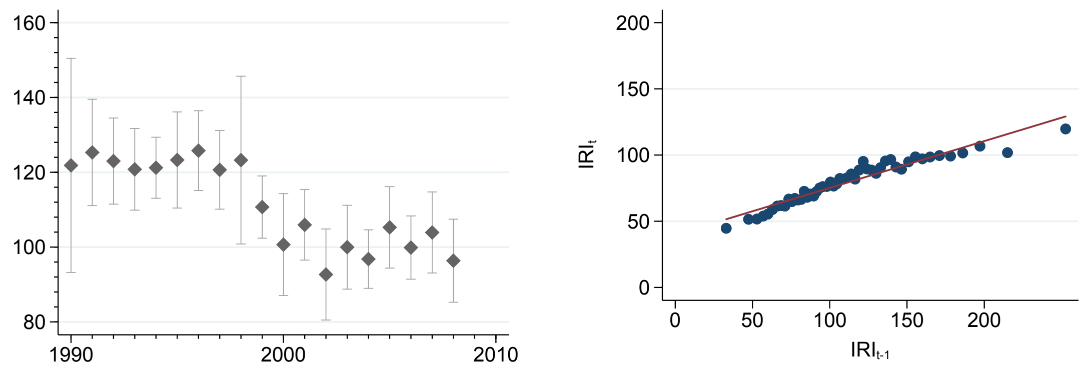
Engineering estimate of resurfacing costs: We begin with an estimate of the change in the cost of paving material per lane mile between 1980 and 2008. There are 2552 segments for which we observe a resurfacing event and also observe the segment for at least two years before and after resurfacing. Of these, 926 have flexible pavement. Figure 6 presents the results from the event study showing how structural number changes around resurfacing events. For reference, the figure also shows the corresponding event study for IRI.

The figure shows a sharp increase in structural number around resurfacing events. This increase is between about 0.2 and 0.4, depending on whether we look at the change over the preceding one or two years. Unsurprisingly, we also see that IRI declines dramatically around a resurfacing event.[24]

Since we know the year of each resurfacing event, we can extend the event study research design of figure 6 to check whether the change in structural number is constant throughout our sample. The data do not indicate that the amount of paving material used for resurfacing changes over our study period. This allows us to reject one of the possible channels through which the price of

[24]Except for the different sample, the about 25 inch drop in IRI around resurfacing that we see in figure 6 is comparable to the within segment estimate in table 1 column (6).

Figure 7: Decreasing returns to resurfacing



(a) IRI_{t-1} over time (b) IRI_t vs. IRI_{t-1}

Note: Panel (a) is constructed using the same procedure as figure 2 but with IRI in $t-1$ as the independent variable rather than change in IRI. The point estimate is the interaction term plus the constant. Panel b) is a bin scatter plot relating IRI in t and IRI in t-1. The regression coefficient is 0.35 with a SE of 0.03

roughness may respond to structural number. The price of roughness probably does not increase because resurfacing events later in the sample put down a thicker layer of new material.

By restricting attention to flexible segments, we can be certain that the change in structural number reflects the addition of asphaltic concrete.[25] Given that each inch of asphaltic concrete contributes 0.4 to structural number (Mannering et al., 2007), figure 6 indicates that resurfacing events involve the addition between one half and one full inch of material. This corresponds closely to the definition of resurfacing given HPMS documentation (Office of Highway Policy Information, 2005, Ch 4, item 53.) that is reflected in our resurfacing indicator. The HPMS defines 'resurfacing' to involve the application at least one inch of material.

For the sake of illustration, suppose a resurfacing event involves the application of exactly one inch of material. Since an average lane of interstate is 12 feet wide,[26] resurfacing one lane mile requires about 196 cubic yards of asphaltic concrete. At about two tons per cubic yard, this is 392 tons of paving material. The price of asphaltic paving material of 45.77 per ton in 1990 and 116.74 per ton in 2008. Multiplying the difference, 70.97, by 392 tons per lane mile, we have an increase of 27,820 dollars per lane mile that we can attribute entirely to increases in the cost of asphaltic concrete.

[25] For composite and rigid segments our data do not unambiguously determine the material used for the resurfacing layer.

[26] See, for example, Highway Statistics 2006, table HM-53.

Regression based estimate of resurfacing costs: Our regressions also imply a per lane mile increase in the cost of resurfacing. From table 1 column 3, resurfacing reduced roughness by 34.32 inches per mile. Similarly, from table 2 column 7, one million dollars of expenditure reduced roughness by 978.23 inches in 1990 and 454.43 inches in 2008.[27] Taking the ratios of each year's values, we conclude that on average one million dollars of expenditure resurfaced 28.50 lane miles in 1990 and 13.24 in 2008. Inverting, this is 35,084 dollars per lane mile in 1990 and 75,523 in 2008. Taking the difference, the increase in per lane mile resurfacing costs implied by our regressions is 40,439 dollars per lane mile.

The engineering based estimate is about 70% as large as regression based estimate. This seems quite close, particularly when we consider that paving material is not the only input to resurfacing. With that said, the closeness of the two estimates is at least partly accidental. For example, there is no reason to think that resurfacing events involve exactly one inch of paving material, and indeed, our estimates suggest it may be somewhat less. Second, our engineering estimate is based on segments with flexible pavement while our regression based estimate reflects the sample of all segments. We have not quite calculated price changes for identical objects.

We can compare engineering and regression based estimate in a second way. Figure 3(b) shows annual estimates of the number of inches of roughness repaired by one million dollars. Using our asphaltic price series, and assuming 392 tons per lane mile of resurfacing, we can calculate the number of lane miles of paving material per million dollars of expenditure on the basis of each years price for asphaltic concrete. To ease comparison with figure 3(b), we multiply this price series by minus 1 and plot the result in figure 3(c). Comparing panels (b) and (c) we see that the inverse price of roughness in panel (b) seems to track the inverse price of paving material closely.

Our object is not to explain the price of resurfacing, but the price of roughness. Table 1 and figure 3a suggest a small decrease in the effect of resurfacing on roughness over time. The two panels of figure 7 suggest that the decrease in the effect of resurfacing reflects the fact that over time the average resurfaced segment is smoother before it is resurfaced. To construct these figures, we consider each of the 8,860 resurfacing events for which we observe segment IRI in the year prior and following resurfacing. Panel (a) plots mean IRI (lagged one year) for these segments over time, along with confidence intervals based on errors clustered at the state-year level. Unsurprisingly, IRI on this subset tracks the national average and we see that over time segments are smoother before they are resurfaced. Panel (b) shows the relationship between initial and final IRI for these resurfacing events. We see that very smooth segments, those with IRI of about 50 inches per mile,

[27] That is, $987.23 - 18 \times 29.10$.

do not change there IRI at all when they are resurfaced. On the other hand, as initial IRI increases, final IRI grows at about half the rate. Thus, resurfacing results in one additional inch of reduction of IRI for each additional two inches of initial IRI. Part of the increase in the price of IRI appears to reflect decreasing returns to effort. It is progressively more difficult to reduce IRI as initial IRI falls.

Together, increases in the price of asphaltic concrete and decreasing returns to resurfacing effort on smoother segments seem to completely explain the observed trend in the price of roughness.

8 Materials costs and the price of new construction

Our efforts in table 6 to attribute the increase in the price of new construction to particular road attributes was less conclusive than were our corresponding efforts for the price of roughness. With that said, our two measures of the physical attributes of the state highway network, 'structural number' and 'share rigid', were the only variables in table 6 for which the interacted trend term was measurably negative and the un-interacted trend term ceased to be distinguishable from zero. Thus, from a purely statistical point of view, something to do with the nature of construction is our best guess to explain the trend in new construction price.

Given this, we here assess the extent to which the cost of paving material can account for the observed increase in the price of new construction as it did for resurfacing. As for resurfacing, we construct both regression based and engineering based estimates and then check the extent to which they agree.

For our engineering estimate, we focus attention on flexible roads because they are relatively simple.[28] Flexible roads are just asphaltic concrete, rigid roads are often steel reinforced. A typical flexible segment of the interstate consists of 12 inches of asphaltic concrete.[29] Using the same conversion as above, this means that each lane mile of flexible interstate construction requires 4692 tons of material. Using the same sources as above, the price of a ton of asphalt in 1984 was 48.00 (slightly higher than 1990) so the change in price per ton from 1984 to 2008 was 68.74. Multiplying tons by the change in the price per ton, we have that the cost of the price of asphalt required to build a lane mile of interstate increased by about 323 thousand dollars between 1984 and 2008.

We can read our regression based estimate off figure 6.2. In 1984, one million dollars bought about 0.2 lane miles, and by 2008 this had fallen by about a factor of five to 0.04 lane miles. Inverting, the price of a lane mile increased from about 5 to about 20 million dollars. This is an

[28]There is heterogeneity within the class of rigid roads in the extent and nature of expensive steel reinforcement. Flexible roads are just a layer of asphaltic concrete.

[29]Table IV-3 of HPMS item descriptions for 1993-8.

order of magnitude larger than 323 thousand dollar per lane mile that we can ascribe to the price of paving materials.

Summing up, of all of the variables we consider table 6, only the two describing the physical attributes of the roadway appear to be related to the trend in prices, although this relationship is not particularly strong. At the same time, comparing regression based estimates of the increase in construction costs to engineering based estimates, we see that increases in materials prices result in a large increase in construction costs, but one that is still small relative to the total increase suggested by our regression based estimates.

9 What is the 'cost of infrastructure'?

Over our study period, the increase in total expenditure is about proportional to the increase in vehicle miles travelled and the extent and condition of the network has improved. Stated in this way, the data do not suggest a problem with the cost of the interstate system. This is contrary to the conclusion suggested by the rapid increases in the prices of roughness and lane miles. This makes clear that we have not been precise about what is meant by 'an infrastructure cost problem'.

To address this issue, we develop and calibrate a stylized model of the investment problem faced by profit maximizing highway manager. This model suggests a precise definition of 'the cost of the interstate' as 'the user cost per vehicle mile travelled that rationalizes the observed path of investment, taking prices and the demand for interstate services as given.' This precise definition of capital costs enables a correspondingly precise answer to the question of whether the US has an infrastructure cost problem, at least in regard to the interstate highway system.

Consider the behavior of a highway manager who collects a user fee r_t^h per interstate vehicle mile travelled and is responsible for construction, resurfacing and other maintenance. The highway manager takes this user fee as given. There are L_t lane miles of highway. Demand for VMT depends on lane miles and pavement quality. Pavement smoothness q_t is measured by IRI. We assume the following demand function for aggregate interstate VMT,

$$D\left(q_t, L_t\right) = A_t \left(\frac{1}{q_t}\right)^{\alpha} L_t^{1-\alpha} \tag{9.1}$$

This demand function is decreasing in IRI and increasing in lane miles. The parameter A_t is a scaling parameter to map IRI and lane miles into VMT. To facilitate calibration of our model, A_t is time varying. The parameter $\alpha < 1$ determines the relative importance of pavement condition and lane miles the demand for VMT.

Duranton & Turner (2011) find that the elasticity of vehicle miles travelled to new lane miles is one. If we suppose that a new lane mile consists of a lane mile of highway with uniform initial roughness, this motivates our assumption that D is constant returns to scale. To our knowledge, there is no other empirical evidence about how VMT responds to road quality. We return to this issue in our calibration exercise. That D does not vary with the user fee is consistent with results in (Hughes et al., 2008) suggesting that the gas price elasticity of vehicle miles travelled is tiny.

Pavement condition depreciates with use but the length of the highway capital stock does not. To specify the relationship between use and depreciation, let q_0 denote smoothness immediately following a resurfacing event and let q_f denote a terminal smoothness immediately prior to resurfacing. We treat these thresholds as exogenous. A section of highway is engineered to withstand K standardized loadings. Following the engineering literature, call these loading 'Equivalent Standard Axle Loads (ESALs). We assume that the number of ESALs is proportional to the Average Annual Daily Traffic, or D/L. This notation in place we specify the following law of motion for IRI per lane mile:

$$q_{t+1} = q_t + \kappa \frac{D_t}{L_t}. \tag{9.2}$$

$\kappa = \gamma \frac{q_f - q_0}{K}$ is a scalar that describes the relationship between AADT and inches of roughness in two steps: γ relates AADT to ESALs and $\frac{q_f - q_0}{K}$ relates ESALs to changes in IRI. This function is broadly consistent with the more detailed depreciation functions reported in Small & Winston (1988) and Mannering et al. (2007), with two caveats. First the engineering literature relies on much more complicated functions in order to allow the marginal damage of a loading to vary with current road condition and pavement attributes. Second, because damage is sensitive to the axle weight, the engineering literature is typically considers several of classes of users (e.g. combination trucks, single axle trucks), while we aggregate to a single class. We discuss our estimate of κ below.

The highway manager invests in both smoothness, $\imath_t^q$, and lane miles, I_t^l. These two types of investment are distinct, carrying prices p_t^q and p_t^l respectively. These are the prices we estimated earlier.

We can now state the highway manager's profit maximization problem,

$$V(L_0, q_0) = \max_{I_t^l, \imath_t^q} \sum_{t=0}^{\infty} \frac{\pi_t}{(1+r)^t}$$

$$\text{subject to} \quad \pi_t = r_t^h A_t q_t^{-\alpha} L_t^{1-\alpha} - p_t^l I_t^l - p_t^q \imath_t^q L_t \tag{9.3}$$

$$L_{t+1} = L_t + I_t^l \tag{9.4}$$

$$q_{t+1} = q_t + \kappa A_t (q_t L_t)^{-\alpha} - \imath_t^q \ , \tag{9.5}$$

where r is the real interest rate (or more generally, in the presence of uncertainty, the risk-adjusted return on capital). $\imath^q$ is expenditure on quality per mile,[30] while I^l is total investment expenditure for new lane miles. Hence, L_t multiplies $\imath^q$ in the expression for period profits. This difference reflects the fact that we are treating 'quality' as an average quantity to match the way we measure pavement condition with IRI.[31]

Ignoring the possibility of empirically irrelevant corner solutions, standard Euler equations determine the optimal dynamic choices for next period lane miles L_{t+1} and next period IRI q_{t+1},

$$\begin{aligned} p_t^l = & \frac{1}{1+r}\left((1-\alpha)\, r_{t+1}^h A q_{t+1}^{-\alpha} L_{t+1}^{-\alpha} + p_{t+1}^l\right) \\ & + \frac{1}{1+r}\left(\alpha p_{t+1}^q \kappa A \left(q_{t+1} L_{t+1}\right)^{-\alpha} - p_{t+1}^q \left(q_{t+1} + \kappa A \left(q_{t+1} L_{t+1}\right)^{-\alpha} - q_{t+2}\right)\right) \end{aligned} \tag{9.6}$$

$$p_t^q L_t = \frac{1}{1+r}\left(\alpha r_{t+1}^h A q_{t+1}^{-\alpha-1} L_{t+1}^{1-\alpha} + p_{t+1}^q L_{t+1}\left(1 - \alpha\kappa A q_{t+1}^{\alpha-1} L_{t+1}^{-\alpha}\right)\right) . \tag{9.7}$$

The optimal path of L_t and q_t is subject to initial conditions (L_0, q_0 given) and transversality conditions: $\lim_{T\to\infty} \frac{q_{T+1}}{(1+r)^T} = 0$ and $\lim_{T\to\infty} \frac{L_{T+1}}{(1+r)^T} = 0$.

These Euler equations can be generalized to allow for arbitrary paths of rates of return and depreciation rates by adding time subscripts to the relevant quantities. More importantly, this framework can be easily generalized to take into account regular maintenance expenditures such as traffic management, snow removal, and minor physical improvements by assuming that the highway manager receives rent net of maintenance. This involves replacing rent per vehicle mile, r_t^h, with rent per vehicle mile net of maintenance in all of the expressions above. To accommodate maintenance expenditure in our calibration exercise, we will make exactly this substitution and denote maintenance expenditure per vehicle mile as m_t^h.

Equation (9.8) states that the highway manager's profit maximizing investments in lane miles ensures that marginal cost p_t^l equals marginal revenue. Marginal revenue is the sum of the discounted value of four objects: rental revenues from added vehicle miles travelled; the replacement value of a lane mile p_{t+1}^l; the benefit of reduced congestion on pavement depreciation, $\alpha p_{t+1}^q \kappa \mathrm{VMT}_{t+1}/L_{t+1}$; and finally, minus the cost of smoothness for an additional lane mile, $p_{t+1}^q \left(q_{t+1} + \kappa \mathrm{VMT}_{t+1}/L_{t+1} - q_{t+2}\right)$.

Equation (9.9) states that the optimal investment in smoothness (paying to reduce q_{t+1}) equates the total cost of an additional unit of systemwide smoothness to the discounted value of resulting incremental rental revenues less the replacement value of an additional unit of smoothness net of induced demand due to greater use.

[30] Note that we here define $\imath^q$ as resurfacing expenditure per lane mile. In our econometric exercise, it was resurfacing expenditure per *resurfaced* lane mile.

[31] Alternatively, one could consider 'total inches of suspension travel for the whole system'. Our version maps more neatly into the existing policy framework, which is organized around IRI.

Rearranging and using the definition of VMT from (9.1), we rewrite these two equations as,

$$r^h_{t+1} = \frac{L_{t+1}}{(1-\alpha)\text{VMT}_{t+1}}\left[(1+r_t)p^l_t - p^l_{t+1} + p^q_{t+1}\left(q_{t+1} + \kappa\left(1-\alpha\right)\frac{\text{VMT}_{t+1}}{L_{t+1}} - q_{t+2}\right)\right] \tag{9.8}$$

$$r^h_{t+1} = \frac{q_{t+1}}{\alpha\text{VMT}_{t+1}}\left[p^q_t L_t(1+r_t) - p^q_{t+1}L_{t+1}\left(1-\alpha\kappa\frac{\text{VMT}_{t+1}}{q_{t+1}L_{t+1}}\right)\right] . \tag{9.9}$$

where VMT_t is total vehicle miles traveled and is equivalent to:

$$\text{VMT}_t = A_t q_t^{-\alpha} L_t^{1-\alpha} \tag{9.10}$$

This reformulation accomplishes the primary goal of this model. It provides an expression for the user fee per mile required to rationalize a given path of prices, usage, IRI and lane miles. These equations will be the basis for the calibration exercises below. Because (9.8) derives from a first order condition taken with respect to L_t, the right hand side of this equation describes the return to investment in lane miles. Similarly, (9.9) derives from a first order condition taken with respect to q_t, so the right hand side of this equation describes the return to investment in IRI.

Before we turn to calibration, we analyze steady state behavior and discuss implications of the model. In steady state, pavement quality q and lane miles satisfy the following conditions:

$$rp^l L = (1-\alpha)\, r^h \text{VMT} - p^q\,(1-\alpha)\,\kappa\text{VMT}$$

$$rp^q qL = \alpha r^h \text{VMT} - p^q \alpha\kappa\text{VMT} .$$

By the summing these expressions, we obtain an expression relating the user cost to investment in lane miles and smoothness along the profit maximizing steady state path:

$$r_h = \left[rp^l L + rp^q qL + \kappa p^q \text{VMT}\right]/\text{VMT}. \tag{9.11}$$

This condition seems intuitive. The rental rate required to rationalize given steady state quality and extent must offset the capital cost of lane miles, the capital cost of keeping lanes miles at quality q and offsetting the depreciation of the system represented by κVMT.

Like the two Euler equations (9.12) and (9.13), equation (9.11) provides an answer to the central question we are asking of our model: 'What user tax is required to rationalize observed levels of highway investment?'

Similar to any asset pricing condition, the optimality conditions for investment in lane miles and smoothness include a dividend and capital gain term. Rearranging the optimality conditions

(9.6) and (9.7), we obtain the following expressions,

$$r = \frac{(1-\alpha)\, r^h_{t+1} \mathrm{VMT}_{t+1}/L_{t+1}}{p^l_t} + \frac{p^l_{t+1} - p^q_{t+1}\left(q_{t+1} + (1-\alpha)\,\kappa \frac{\mathrm{VMT}_{t+1}}{L_{t+1}} - q_{t+2}\right)}{p^l_t} - 1 \tag{9.12}$$

$$r = \frac{\alpha r^h_{t+1} \mathrm{VMT}_{t+1}/q_{t+1}}{p^q_t L_t} + \frac{p^q_{t+1} L_{t+1}\left(1 - \alpha\kappa \frac{\mathrm{VMT}_{t+1}}{q_{t+1} L_{t+1}}\right)}{p^q_t L_t} - 1\,. \tag{9.13}$$

The left hand side is the real interest rate (or, more generally, the rate of return on assets with similar riskiness). The right hand side of each equation is composed of a dividend yield term (the first term) and a capital gain term. The dividend yield is the rental rate multiplied by the incremental change in vehicle miles travel due to investments in lane miles and smoothness respectively. The capital gain term is the change in the value of the asset due to changes in the price of adding lane miles or improving smoothness respectively.

What are the implications of these conditions for the optimal levels of highway investment? First, falling interest rates require a fall in the dividend yield holding prices constant.[32] Given the sharp fall in real interest rates experienced over this period, assuming diminishing returns to smoothness, the dynamic optimality conditions imply rising investment in pavement smoothness. Moreover, a decline in the real rental rate for the highway capital r^h_t would also be consistent with falling interest rates. Second, a persistent rise in the price of lane miles or the price of smoothness would also imply rising investment or falling rental rates. Intuitively, if the cost of smoothing lane miles is increasing in the future, it is optimal to smooth more lane miles today. Lastly, higher rates of depreciation reduces the optimal level of investment. For pavement smoothness, this is intuitive; higher depreciation implies that the benefits from increased smoothness are short-lived.

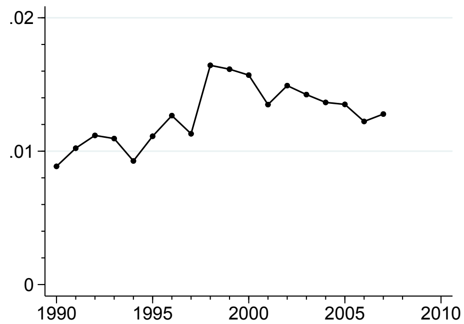
10 Discussion and calibration

We now turn to an evaluation of the steady state equilibrium equation (9.11), where we generalize to allow for maintenance costs by adding m_h to the right hand side.

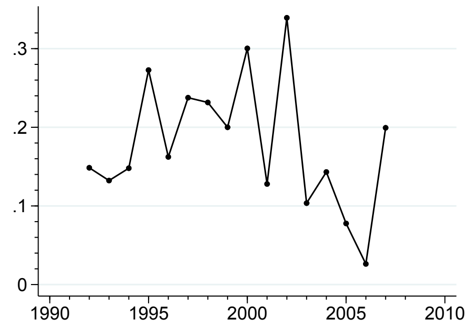
Inspection of equation (9.11) shows that the right hand side consists primarily of easily observed quantities. Much of our effort has been directed to the estimation of p^l and p^q, and in our calibrations we rely on a three year trailing average of p^l and p^q. Maintenance costs per mile, m^h, are described in Figure 5. Total lane miles, L, is described in figure 1. We use IRI as our measure of quality. We calculate total VMT from data on AADT, shown in figure 1, and segment length. For the risk free rate, r, we use the January average of the 10 year Treasury rate net of the annual

[32] See Eggertsson et al. (2019) and Farhi & Gourio (2019) for a discussion.

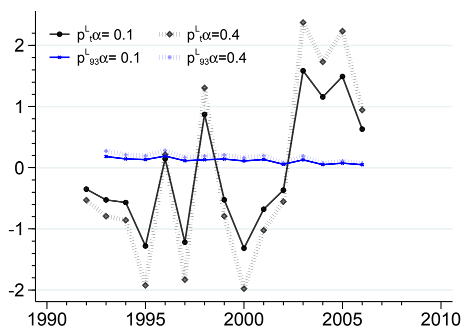
Figure 8: Calibrated and actual user cost dynamics



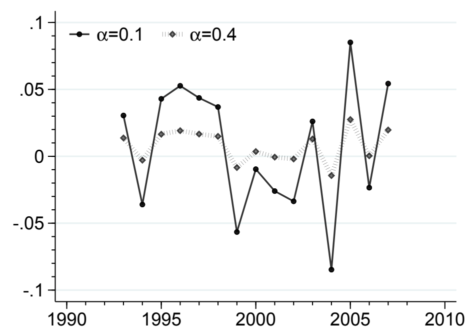
(a) r_h



(b) eq (9.11)



(c) eq (9.8)



(d) eq (9.9)

Note: (a) Observed user cost per mile based on federal gas tax. (b) User cost of interstate capital per vehicle mile implied by steady state condition (9.11). (c) User cost of interstate capital per vehicle mile implied by Euler condition (9.8) (d) User cost of interstate capital per vehicle mile implied by Euler condition (9.9). All figures rely on the data in table 7. Panels (b-d) are based on a three year trailing average of p^q and p^i, In panels (c) and (d) solid black line indicates calibration to actual data with $\alpha = 0.1$; dashed grey line is $\alpha = 0.4$; solid blue indicates counterfactual case when p_t^l is fixed at its (smoothed) 1993 value and $\alpha = 0.1$; dashed blue is counterfactual case with $\alpha = 0.4$.

inflation rate calculated from the CPI.

To calibrate our model we must also pick a value for α, the quality elasticity of VMT. We lack an empirical foundation for this choice. A simple calculation suggests that α is likely to be small. Consider a segment with an IRI value of 100, just a above the good/acceptable threshold. This segment has $q = 80$, so a 1% decrease is about equal to a one inch change. Such a change is likely almost imperceptible, and it is natural to suspect that it will elicit a change in travel volume of much less than one percent. This suggest values of α on the order of 0.1 or 0.01. In our calculations, we use $\alpha = 0.1$.

Such a tiny elasticity seems inconsistent with the fact that by 2008, resurfacing was the largest component of interstate expenditure. An alternative is to imagine that D represents 'highway services' rather than 'VMT', and that the value of highway services is much more sensitive to roughness than is VMT. In this case, one could imagine values of α that were more in line with their share in highway expenditure. That is, around 0.4. In our calibration, we experiment with this larger value of α.

It remains only to evaluate κ. As a first step, we must evaluate γ, the number of ESALs per vehicle. Loosely, an ESAL is caused by the passage of a typical tractor trailer rig or 2000 passenger cars. Assume a truck share of AADT of 12%, consistent with national averages towards the end of our study period. In this case, a segment experiences $.12 + .88/2000 \approx 0.12$ ESALs per average vehicle. A typical design for an interstate segment will withstand 9m Equivalent Standard Axle Loads (Mannering et al., 2007). During its lifetime, we expect a road to increase from an initial IRI around 50 to the acceptable/poor threshold of 170. These are q_0 and q_f. Thus we have $\kappa = 0.12 \times (170 - 50)/9,000,000 \approx 0.0000016$ inches of IRI per average vehicle. Given this value of κ, a new segment experiencing an about average AADT of 8000 depreciates completely in about 26 years.

We can now evaluate the right hand side of (9.11) in each year from 1993 until 2007 (we omit 2008 because real interest rates were negative). We plot the results in panel (b) of figure 8. The annual data on which this figure is based is given in appendix table 7. The units on the y axis of this figure are dollars per mile. Thus, conditional on steady state profit maximization, this figure shows that the user tax required to rationalized observed highway length and quality under the prevailing prices and interest rates does not exhibit a clear trend and, except for 2004-5, varies between about 10 and about 30 cents per vehicle mile.

Two comments about this graph are in order. First, maintenance costs are not important. As we see in table 7 annual maintenance expenditure divided by annual VMT is comfortably under a penny per mile in all years. Second, the variation in the optimal steady state user fee primarily reflects variation in our estimated prices of p^q and p^l, and of these, it is the price of length that dominates.

For comparison's sake, panel (a) of figure 8 shows an estimate of the actual user fee collected per mile on interstate VMT. To calculate this value, we start with the annual total of all user fees and taxes (mainly gas tax revenue) from Highway Statistics table FE9. We next discount by the fraction of all VMT carried by the interstate.[33] Finally, we divide by total annual interstate VMT to arrive at the (federal) user fee per interstate vehicle mile travelled. As for panel (b), the y axis is dollars per mile, so this actual user fee ranges between 1 and 1.5 cents per mile. Comparing panel

[33]We estimate this share annually by using VMT calculations from the HPMS sample data. It varies between 25 and 29 percent.

(a) to panel (b), we see that the federal user fee per mile is about one order of magnitude below the level of user fee required to rationalize realized investments in a steady state equilibrium. At face value, this suggests that while highway services are underpriced, the degree of underpricing has not clearly worsened despite rising costs for lane miles and smoothness. Declining interest rates and rising usage offset rising prices trends.

More importantly however, our results suggest that the interstate highway system is not at a steady state. Given this, we next turn to an evaluation of right hand side of equations (9.8) and (9.9). As in our analysis of the steady state, we generalize to allow for maintenance by adding m_h to the right hand side of both (9.8) and (9.9), and base our calibrations on a three year trailing average of p^q and p^l.

Panel (c) of figure 8 shows our evaluation of equation (9.8), again using the data in table 7. The y axis of this figure is in dollars per vehicle mile, so this figure shows that the user fee per mile required to rationalize observed investment lane miles. The black line is based on $\alpha = 0.1$, dashed grey is $\alpha = 0.4$.

The black line is our benchmark case, and it shows that the user fee required to rationalize observed investments in lane miles increases from about -0.5 dollars per mile to over 1 dollar per mile. A larger value of α in the light gray line affects the path of user costs only marginally. In contrast to panel (b), panel (c) suggests that user costs must increase substantially over the study period to rationalize observed investments in lane miles. However, it is worth noting that the user cost on average is close to zero.

To understand the level and dynamics of the user fee in panel (b), it's worth highlighting the large anticipation effect of prices on user cost. As can be seen in (9.8), a high anticipated future price of investment in lane miles (all things equal) lowers the current user cost. Put another way, high user costs are not needed to justify investment in new lane miles if the price of lane miles and future usage are expected to be even higher; the planner wishes to invest in new lane miles because relative prices are low today. A modest and low gas tax may be rational if highway managers expect prices for new lane miles and usage to continue to rise as they have in the past.

The dashed and solid blue lines in panel (c) report counterfactual evaluations of equation (9.8) (with $\alpha = 0.1$ and 0.4) under the assumption that the price of lane miles is fixed at its 1993 value. In this counterfactual case, initial user costs are higher and terminal user costs are lower; user fees are more modest and declining over time. The fact that user costs are higher under the counterfactual even though the counterfactual and actual prices coincide in 1993 indicates the importance of dynamic considerations in the planner's problem. Because the planner anticipates price increases, initial user fees are low to rationalize the early accumulation of highway miles to meet later demand. Absent the expectation of increases in the price of length, the counterfactual case, there is no need to 'stock up' on relatively inexpensive highways early in the period to meet demand later when prices are higher. Comparing the counterfactual and actual cases in panel (c) suggests that much of the rapid increase in the actual user cost of capital per VMT reflects these dynamic considerations rather than increase in the price of length itself.

Panel (d) of figure 8 plots our calibration of equation (9.9). As in panel (c), the black line is based on the data in table 7 and $\alpha = 0.1$, dashed grey uses $\alpha = 0.4$. Like panel (c), variation in α does not result in economically important variation in the implied user cost of interstate capital. Like panel (b), user cost calculated from the Euler equation for smoothness exhibits no obvious upward trend and fluctuates around zero. Like the Euler equation for lane miles, the anticipation of future increases in the price of smoothness are consistent with a low (even negative) current user cost. We cannot reject the view that a very modest gas tax may be consistent with the user fee implied by optimal investment in smoothness.

Summing up, the calibration of our model to price, interest rate, and usage trends suggest that user costs are not exhibiting a clear upward trend and that a very low user fee along with substantial investments in system length and quality despite rising prices may be consistent with optimal behavior. Rising usage, lower interest rates, and the dynamic effect of anticipation of future price increases together rationalize a very low user cost for highway services.

11 Conclusion

We document several trends in the interstate system from the mid-1980s until 2008. The length of the system increased modestly. The condition of the system improved dramatically. The number of trips served by a given lane mile of highway about doubled. Total vehicle miles traveled increased by a still greater amount. The average mile of the system became lower, flatter and more urban. Expenditure on the system about doubled. User fees collected per vehicle mile stayed about constant.

We also estimate the prices of construction and resurfacing. We find dramatic increases in both. On the basis of point estimates, the cost to build an average lane mile of interstate increased by a factor of about 5.5 between 1990 and 2008, and by about a factor of seven between 1984 and 2008. The price of maintaining existing lane miles also increased, although less dramatically than the cost of new construction. Smoothing an inch of roughness cost almost twice as much in 2008 as in 1990.

Given the obvious trends in the composition of the network, it is natural to suspect that some of the increase in the cost of construction and resurfacing is due to composition effects. In fact, like Brooks & Liscow (2020), we are unable to find evidence to support this hypothesis. With that said, our regression results suggest that urban construction and resurfacing is more expensive, but that the rural-urban cost gap attenuated over our study period.

On the other hand, we find clear evidence that the increase in the cost of resurfacing largely reflects increases in the cost of paving material, and to a smaller extent, the decreasing returns to investment in resurfacing. Our efforts to explain the increase in the price of construction are less conclusive. The data suggest that some hard to observe physical characteristic of the road may have changed and do not suggest a big role for materials or labor prices. This seems to be consistent with the finding in Brooks & Liscow (2020) that increases in construction costs over 1955 to 1993 reflect increases in citizen activism around highway construction and design. Presumably such involvement results in the hard to observe changes in the physical attributes of highway segments that our estimates seem to be picking up.

Natural policy responses to the increase in the price of smoothness should revolve around procurement policies to reduce the price of paving material. The response to the increase in the price of construction is less clear. Recent work by Brinkman & Lin (2019) suggests that the external costs of interstate construction may be large, while the history of interstate construction provided by Brooks & Liscow (2020) suggests that early interstate mileage was constructed without regard for possible externalities. Thus, it is natural to wonder whether progressively more costly highway construction might pass a cost-benefit test. Addressing these sorts of questions would most likely require contract level data. Similarly, it seems likely that refining our understanding of the increasing costs of new construction will also require more disaggregated expenditure data.

Expenditure on new construction, resurfacing and other maintenance account for about 35%, 45% and 20% of total expenditure on the interstate in 2008. We have established that maintenance expenditure per lane mile is about constant over our study period and that increases in the price of roughness largely reflect increases in input prices. Increases in the cost of construction are dramatic, but only affect 35% of highway expenditure. Whether user cost per vehicle mile is increasing is less obvious. Increases in AADT and decreases in the price of capital work against other price increases, while the improvements in condition and increases in extent indicate that the observed doubling of total expenditure partly reflects an accumulation of capital.

Our model and calibration is an effort to clarify these issues. We find no clear trend in user costs and, more surprisingly, that even very low user fees in the form of the gas tax may be optimal given trends in prices, usage, and interest rates. In particular, low current user costs today are optimal if the price of investment in lane miles and smoothness are expected to rise. Our dynamic model clarifies that it remains optimal to invest in the extent and smoothness of the highway system despite low current user fees because of anticipated increases in the price of future investment and anticipated higher usage.

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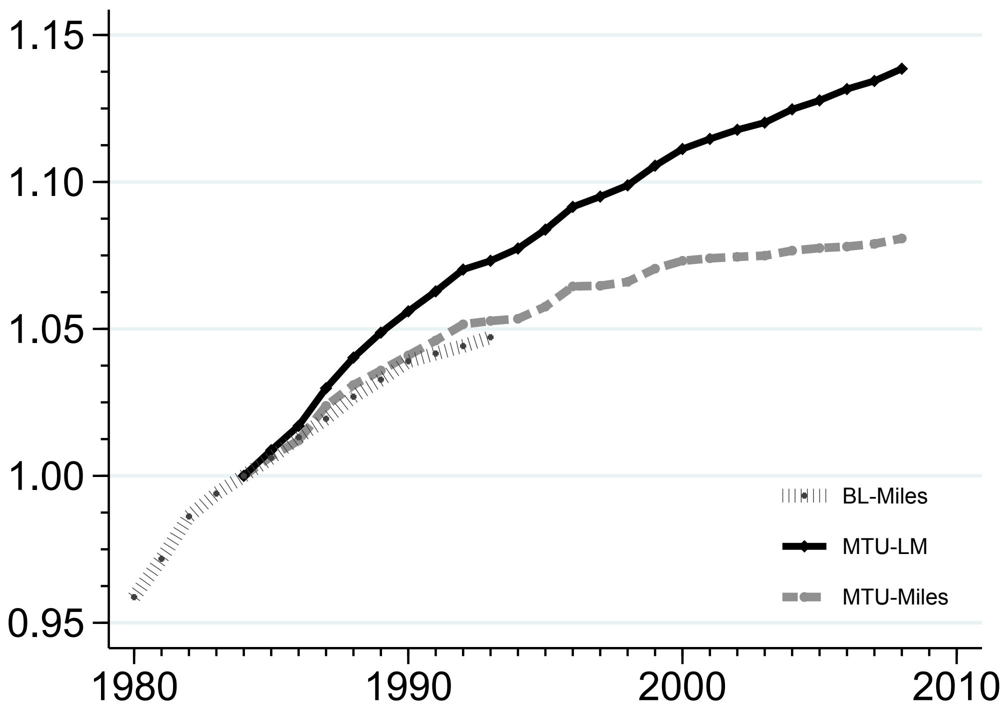
12 Appendix: Supplemental tables and figures

Figure 9: Comparing PR511 and HPMS aggregate mileage



Note: Light gray dashed line is total miles of interstate by year from the PR511 data on which Brooks & Liscow (2020) is based. Medium gray line is corresponding quality from the HPMS data on which this paper is based. Black line in lane miles of interstate from the HPMS. All three series are normalized to 1 in 1984, the first year we study. We see that the two mileage estimates track each other very closely. Lane miles, however, grow more quickly.

Table 7: National variables for the calibration

	VMT	L_t	q_t	r_h	r	p_L	p_q	m_h
1980	$2.92{\times}10^{11}$	176,308.1	.	.	.	.	.	.
1981	$3.03{\times}10^{11}$	178,904.4	.	.	0.008	.	.	.
1982	$3.09{\times}10^{11}$	179,896.8	.	.	0.063	.	.	.
1983	$3.32{\times}10^{11}$	183,332.3	.	.	0.067	.	.	.
1984	$3.51{\times}10^{11}$	185,108.6	.	.	0.074	$2.94{\times}10^{6}$	.	0.006
1985	$3.67{\times}10^{11}$	186,723.3	.	.	0.079	$4.93{\times}10^{6}$	.	0.007
1986	$3.89{\times}10^{11}$	188,257.7	.	.	0.052	$4.49{\times}10^{6}$	.	0.008
1987	$4.14{\times}10^{11}$	190,627.3	.	.	0.057	$5.61{\times}10^{6}$	.	0.008
1988	$4.36{\times}10^{11}$	192,557.6	.	0.011	0.045	$5.32{\times}10^{6}$	.	0.007
1989	$4.58{\times}10^{11}$	194,128.3	.	0.011	0.046	$4.14{\times}10^{6}$	.	0.007
1990	$4.76{\times}10^{11}$	195,470.1	105.57	0.009	0.030	$7.15{\times}10^{6}$	1,218.8	0.007
1991	$4.87{\times}10^{11}$	196,727.8	109.75	0.010	0.024	$9.78{\times}10^{6}$	1,128.2	0.006
1992	$5.04{\times}10^{11}$	198,103.8	108.57	0.011	0.044	$7.12{\times}10^{6}$	1,345.4	0.007
1993	$5.23{\times}10^{11}$	198,654.8	109.48	0.011	0.033	$1.20{\times}10^{7}$	1,207.8	0.005
1994	$5.42{\times}10^{11}$	199,429.1	112.49	0.009	0.033	$1.50{\times}10^{7}$	1,557.0	0.006
1995	$5.62{\times}10^{11}$	200,617.4	104.17	0.011	0.049	$1.80{\times}10^{7}$	1,171.6	0.006
1996	$5.81{\times}10^{11}$	202,051.2	104.50	0.013	0.029	$1.31{\times}10^{7}$	1,002.9	0.006
1997	$5.99{\times}10^{11}$	202,696.3	103.86	0.011	0.035	$2.61{\times}10^{7}$	1,343.9	0.005
1998	$6.21{\times}10^{11}$	203,407.3	96.07	0.016	0.039	$1.29{\times}10^{7}$	1,004.4	0.006
1999	$6.40{\times}10^{11}$	204,643.5	97.40	0.016	0.031	$1.97{\times}10^{7}$	1,731.6	0.005
2000	$6.56{\times}10^{11}$	205,697.6	95.56	0.016	0.039	$3.93{\times}10^{7}$	1,622.9	0.006
2001	$6.69{\times}10^{11}$	206,328.8	94.43	0.013	0.014	$2.16{\times}10^{7}$	1,507.3	0.005
2002	$6.86{\times}10^{11}$	206,905.1	95.24	0.015	0.038	$2.42{\times}10^{7}$	2,228.0	0.006
2003	$7.00{\times}10^{11}$	207,355.3	92.85	0.014	0.013	$2.82{\times}10^{7}$	1,625.5	0.006
2004	$7.14{\times}10^{11}$	208,194.7	94.30	0.014	0.021	$1.20{\times}10^{7}$	2,577.8	0.005
2005	$7.23{\times}10^{11}$	208,755.4	91.99	0.014	0.014	$1.17{\times}10^{7}$	1,478.7	0.005
2006	$7.30{\times}10^{11}$	209,471.6	89.94	0.012	0.004	$2.30{\times}10^{7}$	2,052.7	0.005
2007	$7.33{\times}10^{11}$	209,982.2	90.74	0.013	0.027	$3.94{\times}10^{7}$	2,053.9	0.005
2008	$7.14{\times}10^{11}$	210,751.0	89.70	0.011	-0.006	$1.08{\times}10^{7}$	2,696.3	0.005

Note: Annual values of all variable used in calibration exercise of section 10. L is total lane miles. q is system average IRI. r^h is user fee revenue per vehicle mile of interstate travel. r is the real interest rate. p^l is millions of 2010USD per lane mile. p^q is inches of roughness eliminate per million dollars of 2010USD expenditure. m^h is non-resurfacing maintenance expenditure per interstate vehicle mile travelled.

Table 8: Composition effects resurfacing, additional variables

	Average Grade	Elevation	NLCD Water
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q}$	-927.76***	-758.75***	-1104.58***
	(96.52)	(134.12)	(124.44)
$\mathbb{1}_{ist}(Q)\imath_{st}^{Q} \times t$	33.15***	19.57+	30.78***
	(7.51)	(10.45)	(8.56)
t	-0.02	-0.02	-0.02
	(0.09)	(0.09)	(0.09)
x	0.01		
	(0.51)		
$x \times \mathbb{1}_{ist}(Q)\imath_{st}^{Q}$	-44.65	-0.73*	2,393.63*
	(47.01)	(0.33)	(1,067.21)
$x \times \mathbb{1}_{ist}(Q)\imath_{st}^{Q} \times t$	-1.74	0.03	-59.39
	(3.38)	(0.03)	(65.68)
Constant	-0.15	-0.04	-0.11
	(1.35)	(1.06)	(1.06)
Segment id FE	Yes	Yes	Yes
Observations	200122	204254	204254
R^2	0.128	0.129	0.129
Adjusted R^2	0.014	0.013	0.013

Standard Errors in Parentheses Clustered at the State-Year Level.
$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.