How Should We Measure Infrastructure? The Case of Highways and Streets

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Abstract The recent debates on infrastructure spending have led to renewed interest in the measurement of infrastructure and its effects on growth and well-being. This paper updates estimates of one important type of infrastructure capital—highways and streets. We compare BEA's capital measures with more readily understood physical measures of road and lane miles, road quality and usage, and other measures from *Highway Statistics* (HS) data from FHWA. We also use the HS data and related research to disaggregate investment in highways and streets into more detailed types, such as new construction, repair and resurfacing, and bridge work, and apply separate depreciation rates to each type to produce updated estimates of net wealth stocks and depreciation. Relative to published BEA estimates, constant-price depreciation is revised up by about $9–$12 billion annually in recent years, and constant-price net stocks are revised down by about 22 percent. For the period from 2007 forward, net stocks per capita are flat in the published BEA estimates but decline slightly in the revised estimates. In addition, we update Fraumeni's (2007) estimates of productive stocks that are converted to wealth stocks to facilitate a comparison. These updated wealth estimates also show lower net stocks and higher depreciation than in the published BEA estimates. We hope this paper encourages discussion about how to measure infrastructure capital, particularly highways and streets, and its effects.

Keywords Depreciation, infrastructure, highways, streets, capital stocks

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Introduction

The recent debates surrounding the passage of legislation to raise infrastructure spending highlight the need to measure infrastructure and its effects on economic growth and well-being. The U.S. Bureau of Economic Analysis (BEA) provides widely cited estimates of capital stocks of several types of infrastructure (Bennett, Kornfeld, Sichel, and Wasshausen, or BKSW 2020) based on the perpetual inventory method (PIM), in which net stocks equal cumulative investment less cumulative depreciation. As Glaeser and Poterba (2020), BKSW (2020), and others point out, these estimates have some limitations: they measure fairly broad categories of infrastructure, and they rely on depreciation rates based on dated research and price measures that may not fully account for changes in quality. In response to these concerns, this paper focuses on the challenges of measuring one important type of infrastructure capital—highways and streets.

We compare BEA's capital measures with measures of road and lane miles, paved road miles, road quality and usage, bridge surface area and quality, and other structures from *Highway Statistics* (HS) data from the Federal Highway Administration (FHWA). These more transparent, readily understood physical measures of capital provide an approximate sense of what reasonable PIM-based capital measures might look like. We review research on the service lives of more detailed categories of highway and street investment, such as new construction, reconstruction, restoration, resurfacing, bridges, and other structures, and we present the HS data on shares of capital outlays for these categories of investment. Using these more disaggregated data, we construct updated estimates of capital stocks and depreciation of highways and streets. This work extends, updates, and borrows from previous research by Fraumeni (1999, 2007), that used HS data and related research to measure productive stocks of highways and streets.

The HS data and related research paint a picture of highway and street infrastructure that is more complex than BEA's measure of net stocks. BEA's measure grows far more rapidly than road miles and lane miles, and somewhat more rapidly than paved road miles. These discrepancies in growth rates arise from investments in capital other than new roads, such as bridges and walls; from investment in road quality through restoration and resurfacing; and possibly from limitations of BEA's measures. Our updated estimates imply upward revisions to constant-price depreciation of about \$9–\$12 billion annually and downward revisions to constant-price capital stocks of roughly 22 percent in recent years, although the size of the revisions is sensitive to assumptions we make to address incomplete data. We also update the estimates of productive highway capital in Fraumeni (2007), constructing wealth (net capital stock) measures from these productive measures to allow for comparisons with other wealth estimates.[2] We hope this work encourages discussion about ways to improve measures of infrastructure capital and its effects on growth and well-being.

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[2] BEA uses the term "net capital stocks" to refer to wealth stocks.

1. BEA's fixed assets accounts and studies of infrastructure capital

BEA's fixed assets accounts (FAAs). The FAAs provide annual estimates of fixed investment (also known as gross fixed capital formation), economic depreciation (consumption of fixed capital or CFC), and net capital stocks (net of depreciation) for over 100 types of government and private fixed assets (structures, equipment, and intellectual property products) used in production in the U.S economy. The FAAs provide data in current- and constant-prices from 1901 (investment) or 1925 (stocks and CFC) to the present.[3]

BEA estimates constant-price net stocks and CFC for each type of asset using the perpetual inventory method (PIM). Under a simplified PIM, the constant-price net stock of each asset type in a year equals last year's constant-price net stock plus the value of constant-price fixed investment through the current year, less constant-price depreciation through the current year. Constant-price CFC for most assets is estimated as a fixed percentage of the net stock (geometric depreciation). Constant-price estimates of investment are, for most assets including roads, obtained by dividing estimates of current-price investment by an average-year price index. BEA generally uses the same estimates of fixed investment and prices for the FAAs and for gross domestic product (GDP). A simplified PIM can be expressed as:

$$K_{jt} = K_{j(t-1)}(1-\delta_j) + I_{jt}(1-\delta_j/2)$$

where: K_{jt} = constant-price net stock for year t for asset type j

δ_j = annual depreciation rate for asset type j

I_{jt} = constant-price investment for year t for asset type j

The PIM can be rewritten as:

$$K_{jt} = K_{j(t-1)} + I_{jt} - M_{jt} \qquad \text{and} \qquad M_{jt} = K_{j(t-1)}\delta_j + I_{jt}\delta_j/2$$

where: M_{jt} = constant-price depreciation or CFC for year t for asset type j

These measures of net stocks, also known as wealth stocks, differ from measures of productive stock unless depreciation is assumed to occur with a geometric pattern as BEA assumes. The current-price estimate of the net stock, estimated by multiplying constant-price net stocks by an end-of -year price

[3] BEA (bea.gov) produces the U.S. National Income and Product Accounts (the NIPAs, or national accounts). The main web page for the FAAs is apps.bea.gov/iTable/index_FA.cfm. See BKSW (2020) and the NIPA handbook for more information on the national accounts and the many uses of the FAAs.

index, is a measure of the market value of the stock at the end of the year.[4] Net stocks or wealth stocks are thus measures of the wealth of the owner of the asset, with adjustments for past and future declines in efficiency. In contrast, productive stock measures are appropriate for estimating productivity and the contribution of the capital stock to economic growth. They are adjusted for current and past declines in efficiency. Productive stock measures are used by the U.S. Bureau of Labor Statistics (BLS) for its estimates of total factor productivity (TFP) and by BEA for its industry-level production account.[5] Except in the geometric case, the distinction between wealth stocks and productive stocks is important.

In BEA's national accounts, the CFC of government capital (including infrastructure) is included in GDP because the contribution to GDP of government, as a nonmarket producer, is measured by the sum of its expenses, which include depreciation. CFC is only a partial measure of the services of government capital because the rate of return on government assets is assumed to be zero even though the price that users might be willing to pay could exceed CFC. The estimates of the services of private capital include depreciation and a net return because there typically are market prices available to determine services from private capital.

Studies of infrastructure capital. Numerous papers have used the FAAs or similar data to explore the link between infrastructure investment, growth, and productivity. Aschauer (1989 and 1990) empirically linked BEA's estimates of government infrastructure capital and growth. In a widely cited critique of these results, Gramlich (1994) raised concerns about the size of estimated effects of infrastructure and the causal relationship between infrastructure spending and growth. Munnell (1990a and b) also used BEA's capital stock estimates to show a link between public capital and growth. Fernald (1999) used BEA investment data and depreciation rates to estimate capital stocks of highways and streets, and showed that their growth was associated with relatively higher productivity growth in more vehicle-intensive industries over the period from 1953 to 1989, but questioned whether this relationship would hold in future years. Nadiri and Mamuneas (1994) and Mamuneas and Nadiri (2003) also studied the possible effects of stocks of infrastructure capital.

More recent studies continued to use BEA's capital stock data to analyze the effects of infrastructure spending. A study by Heintz (2010, cited in Bivens 2017) estimated a significant relationship between

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[4] In contrast to constant- and current-price net stocks (also known as constant- and current-cost net stocks), historical-cost net stocks are estimated using the PIM and a history of investment without adjusting for price changes. Thus, investment from 1950 is valued at prices from 1950, investment from 2020 is valued at prices from 2020, and so on. These historical-cost stocks are an estimate of "book values" of capital. BEA publishes historical-cost net stocks for several types of private capital. This paper focuses on constant- and current-price stock measures.

[5] See the BLS total factor productivity estimates and BEA's industry-level production account for more information. The BLS estimates rely on BEA's investment data but use different depreciation rates derived from a particular form of a hyperbolic function to measure productive capital. The BLS major sector published measures exclude government capital. BLS uses wealth stock depreciation in the depreciation component of its capital service flows, but productive stocks depreciation in its PIM.

U.S. public capital stocks and private productivity. Bom and Ligthart (2014) and Melo, Graham, and Brage-Ardao (2013) reviewed a large number of studies from several countries and found a positive link between infrastructure capital and growth. Cubas (2020) studied the effect of public capital on growth in a sample of 90 countries, using country-specific investment data and building capital stock estimates by relying on estimates of depreciation and other relationships from BEA's FAAs. Cubas found that public capital can explain some cross-country differences in income, but the effect depends on the degree of congestion of public capital. Ramey (2020) used BEA data on capital stocks to examine the empirical evidence on the short- and long-run macroeconomic effects of infrastructure spending, considering both neoclassical and New Keynesian models. This paper found that infrastructure investment results in limited stimulus in the short run but possibly greater stimulus in the long run. In a model used in the paper, an upward revision to the depreciation rate lowers the steady-state output and the optimal government capital stock but raises government investment.

BKSW (2020) documented trends in investment and net stocks of a subset of assets in the FAAs classified as infrastructure. "Basic infrastructure" includes capital for water and sewer, conservation and development, power, and several types of transportation-related assets, including highways and streets. This paper found that capital stocks of basic infrastructure have grown more slowly than GDP over the past 20 years, and that the annual growth in constant-price net stock per capita (a metric that can be linked to productivity measures) of highways and streets has fallen to nearly zero percent in recent years, after rising at about 1 percent from the late 1980s to the early 2000s.

This brief overview of the extensive and sometimes conflicting literature on the effects of infrastructure highlights the importance of BEA's measures of infrastructure capital. As Glaeser and Poterba and BKSW (2020) point out, however, BEA's estimates have limitations, including their reliance on somewhat dated research on depreciation rates, and on price measures that may not adequately account for changes in quality. Because "infrastructure capital" includes such a diverse range of asset types, each of which has its own unique estimation challenges, it is difficult to update these measures all at once. One way to assess these estimates is to focus on a single type of infrastructure capital. Accordingly, the rest of this paper focuses on estimates of highways and streets.

2. BEA's estimates of capital stocks for highways and streets

Fixed investment. BEA's measure of investment in highways and streets (figure 1) comprises much more than outlays for the construction of new roads. It also includes outlays for reconstruction, rehabilitation, widening, and resurfacing of roads; structures such as bridges, trestles, railroad crossings, tunnels, street lighting, signs and traffic signals, walls and fences, service areas, and administrative buildings; and other features such as alleys, sidewalks, curbs, gutters, grade separations, and storm drains. Also included are expenses for design, planning, and engineering. Investment excludes spending for routine maintenance and repair, and for the purchase of existing structures and land.

This definition of fixed investment (or gross fixed capital formation) is consistent with international standards, as stated in the 2008 *System of National Accounts* (SNA).[6] The SNA defines fixed assets as produced assets that are used repeatedly in production processes for more than one year. "Fixed investment" includes the purchase of new assets or improvements to existing assets that increase their productive capacity or extend their service lives.[7] Fixed investment includes improvements to land but excludes the purchase of land, which is not produced. Fixed investment excludes spending for routine maintenance and repair that maintains a fixed asset in working order but does not change the asset's productive capacity or service life.

BEA's inclusion of this wide range of assets within "fixed investment in highways and streets" is consistent with its data sources, namely the U.S. Census Bureau's Surveys of State and Local Government Finances (GF).[8] These surveys define capital outlays in a manner consistent with the SNA. The survey (part 3) asks for total direct expenditures for highways and toll highways, and these spending categories include all of items listed above. The GF survey then divides direct expenditures into current operations and capital outlays. Current operations include "expenditures for ... repair and maintenance … to maintain required standards of compliance for their intended use." Capital outlays are divided into "purchase of equipment, land, and existing structures, including capital leases" and "construction." "Construction" (category F) is defined as "production, additions, replacements, or major structural

[6] The SNA is a widely agreed upon set of international standards for national economic accounts.

[7] When a new public road is constructed, construction expenses are considered fixed investment. Total fixed investment in a period excludes the purchase of existing assets, which were constructed in a previous period. One complication is the transfer of assets between the private sector and the government. For example, if government buys a building from a business, for the purpose of building a road through the property, that transaction should count as an addition to the government capital stock and as a subtraction from the private-sector capital stock. BEA estimates the net value of these purchases/sales using data from several sources but does not precisely itemize these transactions for purpose of road building.

[8] For more information on the NIPA measures of fixed investment, see the NIPA handbook chapters 6 and 9. BEA also uses data from the Census Bureau's monthly survey of construction spending to extrapolate estimates for the months before the next round of GF data is available. In the NIPAs and FAAs, state and local governments are responsible for almost all fixed investment in highways and streets; the federal government provides capital grants for this purpose but is directly responsible for only about one percent of this investment.

alterations to fixed works." BEA classifies only capital outlays for "construction" for highways and toll highways as investment in highways and streets.[9]

As one might expect, this distinction between spending for capital investment and for maintenance and repairs can be difficult to recognize in practice. Governments record spending for resurfacing of roads (which might have a service life of 20 years) as capital outlays but record spending for sealants or thin "milling and overlay" treatments (which might occur every few years for busy roads) as maintenance.[10] BKSW (2020) show that spending for maintenance and repairs for highways and streets can be substantial.

Price measures. BEA's price indexes are chosen to be as consistent as possible with the scope and definition of each category of investment. To deflate investment in highways and streets over the past several decades, BEA has used several price measures depending on availability. These price measures have included the BLS PPI for inputs to highway and street construction; the PPI for inputs to other nonresidential construction goods; the PPI for inputs to highways and streets excluding capital investment, labor, and imports; the BLS Employment Cost Index for total compensation by industry for construction; and the Federal Highway Administration composite index for highway construction costs; known as the national Highway Construction Cost Index (NHCCI).[11]

These BLS price measures and the NHCCI reflect a careful, detailed accounting of a diverse mix of inputs and projects. For example, the FHWA constructs the NHCCI using state data on winning bids on highway construction contracts and is thus an output cost index as opposed to an input price index, although one would expect input costs to influence the price index. The data for the NHCCI include project level details on prices and quantities of pay items for those winning contracts. A pay item is a unit of work, construction material, labor, or service for which price and quantity is provided in the contract. The price index measures changes in the typical basket of pay items. The NHCCI is a chained Fisher index and reflects the changing mix of inputs and projects over time.

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[9] To clarify the distinction between construction and maintenance and repair, the GF survey instructions state that "if the term refers to activities that materially extend the life or add value to the property, then they are classified under construction; otherwise, they are classified under current operations."

[10] We learned from conversations with FHWA staff that the difference between pavement work classified as maintenance rather than capital outlay can depend on the depth and magnitude of rehabilitation. Maintenance (in the form of sealants, or thin milling and overlay treatments) is typically administered to the top roughly 2 inches of asphalt surface. Capital outlays for rehabilitation of the pavement tend to extend farther below the wearing surface, and typically involve restoration of intermediate pavement layers and or the subgrade. These distinctions illustrate the challenges of distinguishing maintenance and investment.

[11] See www.fhwa.dot.gov/policy/otps/nhcci for more information. For several years, the BLS produced a PPI for highways and streets that measured the average change over time in the selling prices received by producers, without adjusting for quality changes. In 2010, BLS discontinued this PPI.

BEA's price measure for highway and street investment rose substantially over time (figure 2). These striking price increases are very similar to increases in other price measures for road construction in recent research and are widely noted in the transportation literature. BEA's price index roughly doubled from 1945 to 1968, tripled from the 1960s to the 1980s, and roughly tripled again from 1990 to 2019. Brooks and Liscow (2019) also find that highway construction costs per mile roughly tripled from the 1960s to the 1980s. They conclude that these cost increases are not mainly the result of increases in input and labor costs, or changes in the location and geography of new construction, but to "mitigation expenditures" to address environmental or other local externalities, resulting in increasingly wiggly roads, in response to "citizen voice" to avoid disturbing existing neighborhoods. Duranton, Nagpal and Turner (2020) document similar increases in highway construction costs. Mehrotra et al (2020) find that increases in materials costs (such as petroleum related inputs) can explain most of the doubling in the price of resurfacing from 1990 to 2008, but very little of the quadrupling of prices of new construction, consistent with Brooks and Liscow. Redding (2020) comments that these cost increases merit more research and speculates that roads built earlier and later may differ in that roads built later have lower benefits relative to costs and include more mitigating features that affect costs.

BEA currently lacks quality-adjusted price measures for narrower categories of investment, such as new roads, repaving, bridges, walls, and so on, although BLS PPIs and the NHCCI do include changes in the cost of construction of these items. To be clear, the BLS does use several methods to adjust PPIs for quality changes, including asking respondents to report the likely effects of quality changes on costs,[12] but these methods may not fully capture all quality changes. A quality-adjusted price index, like BEA's price index for computers, measures changes in the price of a well-defined unit of output of constant quality. As quality improves over time, a quality-adjusted price index increases less rapidly than a price index without quality adjustment.

Depreciation rates and service lives. BEA defines depreciation as the decline in value due to wear and tear, obsolescence, accidental damage, aging, and retirement of assets from service. In 1997, BEA adopted geometric depreciation rates for most assets, including highways and streets. These rates were generally based on the work of Hulten and Wykoff (HW, 1981a, and 1981b) and other researchers as summarized by Fraumeni (1997). The HW recommendations were based on an analysis of age-price profiles data sets on sales of private used assets. For many assets, these studies estimated a typical service life and converted this service life to a geometric depreciation rate using the relationship $\Delta = DBR / T$, where Δ is the geometric depreciation rate, T is the service life, and DBR is the declining balance rate.

[12] See Chapter 14 of the BLS Handbook of Methods, p. 3–4, for a description of methods to adjust for quality changes.

Beemiller (1999) estimated service lives for several types of road-related assets from a survey of seven state agencies. The estimated service lives by asset type were weighted by expenditure data from HS and the state DOTs. This methodology resulted in an average service life of all forms of highway and street capital of 45 years. The Beemiller service life of 45 years was adopted by BEA as recommended by Fraumeni and Bennett.[13] For several types of nonresidential structures, including highways and streets, BEA had been using a declining balance rate of .91. The combination of Beemiller's proposed service life and the .91 default rate resulted in a BEA geometric depreciation rate for highways and streets of 0.0202 or 2.02 percent per year.[14]

This single depreciation rate provides a reasonable measure of economic depreciation and of the services of highway and street capital in GDP, but it has not been updated in several years.[15] As Fraumeni (1999, 2007) and others note, different categories of highway and street investment are likely to have different service lives, so a single, fixed depreciation rate may or may not reflect the changing mix of investment in a diverse array of road-related capital assets over time. Improvements in quality over time may also appear as changes in depreciation rates. Ideally, we should estimate net stocks using disaggregated investment data for narrower types of investment (new roads, repaving, bridges etc.) and different depreciation rates and quality-adjusted price indexes for well-defined units of each of these investment types. Instead, we have only single, aggregate measures of investment, prices, and depreciation rates.

As BKSW (2020) pointed out, estimates of maintenance and repair expenditures—while not part of investment—could also be useful for improving models of depreciation. Diewert (2005) developed a model in which maintenance spending can sustain the services from an asset. In this model, retirement decisions become endogenous (rather than a physical feature of an asset) and depend on how long an owner is willing to continue paying for maintenance. Diewert's model still yields a geometric pattern of depreciation although the pattern would be more nuanced than in the standard geometric depreciation rates.

BEA's estimates of investment and net stocks. Constant-price fixed investment in highways and streets (2012 dollars, figure 1) tended to rise over time, despite some periods of decline. Investment rose unevenly from 1901 through the 1930s, fell during the war years, then rose from 1945 to 1968 with the

[13] Fraumeni and Bennett noted that the research of Fraumeni (1997) supported the adoption of a lower service life.

[14] Higher values of the DBR imply faster depreciation rates, all else equal. A DBR of 2 (double-declining balance) is often assumed by accountants to allow taxpayers to write off more depreciation expenses in the earlier years of asset ownership. HW concluded that the use of a double-declining balance rate for accounting purposes typically does not portray an accurate picture of observed depreciation for many nonresidential structures.

[15] Fraumeni and Bennett wrote: "Fraumeni expects to be making additional recommendations regarding the treatment of highways for a later benchmark." This did not happen.

Interstate Highway System and other road construction programs, peaking at about $94 billion in 1968. Investment then tended to fall over the next several years, as the Interstate Highway System neared completion, to $52 billion in 1982. After 1982, investment rose again, peaking at $113 billion in 2002, and then dropped to $79 billion in 2013. Investment then rose to $87 billion in 2019.

Constant-price economic depreciation or CFC grew more steadily over these decades, reflecting the arithmetic of the PIM: stocks grow only gradually over time, and BEA uses a fixed depreciation rate of 2.02 percent over the entire period. Net investment (investment less depreciation), a measure of the extent to which investment adds to the stock of capital or merely replaces depreciated capital, remained above zero in all years except for a few years in the 1940s.

Constant-price net stocks (figure 3 and table 1) rose over time, with accelerations and decelerations reflecting the trends in net investment. The average annual increase in the net stock grew to almost 4 percent from 1945 to 1968, decelerated to roughly 2 percent from 1968 to 1982, to 1.7 percent from 1982 to 2007, and slowed to 0.7 percent from 2007 to 2018. The cumulative growth was substantial: in 2018, net stocks were over 5 times larger than in 1945 and over 2 times larger than in 1968. While these estimates are based on solid data and reasonable assumptions, they have limitations as well. It can be difficult to interpret these estimates and assess their quality, in part because neither roads nor their services are frequently sold in private markets, so we cannot observe their market value or otherwise "benchmark" these results.

3. Measures of highway and street capital from Highway Statistics

We next compare BEA's capital measures with statistics on road and lane length, road quality and usage, the number and quality of the nation's bridges, and other statistics on the nation's highways and streets from *Highway Statistics* (HS), a set of annual statistics produced by FHWA, Office of Highway Policy Information.[16] FHWA compiles the HS data from the Highway Performance Monitoring System (HPMS), a cooperative effort between the FHWA and state and local governments to collect detailed data on the state of the nation's roads. The widely respected HS data are used by all levels of government, researchers, and private industry to analyze the condition, performance, and use of the nation's roads and related structures. They provide an alternative and perhaps more "real world" set of physical measures of highway and street capital.

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[16] The *Highway Statistics* webpage contains all HS data used in this paper.

Because capital is generally very difficult to measure in national accounts and because we lack similar physical measures for most forms of public or private capital, many may find these comparisons interesting and informative. It should be noted, however, that these physical measures from the HS data do not have a precise, clear-cut relationship with the net stock estimates. This comparison gives us a rough, impressionistic sense as to the types of capital the net stock measures may capture, and whether the net stock growth rates fall within a reasonable range.

Road- and lane-miles. BEA's constant-price net capital stock estimate grew far more rapidly than total road miles, the simplest measure of capital in the HS data (table 1, figures 3 and 4). From 1945 to 2018, the average annual rate of growth of net stocks, at 2.3 percent, was over 7 times greater than that for road miles, at .3 percent. The growth rate of road miles and net stocks accelerated and decelerated in roughly similar ways over the past several decades: both grew more slowly from 1939 to 1945, more rapidly from 1945 to 1968, and more slowly on in the years afterward. In almost every year from 1925 forward, BEA's net stocks grew more rapidly than road miles. Net stocks also grew more rapidly than lane miles, which are reported from 1980 forward and which grew at about the same rate as road miles. Lane miles may have grown more rapidly than road miles in previous years, with the construction of interstate highways and other major roads.

Several explanations could account for the faster growth in net stocks than in road- and lane-miles. If constant-price fixed investment reflected only the building of new roads and the repair of old roads, with no quality or technological changes, then one might expect trends in net stocks to be similar to trends in road- or lane-miles. Under these assumptions, the portion of investment that funds new lane miles would lead to parallel increases in net stocks and lane miles, while depreciation and the portion of investment that makes up for depreciation would roughly offset one another in the calculation of net stocks over time. Accordingly, the relatively faster growth rates of BEA's net stock measure may reflect investment in capital such as traffic and safety improvements and better bridges, or road quality improvements, or issues in measures of investment, prices, or depreciation rates.

Some, but perhaps not all, of the faster growth in BEA's net stocks reflects an increase in the number of paved road miles over time. The growth in paved road miles, recorded since 1960, has been much closer to (but still less than) the growth in net stocks. From 1960 to 2018, paved road miles grew 2.3 times larger (1.5 percent per year), while net stocks grew 3.2 times larger (2.0 percent per year). Paved road miles grew more rapidly than net stocks over some periods, such as the 1970s, but more slowly than net stocks in most other periods. Much of the growth in paved road miles appears to reflect the paving of already existing unpaved roads rather than the creation of new roads. From 1960 to 2018, paved road miles rose by 1.6 million, while unpaved road miles (mostly local roads in rural areas) fell by 1.0 million.

Whether net stocks should grow more or less rapidly than paved road miles is unclear. A length of paved road requires much more capital than the same length of unpaved road. Because capital-intensive paved road miles are growing while unpaved road miles are declining, one might expect the growth in paved road miles to contribute to the growth in net stocks, and to grow more rapidly than total net stocks, which also include unpaved roads. On the other hand, one might expect net stocks to grow more rapidly than paved road miles because net stocks also reflect investment in road quality and other related capital.

Other breakouts of road- and lane-miles in the HS data do not immediately explain why net stocks grew more rapidly than road miles. The published HS data show that, since 1980, road- and lane-miles of different types of roads—interstate highways, other freeways and expressways, other principal arterials, minor arterials, collectors, and local roads—all grew more slowly than net stocks.[17] (figure 5). The growth rate in road miles classified as "urban," reported from 1960 forward (figure 4), did grow as rapidly or slightly more rapidly than net stocks, but much of this growth reflects changes in the Census Bureau's classification of specific areas as urban versus rural; from 1960-2018, miles of urban roads grew while miles of rural roads declined.

Capital other than roads. Some of the relatively faster increase in net capital stocks also results from an increase in the capital stock of bridges. FHWA maintains the National Bridge Inventory (NBI),[18] which records statistics on bridges for several years. From 1992 to 2018, the number of bridges grew by almost 8 percent and the total deck area of bridges grew by 40 percent (figure 6 and 7). Based on somewhat less detailed data, the number and deck area of bridges has grown steadily over previous decades. The NBI data also show that there has been substantial reconstruction of bridges over the past decades as well as new bridge construction.

According to various measures, the quality of bridges, while far from perfect, has either remained roughly the same or improved in recent years. From 1992 to 2015, the share of the nation's bridge deck area that was classified as "structurally deficient" fell by almost half, to less than 7 percent in 2015, while the share classified as "functionally obsolete" stayed at about 20 percent, and the share classified as neither deficient nor obsolete rose to 73 percent of the total in 2015. From 2000 to 2018, based on a

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[17] These types of roads have a precise definition. "Other freeways and expressways" are similar to interstates in that they have directional travel lanes, usually separated by a barrier, with access and egress points are limited primarily to on- and off-ramps. "Other principal arterials" can serve specific land parcels directly and have at-grade intersections with other roadways that are managed by traffic devices. "Minor arterials" are for trips of moderate length between higher arterial classifications and roads with lower classifications that provide access to businesses and homes. "Collectors" gather traffic from local roads and into the arterial network. Local roads are not intended for long-distance travel and are often designed to discourage through traffic. See *Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance, 23rd edition*, Department of Transportation.

[18] See the NBI webpage for data, definitions, and more information.

different set of quality measures, the share of total deck area of bridges classified as in “good condition” fell slightly from 47 to 45 percent, while the share classified as in "fair condition” rose from 43 to 49 percent, and the share classified as in “poor condition” fell from 10 to 5 percent.

Another type of capital included in BEA estimates are highway noise barriers. The number of miles of highway noise barrier construction also increased from 1989 to 2016, from 747 to 3,284 (figure 8). This increase in sound walls is consistent with a rise in road miles in urban areas and perhaps the growing role of “citizen voice” as argued by Brooks and Liscow (2020). The stock of structures other than roads may have also increased over time, although physical measures of other structures are not available.

Road quality. The HPMS tracks the condition of roads using the International Roughness Index (IRI), which measures the number of inches of suspended travel a typical car experiences on a particular mile of roadway. The units of the IRI are inches per mile, and a decline in IRI reflects an improvement in pavement quality. FHWA classifies roads as in “good condition” when the IRI value is below 95, “fair” when the IRI value is between 95 and 170, and “poor” when the IRI value is above 170 (Department of Transportation, 2018). IRI data are available for interstate highways, expressways, and primary arterials from 1992 forward, and for minor arterials and collectors from 1999 forward. IRI data for local roads are not available.

The available IRI measures suggest that some of the increase in BEA’s net stock measure over time may reflect an increase in road quality of certain types of roads (figure 9). The quality of interstate highways clearly improved, as the share of road miles in good condition almost doubled, from about 43 to almost 80 percent while the share in fair condition fell from about 50 to 17 percent and the share in poor condition fell to well below 5 percent. The quality of expressways and principal arterials also improved. From 1999 to 2018 (when data are available), the condition of minor arterials and collectors improved somewhat as the percent of roads rated as poor or fair dropped slightly and the percent of roads rated as good increased somewhat. Rural roads are in better condition than urban roads, with half of all rural roads being rated as good in 2018. By 2018, 97 percent of interstate miles, 84-87 percent of arterial miles, and 72 percent of collector miles were in good or fair condition.

Road usage. These measures of the quality of roads and bridges have improved or remained steady despite substantial increases in road usage. Vehicle miles traveled (VMT), a measure of total road usage, has increased far more rapidly than road miles or lane miles, overall (figure 10) and for interstates, arterials, collectors, and local roads. VMT and constant-price CFC can be viewed as two informative but imperfect measures of the services we obtain from highways and streets (neither is clearly a better estimate, and neither includes a complete measure of capital services). Comparing the two measures, VMT grew more rapidly than CFC (3.58 percent per year versus 2.30 percent from 1945 to 2018, table 2). The growth in VMT was notably faster than the growth in CFC from 1945 to 1960 and from 1968 to 1997; the two measures grew at similar rates in other periods. The intensity of road usage, as measured by the annual average daily traffic (AADT, equal to VMT divided by lane length and by 365 days), also grew in recent years (table 2 and figure 11).

Summary. These measures paint a picture of the nation's highways and street capital that is more nuanced and detailed than a single monetary measure of capital stock. Over the past several decades, BEA's net stock measure grew at a faster rate than the number of road miles and lane miles. At least some of the relatively faster increase in net stocks resulted from an increase in the quality of many roads, as measured by paved road miles and by the IRI; from an increase in the surface area and possibly the quality of the nation's bridges; and from an increase in miles of sound walls and perhaps to other types of "nonroad" capital. The quality of roads and bridges has improved or remained roughly stable in many ways.[19] in spite of substantial increases in the usage of roads, as measured by VMT. While there is no precise relationship between these physical measures of road capital and BEA's net stocks, these measures suggest that a reasonable net stock measure should be rising over time, although the appropriate rate of increase is less clear.

4. Evidence on service lives

We can update and possibly improve BEA's estimates of net stocks of highways and streets, and better understand the relationship between these net stocks and the physical measures of highway and street capital from the HS data, with more disaggregated data on depreciation rates and capital outlays for key subcategories of investment in highways and streets, such as new construction, resurfacing, bridges, and so on. We next describe the available studies of service lives by type of investment (this section) and the HS data on capital outlays by type of investment (next section). The available evidence indicates, as expected, that different types of capital have different service lives, confirming the value of a more disaggregated approach.

This research updates, borrows, and extends many of the ideas and data in Fraumeni's (1999, 2007) detailed studies of productive highway capital stocks. These studies used disaggregated HS data on spending for interstate highways, state roads, and local roads, and for several types of outlays. Using some reasonable assumptions to impute some missing data, these studies created a full time series of detailed data on investment from the 1920s forward and estimated productive capital stocks

[19] See Glaeser and Poterba (2020) for a brief overview of how this assessment based on FHWA data differs from the more pessimistic assessment in the American Society of Civil Engineers' (ASCE) *Infrastructure Report Card*.

through 2005. The productive stocks were adjusted for depreciation and also for efficiency losses which increase as roads deteriorate over time, causing lower driving speeds and rising vehicle operating costs. The estimated capital stocks were lower than BEA's published net stocks in part because BEAs stocks depreciated at a constant rate while the stocks in Fraumeni (1999, 2007) deteriorated as a varying rate depending on the composition of capital outlays. Recently Fraumeni's study was updated through 2019, and the results will be presented later in this paper.

Key types of investment. The HS capital outlays data and the research on service lives often separate capital into several clearly defined types. Outlays directly related to road building are often separated into new road construction and relocation, road reconstruction, major road widening, and so called "3R" outlays, which are further split into minor widening, road restoration and rehabilitation, and road resurfacing or repaving. Bridge work consists of construction of new bridges and the reconstruction and repair of existing bridges. "Safety-related" outlays pay for items like rumble strips, barriers, guardrails, and paved shoulders. Outlays for "traffic management" pay for traffic signal controls, freeway management, incident management, road and bridge surveillance and control, electronic message boards, video monitoring, motorist information radio, and other "intelligent transportation infrastructure (ITI)." "Environmental improvements" fund noise barriers, beautification, and similar projects, while other enhancements include bike paths, bicycle rest areas, and pedestrian overpasses.

An additional complication is that the available data on capital outlays related to road building splits outlays into new construction/relocation, reconstruction, major widening, and types of "3R" outlays, but the studies of service lives provide estimates only for three types of capital within each of these types of investment—road resurfacing/ paving, road grading (smoothing a roadbed with earthmoving equipment), and other structures (such as bridges and administrative buildings). While the service lives for paving, grading, and structures differ, the published capital outlays data do not report outlays for these three types of capital. To estimate service lives for each type of road-related investment, we therefore need estimates of the shares of each type of investment for paving, grading, and structures.

Service lives and depreciation rates. For our main updated estimates of net stocks and CFC, we assign different service lives to each type of investment (table 3.) These estimates, based on engineering- and benefit-cost studies of construction projects from several sources, are not known precisely. The expected service life of an asset, reflecting an expected rate of physical deterioration, may exceed the actual service life because of unexpected increases in usage, less than ideal maintenance, or obsolescence, such as a need to replace older roads and bridges to accommodate more traffic. The available studies nevertheless provide useful information. For our main estimates we use these service lives for all years from the 1920s forward.

For road-related construction, we follow Fraumeni (2007) and use a service life of 80 years for road grading and 20 years for road resurfacing or repaving. These service lives were obtained from studies by Faucett and Sheppach (1974) and Gedeon Picher (see Fraumeni 1999, 2007), respectively. For other structures and bridge work, we use a service life of 50 years, consistent with Fraumeni (2007) and BEA's estimates for many nonresidential structures. It was decided that environmental improvements probably are fairly long-lived; lacking other information, a service life of 50 years was also assumed. For safety-related and traffic management structures, we use a service life of 15 years based on information from FHWA on the expected service lives for assets within these categories.

These estimated service lives differ somewhat from the service lives used in Beemiller (1999), based on information collected from discussions with staff at seven state agencies. This study used service lives of 100 years for earthworks (similar to grading), 44 years for drainage and concrete work, 22 years for road surfaces, 53 years for bridges and other major structures, and 12 years for safety and traffic management, where all service lives except for those for earthworks were based on agency responses. Although we believe our study is based on updated and more extensive evidence, the rough similarity in some of these service lives is reassuring.[20]

We acknowledge that in the last two decades the typical design life for some forms of capital may have increased because of technological improvements. The design life for new pavement, for example, may be longer due to the use of more advanced materials, "superpave" technology, and "perpetual pavement designs." Based on information from some state design guides obtained from FHWA, the design life for interstates (assuming standard maintenance) may have increased to 25–40 years for asphalt pavement and 35–65 years for concrete pavement, but actual service lives may still be lower depending on usage, weather, and other factors. According to FHWA staff, the expected design life of a bridge has risen due to technological advances from 75 years to 100 in very recent years, but the NBI data and capital outlays data (presented below) confirm that substantial outlays fund bridge replacement and repair, suggesting the actual service life of bridge-related investment is shorter than the ideal design life. For our estimates of net stocks, we assess the effect of assuming longer service lives for some types of capital.

We estimate depreciation rates by dividing the declining balance rate (DBR, 0.91) by the service lives (table 3). The DBR is the BEA default rate for non-residential structures. Geometric rates are valid even with the inevitable fact that assets' actual service lives are distributed around the specified service life.[21]

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[20] Beemiller (1999) estimated service lives based on interviews with staff in seven states, as a weighted average of these service lives, with weights determined by shares of capital outlays, as reported by FHWA data and state staff.
[21] Hulten (2008).

Note that with a service life of 20 years and a DBR of 0.91 about 40 percent of capital remains after 20 years. If we assume a higher DBR, the assets depreciate more quickly.

Shares of road-related construction for paving, grading, and structures. To estimate shares of outlays for paving, grading, and other structures (table 4), we also follow Fraumeni (2007) and rely on an internal 1997 Cost Allocation Study (CAS, Jacoby, Department of Transportation) that provides estimates of spending for grading as a share of the sum of spending for grading plus paving for several types of roads. This study found that a much larger share of outlays funds paving (with a lower service life) than grading (with a higher service life). For new construction or reconstruction, spending for paving is 2-4 times greater than spending for grading. For restoration and rehabilitation and for resurfacing, the relative share of spending for paving is even higher. The grading and paving shares vary little by type of road and rural/urban status.

The CAS results show only the relative shares of spending for paving and grading, so we need to estimate the share of these types of road-related investment for all other structures (for which we assume a service life of 50 years). We assume that whenever governments report outlays for these types of road-related construction projects, they include some spending for not only road paving and grading but also related structures. The share of road-related investment for these other structures is estimated to be under 20 percent, based on the research described in the Fraumeni studies (1999, 2007). Applying these shares yields an estimate of the proportion of each type of road-related investment for paving, grading, and other structures (table 4).

5. Capital outlays by type of investment

These widely varying depreciation rates highlight the benefit of having disaggregated investment data. *Highway Statistics* fortunately reports capital outlays by type of investment for several years. The scope and definition of capital outlays in the HS data, in the Census Bureau's GF survey, and in BEAs investment in highways and streets are all very similar. All include capital spending for a similar range of assets and exclude maintenance and repair expenses. As one would expect, the sum of HS-reported capital outlays is generally close to BEA's estimates of investment in highways and streets over the past several decades.[22] We therefore assume that we can use the shares of types of outlays in the HS data to disaggregate BEA's investment data.

[22] The two estimates are very similar but may differ because various data "vintage" issues and the timing of BEA revisions, and various internal BEA adjustments.

The availability of capital outlays data by type of investment varies over time and type of road. The HS data report total capital outlays separately for interstate highways for 1956 forward (around the start of the Interstate Highway System) and for non-interstate state roads and for local roads for 1921 forward (figure 12, some years are not available). Trends in outlays for these three types of roads differ substantially.[23] For interstate and state roads, the published HS data tables provide the most detailed breakouts of capital outlays by type for 1998 forward, less detailed breakouts for 1981–1997, and very little detail for years before 1981. For local roads, the published HS data tables do not provide breakouts of capital outlays by type, but they do provide breakouts of obligations, with the most detail for 1998 forward. We first describe the available data from 1981 forward, then discuss key findings, and then discuss the imputations to create a full history of capital outlays by type of investment.

Capital outlays data, Highway Statistics, 1981–2018. For these years, the published HS data tables report outlays separately for six categories of roads: rural and urban interstates, rural and urban state arterials, and rural and urban state collectors.[24] For 1998–2018, within these six categories of roads, outlays are split into right of way (ROW), engineering, new construction and relocation, reconstruction, major widening, minor widening, restoration and rehabilitation, resurfacing, bridge work (further separated into new bridges and reconstruction and repair of bridges), safety, traffic operation and control, and environmental enhancement and other. For 1981–1997, for the same six categories of roads, outlays are reported only for the sum of ROW and engineering, the sum of new construction plus relocation, total reconstruction, major widening, total "3R" (the sum of minor widening, restoration and rehabilitation, and resurfacing), total bridge work, and the sum of all other types. To estimate an equally detailed breakout for the full 1981–2018 period, we apply the 1998–2003 shares of more detailed breakout of outlays to the less detailed breakout of outlays for 1981–1997.

For estimates of shares of resurfacing within "3R" capital outlays, and for estimates of shares for all types of capital outlays for local roads, we rely on detailed data on obligations, available for 1998 forward, to overcome some limitations in the capital outlays data. For interstate and state roads, outlays for resurfacing are reported only unevenly for a few years and then appear to be reported as part of restoration and rehabilitation. For local roads, detailed outlays data are not available. Although the obligations data include spending other than capital outlays and vary considerably from year-to-year

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[23] The capital outlays for interstate highways, state roads, and local roads are obtained from HS tables SF12A, "State Highway Agency Capital Outlay," table HF-210 or HF-10, "Funding for Highways, All Units of Government," table HF-221, "Estimated Capital Expenditures by Federal Systems and Expending Agencies, 1956-1986," table SF-212A, " State Capital Outlay on Arterials and Collectors, by Improvement Type, 1981-1995, table SF-12, "State Highway agency Capital Outlay and Maintenance, tables LGF-2 and LGF-202 "Disbursements of Local Governments for Highways."

[24] Arterials, other than interstates, include freeways, multilane highways, and other important roadways that supplement the interstate System. Collectors are major and minor roads that connect local roads and streets with arterials. See U.S. Department of Transportation (2018).

(obligations include amounts to be spent over several years), they give us some information on shares of spending. For interstate and state roads, we estimate the average share of 3R obligations for resurfacing over the period from 1998 forward, for each of the six categories of roads, and apply these shares to estimate capital outlays for resurfacing for 1998 forward. Similarly, for local roads, we estimate average shares of types of obligations for rural and urban roads over the period from 1998 forward to estimate capital outlays by type for local road for 1981–2018.[25]

Trends in capital outlays, 1981–2018. The shares of capital outlays by type (figures 13–15) confirm that most capital outlays are not simply for new road construction. For interstate highways, the share of outlays for new construction fell from about 30 percent in the early 1980s to less than 10 percent in recent years. The shares for new construction range from 7 to 24 percent for state roads, with no clear trend, and are 7–8 percent for local roads. These results help explain why road miles grow more slowly than net stocks.

The substantial shares of outlays for road improvements are consistent with the increases in paved road miles and the typical steady or rising measures of road quality despite increases in road usage. The shares for reconstruction and major widening rose to about 26 percent for interstates and range from 15 to 27 percent for state roads and from 20 to 24 percent for local roads. The share of outlays for minor widening and restoration and rehabilitation rose from about 8 to 20 percent for interstates and ranged from 7 to 14 percent for state roads and 7 to 9 percent for local roads. The share of outlays for resurfacing rose from about 7 to about 19 percent for interstates and ranged from 10 to 17 percent for state roads and 7 to 8 percent for local roads.

The remaining capital outlays fund other types of capital. The share of outlays for new bridges is well under 5 percent, far smaller than the share of outlays for bridge replacement and rehabilitation. These patterns seem consistent with the limited growth in the number of bridges, the more rapid increases in bridge surface area, and the steady or slightly improving measures of bridge quality. The relatively larger share of outlays for bridge replacement and repair rather than new bridge construction also suggests that a substantial number of bridges may not last their entire expected service life because of wear and tear or obsolescence. Outlays for safety, traffic operation, and environmental and other functions together typically amount to 10 percent or less annually for interstate, state, or local roads. The share of outlays for ROW (which we will exclude from investment) varies from 2 to 13 percent, while the share of outlays for engineering (which we will allocate proportionately to the other capital types) varies from 6 to 17 percent.

[25] For estimating shares of capital outlays for resurfacing within total 3R outlays, and for local roads, we use obligations data from HS table FA-6 "Obligation of National Highway System and Surface Transportation Program funds by Functional Class and Improvement Type."

Creating a full history of capital outlays. To update our net stock estimates based on these data, we need to impute investment shares back to 1956 (interstates) or 1921 (state and local). To impute outlays for investment types except ROW and engineering for interstate highways back to 1956, we first applied average 1983–1987 shares for all investment types back in time, and then tapered the shares for 3R, safety, traffic, and environmental outlays to zero by 1971 and reallocated these outlays to new construction. These assumptions, similar to those in Fraumeni (2007), are consistent with the observation that the first several years of the interstate highway system were mainly devoted to new construction or bridge work.

To impute outlays for investment types except ROW and engineering for state and local roads back to 1921, we applied average 1983–1987 shares for investment types back in time, also similar to the approach used in Fraumeni (2007). Under the assumption that the shares of outlays for safety, traffic, environment, and paving were lower before 1950, we tapered investment shares for safety, traffic, environment to zero from 1945 back to 1921 and reallocated these outlays to grading, paving, bridges, and other structures, and we gradually reduced shares of outlays for paving by an additional third from 1945 back to 1921 and reallocated these outlays to grading, bridges, and other structures.

Capital outlays for ROW and engineering receive special treatment. ROW outlays include land, improvements, and the costs of moving and relocating buildings. BEA's definition of investment includes the purchase of land improvements but not land, and outlays for the cost of moving or removing buildings probably do not increase the net stocks of highways and streets. As a result, we assume ROW outlays do not appear in BEA's estimates. Engineering outlays pay for engineering, traffic, and related studies, and for surveys, testing, and preparation of plans, estimates, and specifications. These engineering outlays are included in BEA investment and appear to be integral to the other types of capital outlays. Consequently, we allocate engineering outlays to the non-ROW investment types based the shares of the other types of capital outlays in the HS data.

The next step is to allocate this full history of road-related capital outlays for new road construction, reconstruction, widening, minor widening and restoration and rehabilitation, and resurfacing to paving, grading, and other structures based on the shares from the 1997 CAS study and related research. The results (figure 16), based on these data and assumptions, show that the share of outlays for capital with a faster depreciation rate (paving, safety, and traffic operation) tends to be larger than the share of outlays for capital with the slowest depreciation rate (grading), while the remaining outlays (bridges, road-related structures, and environmental) fund capital with a depreciation rate similar to BEA's current assumption.

For the updated PIM-based estimates of net stocks and depreciation, we leave BEA's published estimates of constant-price investment in highways and streets unrevised and use the estimates of capital outlays by disaggregated type of capital to estimate the shares of total constant-price BEA investment for each type. We estimate benchmark values of wealth stocks for state and local roads in 1921 by applying the same 1920 distribution of benchmark assets as in Fraumeni (2007) to BEA's estimates of total net stocks in 1920. We estimate benchmark stocks of interstates (1956) by assuming that 0.06 percent of state road capital became part of the interstate in 1958 based on Fraumeni (2007). Using the depreciation rate assumptions in table 3, we apply the PIM to build a history of constant-price net stocks and CFC for each type of capital and then aggregate to estimate total net stocks and CFC. With this approach, revisions to total net stocks and CFC arise solely from the use of disaggregated investment and depreciation rates.

6. Updated estimates of wealth stocks and depreciation

Before reviewing the updated estimates of net stocks, we might ask how we can assess their accuracy, given that we cannot observe anything like the true depreciated value of the nation's highway and street capital over time. Our estimates are based on respected data and research, but they are also based on some approximations and assumptions about shares of types of investment over time, service lives, and declining balance rates. One way to assess the results, even in rough terms, is to compare them with physical measures such as road miles, paved road miles, road quality, and so on. A reasonable expectation is that constant-price net stocks should be gradually increasing over time, and that the growth rate should be well above the growth rate of road miles, and above or below the growth rate for paved road miles.

The updated estimates (figures 17–18 and tables 5–6) result in upward revisions to constant-price CFC and downward revisions to constant-price net stocks. Over the most recent two decades, constant-price CFC is revised up \$9–\$12 annually (about 15 to 20 percent). By 2018, constant-price net stocks are revised down \$751 billion, or 22 percent. Net stocks are revised down in all years, although the trends in the revised and published estimates remain similar: both grow most rapidly from 1945 to 1968, grow less than half as rapidly from 1968 to 2007, and then grow less than one percent annually from 2007 to 2018. The revisions occur mainly because the share of investment that depreciates more rapidly than BEA's published estimate (paving, safety, and traffic management) is larger than the share that depreciates more slowly (grading). The revisions would be roughly similar if we use a single aggregate depreciation rate of 3 percent rather than 2.02 percent.

The revised estimates are broadly consistent with the physical measures of capital. The updated net stock estimates increase in all years except for a few years in 1939–1945 and grow more rapidly than road miles. The updated net stocks grow slightly faster than paved road miles: from 1968 to 2018, the average annual growth rate for updated net stocks was 1.32 percent versus and 1.21 for paved road miles; net stocks grew more rapidly than paved road miles from 1982 to 2007 and more slowly from 1968 to 1982 and from 2007 to 2018. We can also divide total stocks into stocks for paving plus grading, and stocks for other structures. The average annual growth rate of net stocks of paving and grading alone was 1.14 percent from 1968 to 2018, close to the rate for paved road miles. Over this period, net stocks of other highway and street capital grew 1.57 percent annually, faster than net stocks of paving and grading. Although there is no exact relationship between these physical measures and net stocks, the results seem generally reasonable.

The revisions are smaller if we assume longer service lives, which we cannot measure precisely. (Estimates of net stocks based on alternative assumptions are presented in figure 19 and the right side of table 5.) If we raise service lives to 25 years for paving and 75 years for bridgework ("updated, longer service lives" in the figure), the upward revisions to constant-price CFC are $5–7 billion annually over the past 20 years, and the downward revision to constant-price net stocks in 2018 is $412 billion. If we assume (not shown in the figure and table) that after 2000, the service lives for new investment in paving and bridgework increase to 25 and 75 years, respectively, because of technological advances, the upward revisions to constant-price CFC range from $11 billion to $5 billion annually over the past 20 years, and the downward revision to constant-price net stocks in 2018 is $690 billion.

If we use service life assumptions closer to those in Beemiller (1999) and assume 22 years for paving, 100 for grading, 55 for bridgework, 12 for safety and traffic structures, and 44 years for environmental structures, we still obtain upward revisions to constant-price CFC of $8–$11 billion annually over the past 20 years, and a downward revision to constant-price net stocks of $637 billion in 2018. Beemiller estimated an aggregate service life as an average of these service lives weighted by shares of capital outlays data from 1984 to 1995. Part of the reason our depreciation rates are higher is that Beemiller's data showed a higher share of outlays for grading, which has a long service life.

We could, on the other hand, use alternative reasonable assumptions that result in even larger downward revisions to net stocks. We obtain slightly larger downward revisions to total net stocks if we choose to lower the shares of 3R outlays for other structures to zero ("smaller share for other structures" in the figure), under the alternative assumption that all outlays for 3R projects fund only grading and paving. We obtain notably larger revisions to net stocks if we assume a higher DBR value. We have assumed a DBR of 0.91 based on older studies of nonresidential buildings, rather than on evidence specific to highways and streets. If we increased our DBR to 1.2, depreciation rates would be higher with the same assumed service lives. This assumption, which might be consistent with faster depreciation of some capital arising from more intensive usage, results in upward revisions to constant-price CFC of $15 to $20 billion in recent years and downward revisions to constant-price net stocks of about $1.2 trillion in 2018. These alternative estimates still result in net stocks that grow consistently and slightly faster than paved road miles for the full period.

We obtain downward revisions to total net stocks similar to those obtained with a DBR of 1.2 if we use a single depreciation rate of 4 percent. If we use depreciation rates of 5 percent or more, net stocks decline in recent years, a result that seems less consistent with the physical measures. Accordingly, the evidence suggests that a reasonable aggregate depreciation rate for all highway and street capital for the full history appears to range between 3 and 4 percent, although we could also allow the rate to vary over time depending on the composition of the stock.

We can also restate our updated net stock estimates as the growth rate in constant-price net stocks per capita, a figure cited in BKSW (2020) and consistent with measures used in models of productivity and growth (table 7). The revised net stock per capita estimates grow more slowly than the net stock estimates, given increases in population over time. The published estimates show a slowdown in growth to roughly zero percent after 2007, and the updated estimates show a decline after 2007, although we draw no strong policy conclusions from these estimates.

7. Updated estimates of Fraumeni stocks

The productive capital stocks, and the corresponding wealth capital stocks for public roads, were also updated using the Fraumeni (1999, 2007) methodology; we call these the "Fraumeni estimates."[26] Differences between the updated estimates of net wealth stocks and depreciation presented in the previous section and the Fraumeni updated wealth stock estimates presented here are almost all due to the difference in the estimation of pavement depreciation. There are three other factors to note which distinguish the updated estimates in the previous section from the Fraumeni updated estimates. The first is the inclusion of capital outlay separately for traffic operation and control systems, safety, environmental enhancement, and engineering. As previously stated, capital outlays for safety, traffic operation, and environmental and other functions together typically amount to 10 percent or less annually for interstate, state, or local roads; the corresponding figure for engineering varies from 6 to 17 percent. These items were not identified separately in the Fraumeni estimates because of the lack of information on their service lives at that time. To the extent that the service lives for these expenditures

[26] See Fraumeni (1999, 2007) for a more detailed explanation of the methodology; this paper presents only a brief summary. All estimates in this section exclude ROW outlays.

differ from the service lives used in Fraumeni ,this issue might matter for the results.[27] The second factor is improvements and changes in the source data, particularly as some HS tables became more detailed beginning in 1998. The last factor is the initial year benchmark.

Pavement depreciation comes from an analysis of road efficiency by Gedeon Picher based on commonly used engineering relationships (Fraumeni, 1999 and 2007, volume I and II). Efficiency depends on structural aspects of roads as well as the level and intensity of traffic adjusted by differential wear and tear on roads by vehicles of different sizes and weights. In addition, efficiency depends on higher time and operating costs from reduced driving speed . American Association of State Highway and Transportation Officials (AASHTO) curves were the basis for Picher's determination of structural aspects of roads. Although not all states use AASHTO curves, those curves that are the basis for state agency road engineering and construction were typically very similar to AASHTO curves. No attempt was made to distinguish between asphalt and concrete roads because the lack of information on construction costs or subsequent expenditures by type of road. No attempt was made to include unpaved roads in the analysis. After the pavement curves were created separately for interstate, non-interstate state, and local roads, time costs were added in to adjust road efficiency. The service life of all roads was set at 20 years; at end of this period roads were considered to be fully depreciated. Efficiency curves were created every 10 years until 1986 the last year for which a curve was created. The curves varied little over time. The separate estimate of different pavement curves for interstate, non-interstate state, and local introduced a quality component to the stock estimates.

Pavement productive depreciation differs significantly from wealth depreciation. For example, in 1986, the last year of the Picher curves estimation, year 20 interstate productive age/efficiency profile is at .93 versus .07 for the wealth age/price profile.[28] The corresponding figures for state roads is .84 versus .06, and for local roads is .73 versus .05. A productive notion only captures what an asset can do for you in the current period, a wealth notion indicates what you would be willing to pay for an asset than has a finite service life. Although a 20-year-old pavement is still efficient, were you to "buy" a paved road, you would pay much less for it than if it were new. The other components of highways and streets are depreciated using a geometric rate, so there is no such contrast between rates of productive and wealth

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[27] In this study, service lives are set at 15 for traffic and safety, and 50 for environmental and engineering expenditures; in Fraumeni they were set at 20 for paving, 50 for structures, including bridges, and 80 for grading.

[28] These profiles have a value of 1 when the asset is new and decline toward zero over time. The depreciation profile of a productive stock differs from the depreciation profile of a wealth stock because the profile of the former only considers the efficiency of the stock in the current period, whereas the profile of the latter considers current and future-year efficiencies and the decrease in price that an entity would pay for an asset because it has fewer years left in its service life.

depreciation. However, with a geometric rate of depreciation, assets continue to have value, however measured, for long after their service life.[29]

Pavement shares of total capital constant-price outlay are very high, ranging from a 67 to 74 percent. These shares remained close to 74 percent except for the years between 1957 and 1978. The lower pavement share during these years certainly reflected the building of the interstate, which required substantial grading and structures outlays.

Figure 20 and table 8 compare updated estimates of stocks presented in the previous section ("updated stock estimates") and the Fraumeni updated stock estimates. Published BEA net capital stock levels are higher than the updated estimates, as already noted, and higher than either Fraumeni productive capital stocks or wealth (net) capital stocks levels. As expected, the Fraumeni productive stock levels are higher than the Fraumeni wealth stock levels because of the treatment of pavement stocks as just outlined. Fraumeni wealth stocks levels are lower than the updated stock levels, initially because of the lower Fraumeni benchmark[30] and lower annual growth rates in some earlier periods, although for other periods the growth rates of the Fraumeni wealth stocks are higher than those of the updated wealth stocks.

8. Conclusions

The recent debates on infrastructure spending have led to renewed interest in the measurement of infrastructure and its effects on growth and well-being. BEA's estimates of capital stocks of several types of infrastructure have been used in many studies of the effects of infrastructure capital on growth. Glaeser and Poterba (2020), BKSW (2020), and others point out that these estimates rely on depreciation rates based on dated research. In response to these questions, this paper updates estimates of one important type of infrastructure capital – highways and streets. We compare BEA's capital measures with more readily understood physical measures of road and lane miles, road quality and usage, and other measures from *Highway Statistics* (HS) data from FHWA. We also use the HS data and related research to disaggregate investment in highways and streets into more detailed types, such as new construction, repair and resurfacing, and bridge work, and apply separate depreciation rates to each type to produce updated estimates of net wealth stocks and depreciation, as well as productive

[29] At 20 years, with a geometric rate of depreciation, with a declining balance rate of .91 and a service life of 20 years as is assumed for all pavement stocks in the updated estimates described above, the year 20 age/efficiency profile (which is identical to the age/price profile under the geometric assumption), is at .39. At year 40 is at .15 and at year 60 it is at .06.

[30] There is a dip in the Fraumeni stocks between 1956 and 1957 as some state roads were transferred from the state system to the interstate system. In general, the first linked components of the interstate system were not ready for usage until 1958, although capital outlay on these systems began in 1956.

capital stocks. In many ways, this work borrows, extends, and updates previous studies by Fraumeni (1999, 2007).

Relative to published BEA estimates, constant-price CFC is revised up by about $9-$12 billion annually in recent years, and constant-price net stocks are revised down by about 22 percent. For the period from 2007 forward, constant-price net stocks per capita are flat in the published BEA estimates but decline slightly in the revised estimates. The revisions arise because we disaggregate total BEA investment based on shares of types of capital in the HS data and apply different depreciation rates, based on available research, to each type; the rates of road paving or resurfacing and some other types of capital reflect service lives shorter than BEA's currently assumed 45 years. The size of the downward revisions to net stocks varies somewhat if we use alternative assumptions about service lives and shares of investment for different types.

In addition, we update Fraumeni's (1999, 2007) estimates of productive stocks. These productive stocks are converted to wealth stocks to facilitate comparisons. These updated Fraumeni wealth estimates also show lower net stocks and higher depreciation than in the published BEA estimates.

We draw no clear policy implications from these results, and we recognize that these revisions have a very modest impact on BEA's core estimates: the revisions to CFC are modest relative to the contribution of government spending to GDP and have little effect on one's general sense of the nation's economic performance. We also recognize the broader limitations of our stock measures in analyses of infrastructure. These stock measures are somewhat abstract measures that provide few details about the impact of our infrastructure on daily life. They do not take into account how different forms of transportation-related assets (roads, subways, buses, etc.) interact within regions, or how current policy influences the use and productivity of existing infrastructure capital (see Winston 2020), or how highways can divide neighborhoods, or environmental concerns. Another limitation of our research is that we do not have price measures for specific types of capital and that our prices may not fully account for changes in quality.[31]

At the same time, we also point out that many researchers have used and continue to use BEA's capital stock estimates to estimate the possible impact of infrastructure on growth and well-being, and that the results of these studies could possibly change with updated estimates of capital stocks. These studies

[31] One interesting and valuable recent study by Swei, Gillen, and Onayev (2020) created a quality adjusted price index for several types of highway expenditures. While the authors categorize these expenditures as maintenance rather than investment, their definition of quality improvement is an increase in the expected service life of the expenditure. With this quality adjustment, the revised price measures fall about 2 percent per year faster. In a PIM capital framework, we might choose to capture a service life increase as a slowdown in depreciation rather than as a price adjustment. Regardless, we hope this research on prices and service lives continues.

are in some ways similar to many studies that seek to measure the effects of private capital stocks (from BEA or BLS) on growth and productivity. We suspect that these measurement challenges for highways and street capital may also exist for other broad categories of public infrastructure, as well as types of private capital. A related implication of this work is that one should exercise caution in comparing capital stocks of infrastructure across countries, because cross-country differences in net stocks may arise from different (and possibly unrealistic) assumptions about depreciation rates, prices, or other data.

This paper also shows that highways and streets, like many types of capital investment, is an aggregation of many different types of investment, each of which could have distinct effects on growth. Future research might go beyond studying the link between total infrastructure capital and growth and analyze the effects of narrower, more precisely defined measures of capital (new road construction, resurfacing, physical measures such as paved road miles etc.) on growth and productivity for specific industries and commodities, or for specific regions. More research on depreciation rates, the distinction between maintenance and capital outlays and the effect of each on productivity, quality adjustment of price measures, and capital outlays by type of investment would also be helpful. We hope this paper encourages discussion about how best to measure infrastructure capital, particularly highways and streets, and its effects.

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Figures and tables

Figure 1: Investment and CFC, Highways and Streets, Billions of 2012 Dollars, BEA

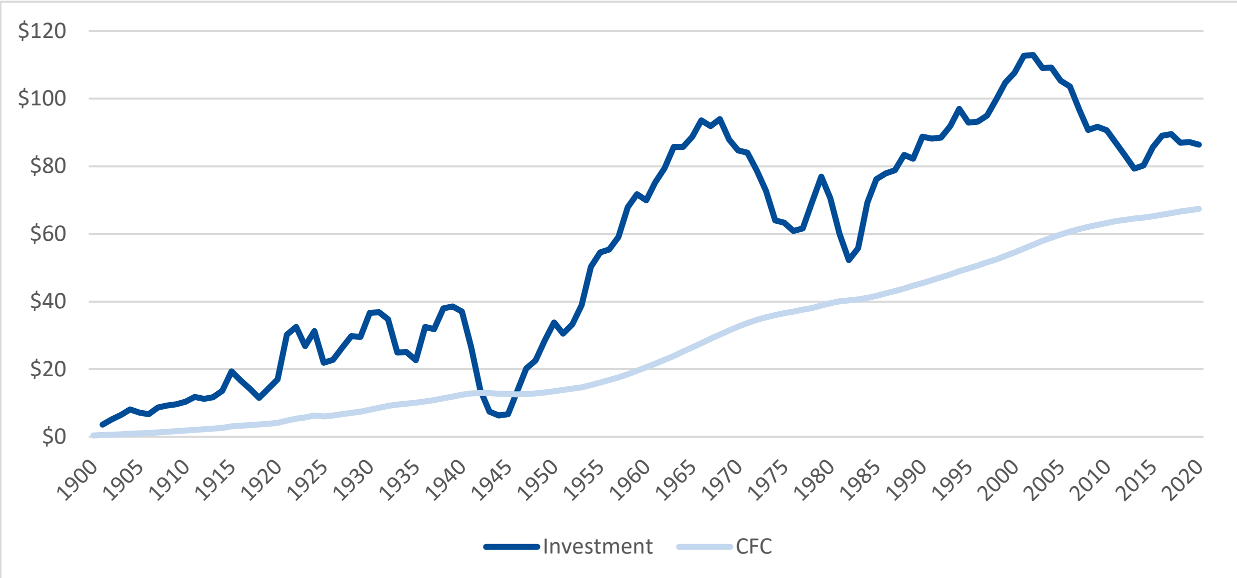


Figure 2: Price Index, Highways and Streets, 2012=100, BEA

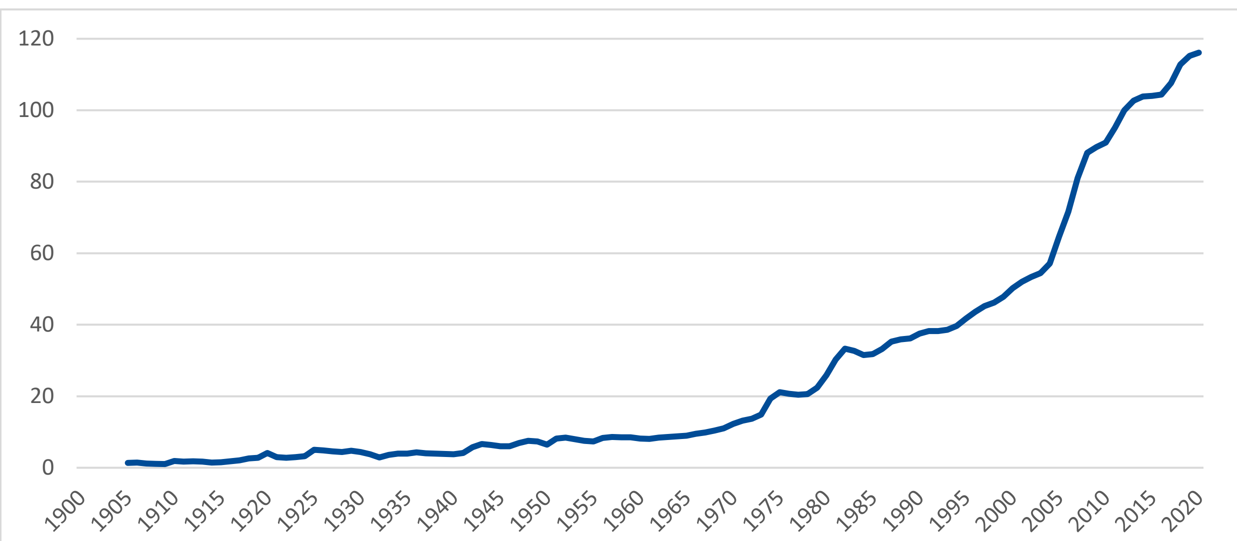


Table 1: Average Annual Growth Rates: Net Stocks, Road Miles, Lane Miles

	Constant (2012) price net stocks	Road miles	Lane miles	Paved road miles
1925-1939	4.20%	0.04%		
1939-1945	0.58%	0.23%		
1945-1960	3.51%	0.44%		
1960-1968	4.94%	0.48%		3.04%
1968-1982	1.95%	0.34%		2.10%
1982-1997	1.67%	0.16%	0.19%	0.93%
1997-2007	1.73%	0.22%	0.26%	0.89%
2007-2018	0.70%	0.32%	0.36%	0.76%
1945-2018	2.32%	0.32%		
1968-2018	1.55%	0.26%		1.21%

Source: BEA and *Highway Statistics*, Tables vmt-421c, 1-4, Highway Profile, HM-220, HM-260

Figure 3: Net Wealth Stocks, Highways and Streets, Billions of 2012 Dollars, BEA

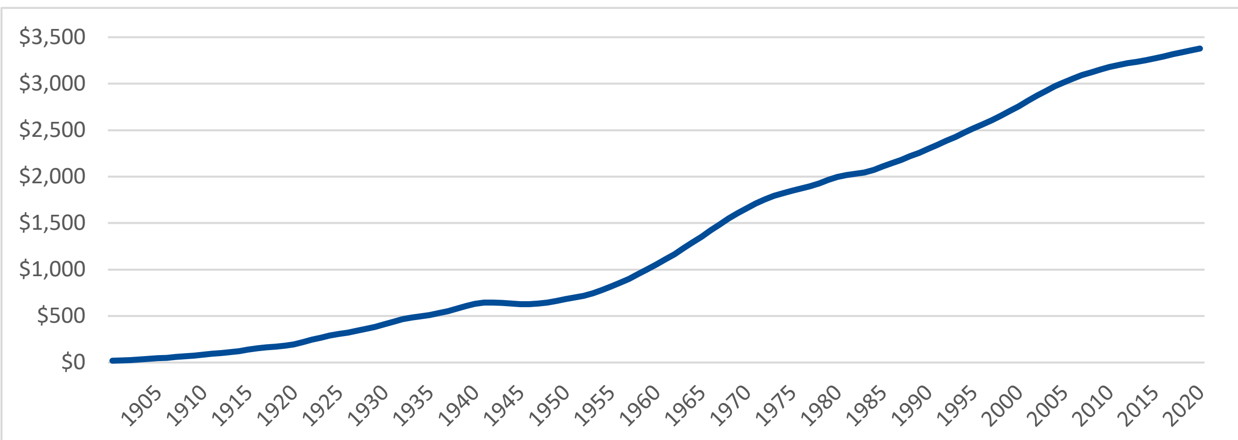
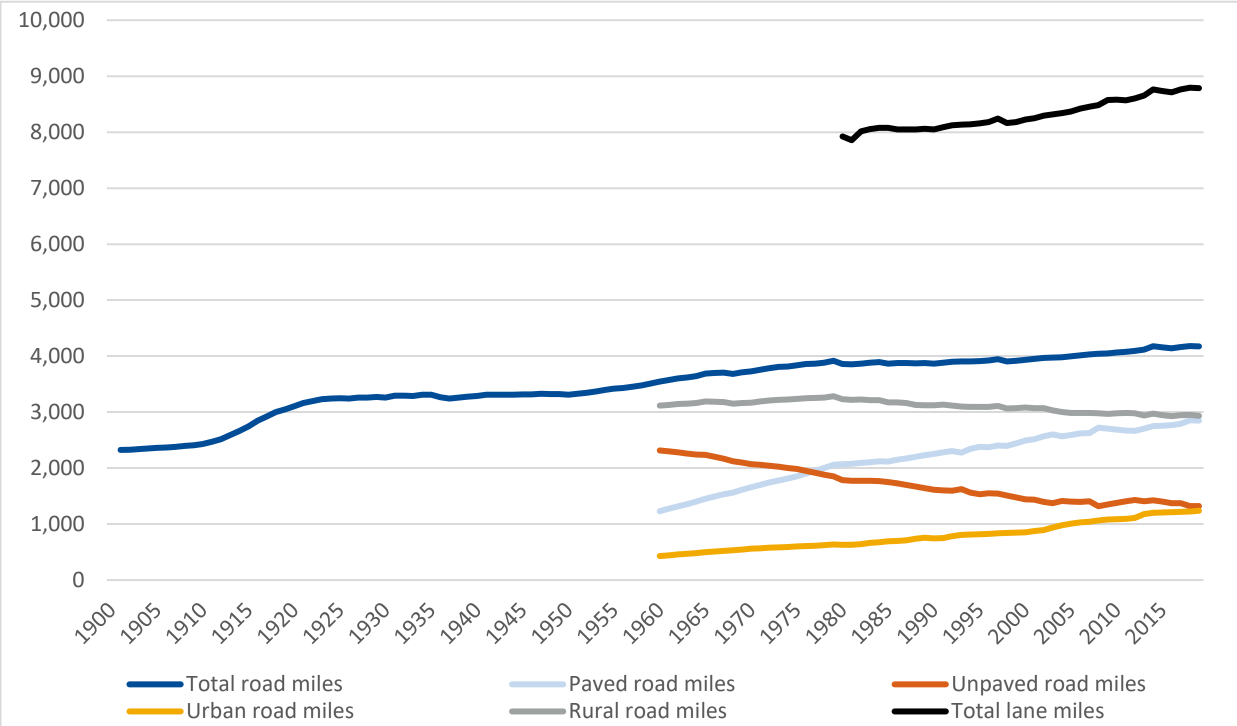
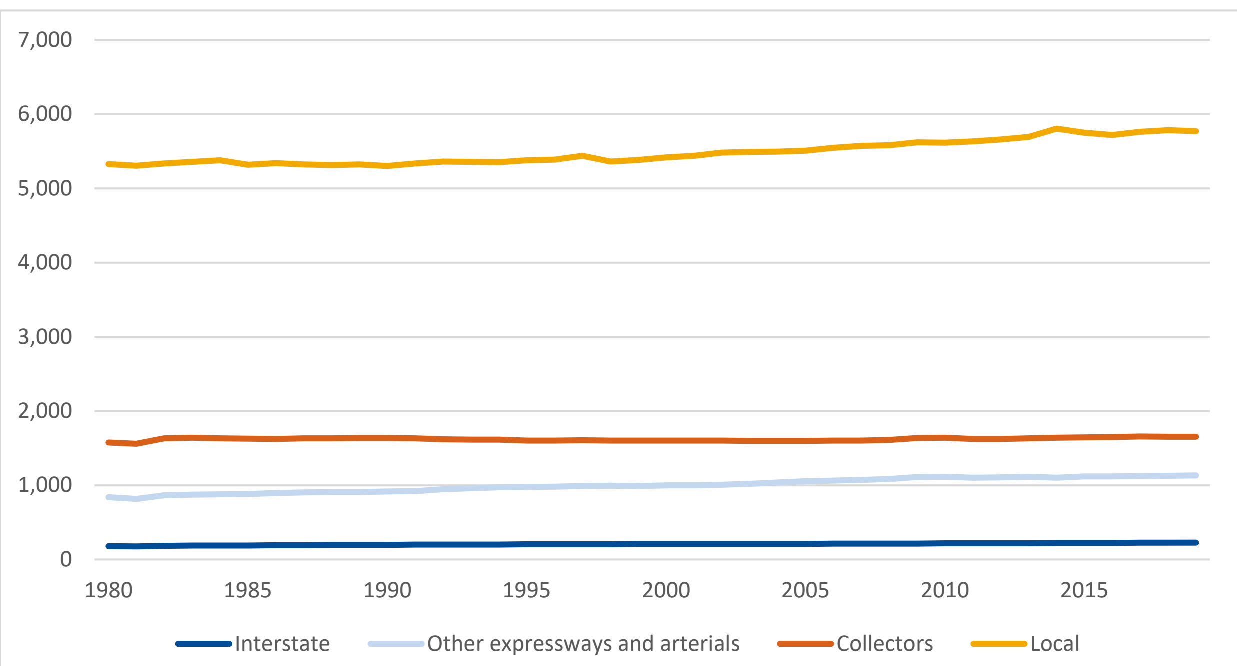


Figure 4: Road and Lane Miles, Thousands, *Highway Statistics*



Source: *Highway Statistics*, Tables vmt-421c, 1-4, Highway Profile, HM-220, HM-260

Figure 5: Lane Miles, by Type of Road, Thousands, *Highway Statistics*, 1980–2018



Source: *Highway Statistics*, Table HM-260

Figure 6: Number of Bridges, Thousands, *Highway Statistics*, 1992–2021

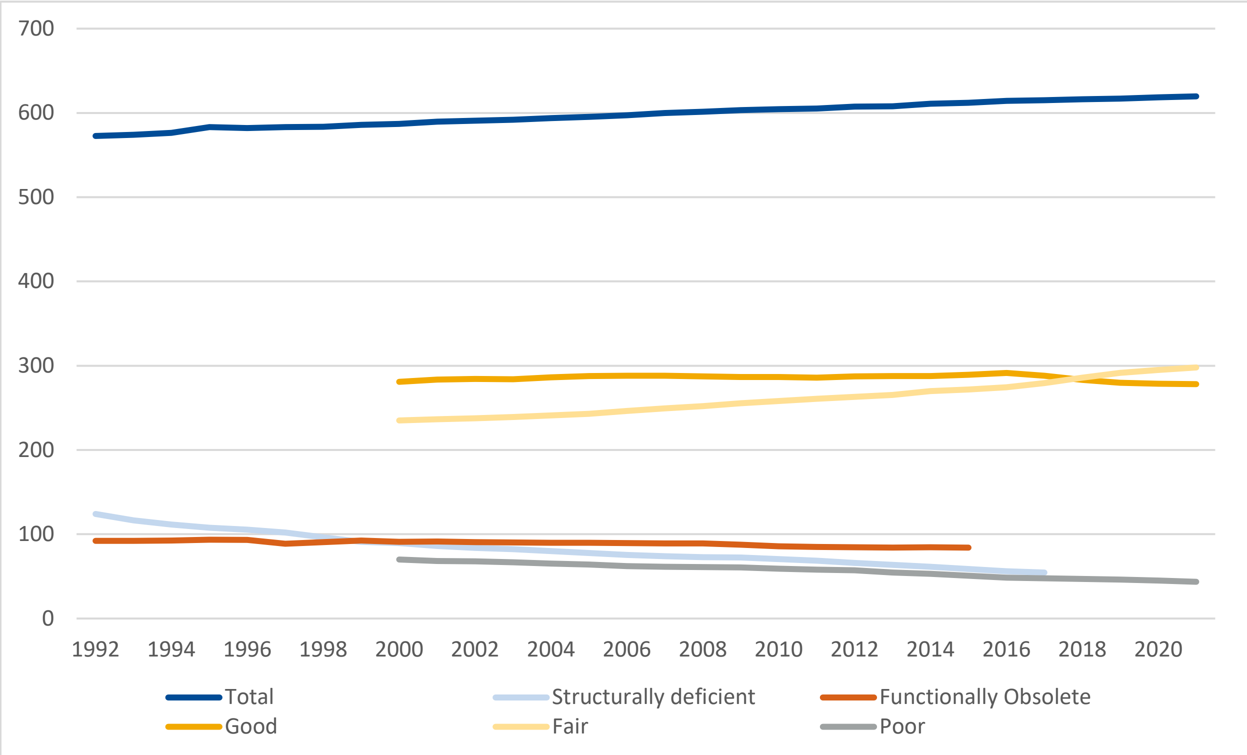
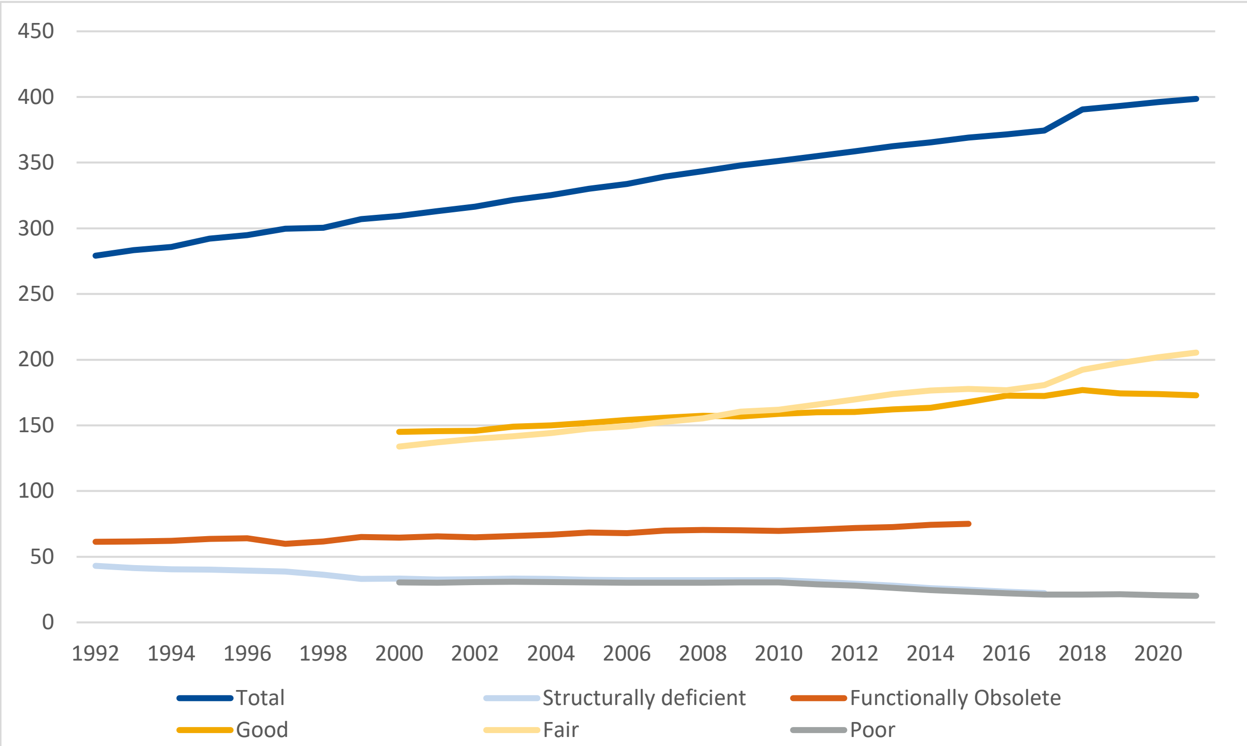
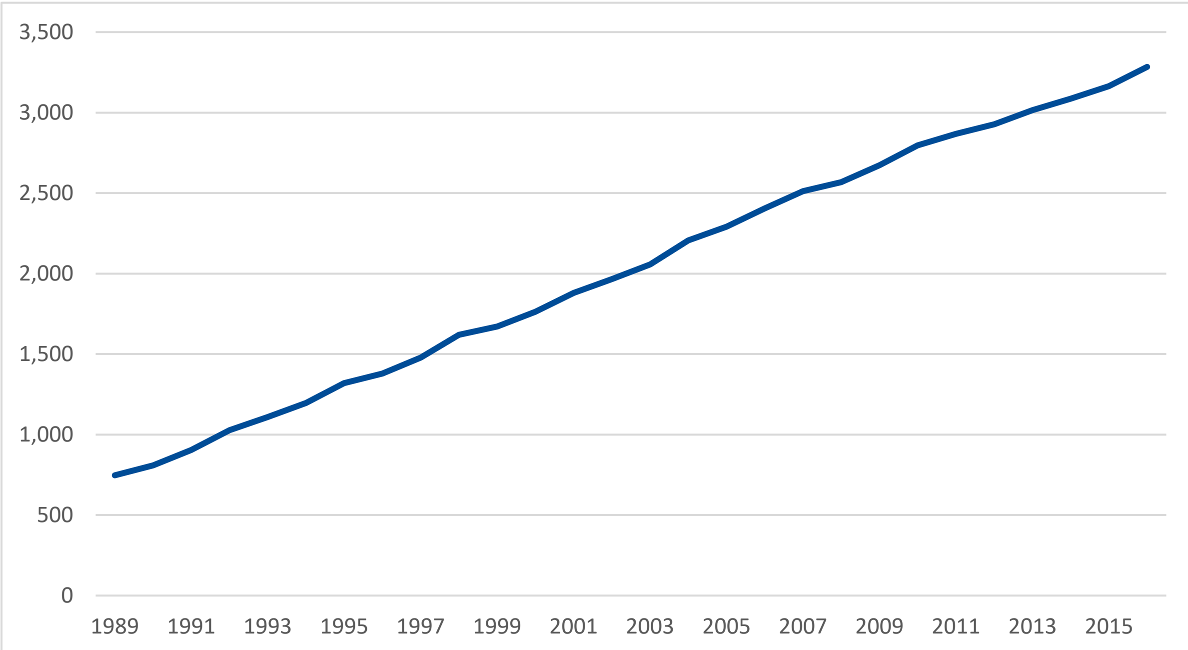


Figure 7: Bridge Surface Area, Square Meters, Millions, *Highway Statistics*, 1992–2021



Source: National Bridge Inventory

Figure 8: Miles of Highway Noise Barriers, *Highway Statistics*, 1992–2021

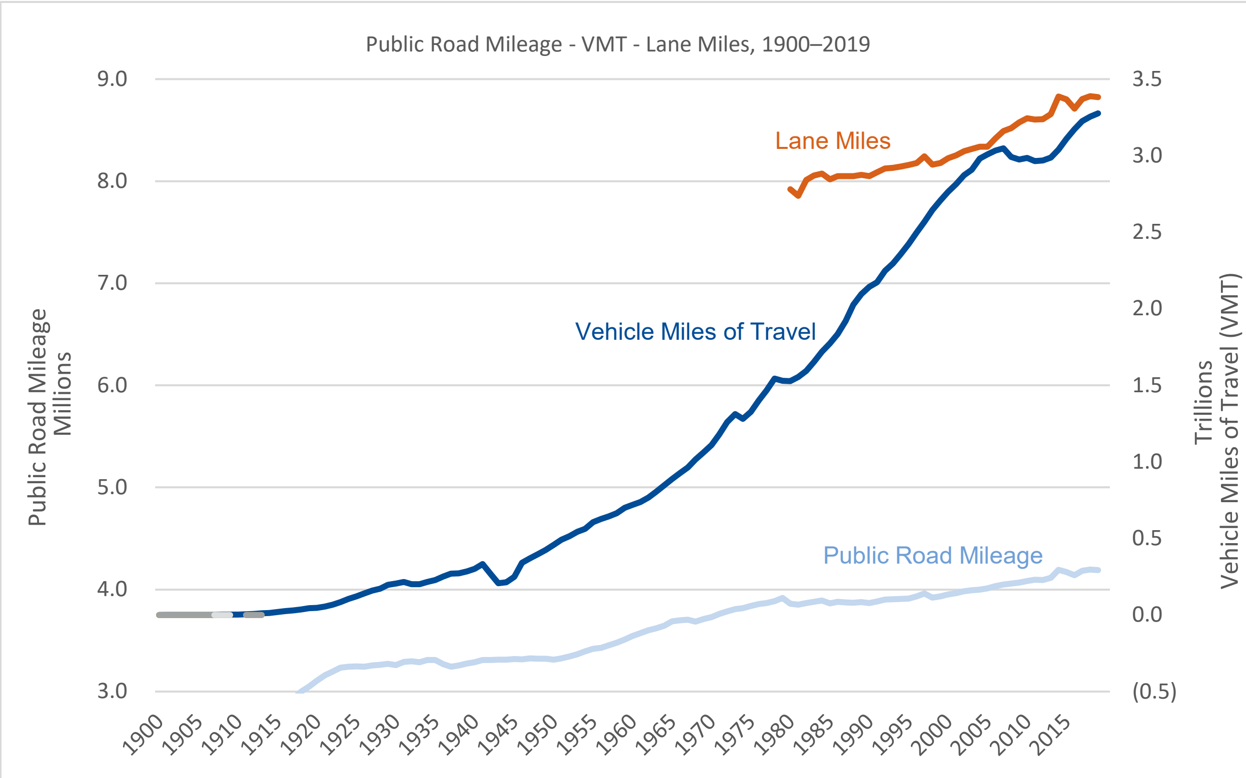


Source: Highway *Statistics* Table 4-56

Figure 9: International Roughness Index, *Highway Statistics*

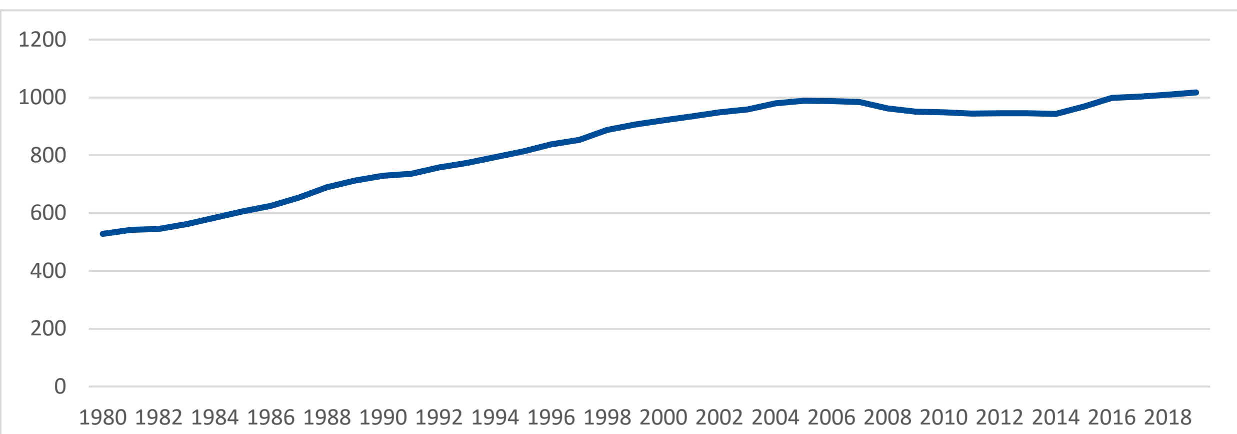
Source: *Highway Statistics* Table 1-27

Figure 10: Vehicle Miles Traveled, *Highway Statistics*



Source: *Highway Statistics*, Table vmt-421c (Table from FHWA web site)

Figure 11: AADT



Source: *Highway Statistics*, Table vmt-421c

Table 2: Average Annual Growth Rates: CFC and Road Usage

	Constant (2012) price CFC	Vehicle Miles Traveled (VMT)	Average Annual Daily Traffic (AADT)
1925-1939	4.23%	4.29%	
1939-1945	1.01%	-2.17%	
1945-1960	3.29%	7.29%	
1960-1968	4.95%	4.42%	
1968-1982	2.08%	3.27%	
1982-1997	1.65%	3.23%	3.03%
1997-2007	1.77%	1.73%	1.43%
2007-2018	0.73%	0.60%	0.24%
1945-2018	2.30%	3.58%	
1968-2018	1.59%	2.36%	

Source: *Highway Statistics*, Tables vmt-421c

Table 3: Service Life Assumptions

	Service life (years)	Annual depreciation rate
Road-related investment: new construction, relocation, reconstruction, major widening, 3R		
Grading	80	0.0114
Paving	20	0.0455
Other structures	50	0.0182
Other investment		
Bridge work	50	0.0182
Safety	15	0.0607
Traffic management	15	0.0607
Environment/other	50	0.0182
Highways and streets, published estimates	45	0.0202

Table 4: Shares of Capital Outlays for Road Paving, Grading, and Other Structures

	Rural roads				Urban roads		
	Paving	Grading	Other structures		Paving	Grading	Other structures
New Construction							
Interstate highways	0.601	0.209	0.190		0.659	0.151	0.190
State arterials	0.570	0.344	0.086		0.577	0.336	0.086
State collectors	0.633	0.280	0.086		0.669	0.245	0.086
Local	0.641	0.243	0.116		0.647	0.237	0.116
Reconstruction							
Interstate highways	0.589	0.221	0.190		0.636	0.174	0.190
State arterials	0.732	0.182	0.086		0.666	0.248	0.086
State collectors	0.692	0.222	0.086		0.672	0.241	0.086
Local	0.662	0.222	0.116		0.651	0.233	0.116
Restoration & Rehabilitation							
Interstate highways	0.707	0.148	0.145		0.723	0.132	0.145
State arterials	0.771	0.116	0.113		0.714	0.173	0.113
State collectors	0.754	0.133	0.113		0.716	0.171	0.113
Local	0.713	0.126	0.161		0.677	0.162	0.161
Resurfacing							
Interstate highways	0.792	0.063	0.145		0.792	0.063	0.145
State arterials	0.832	0.056	0.113		0.782	0.106	0.113
State collectors	0.837	0.051	0.113		0.779	0.108	0.113
Local	0.798	0.041	0.161		0.737	0.102	0.161

Note: For these estimates, the ratio of grading to the sum of grading plus pavings was obtained from the 1997 DoT Cost Allocation Study (CAS). The shares for other structures are based on Fraumeni (2007)

Figure 12: Capital Outlays (Billions of Current Dollars), Highway Statistics

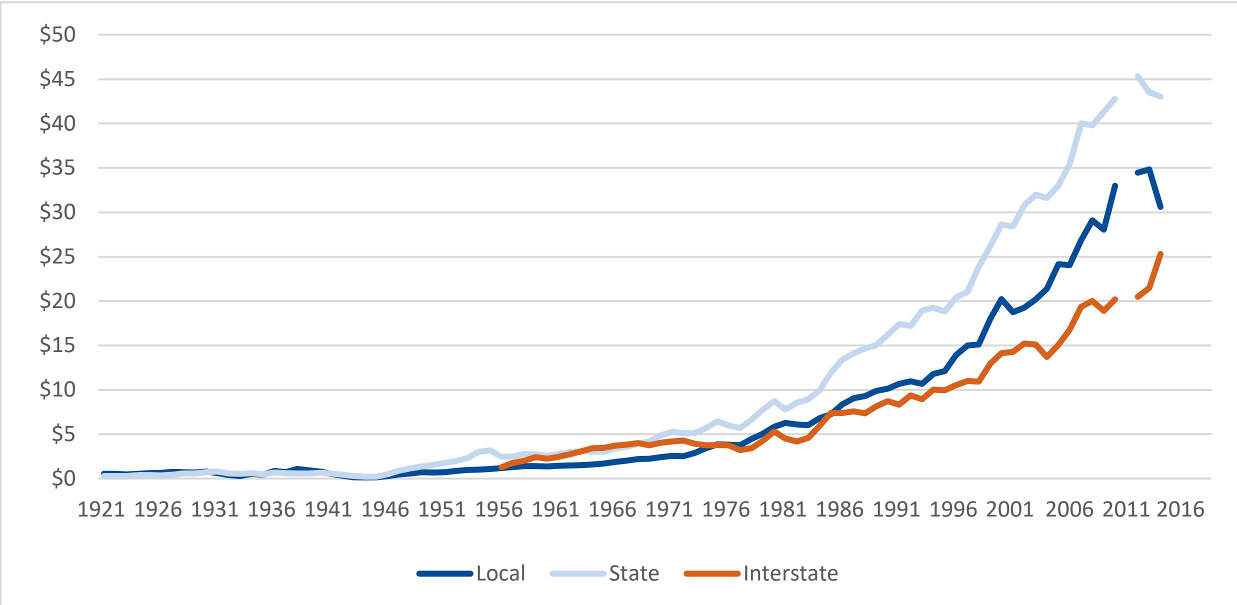


Figure 13: Shares of Capital Outlays: Interstate Highways

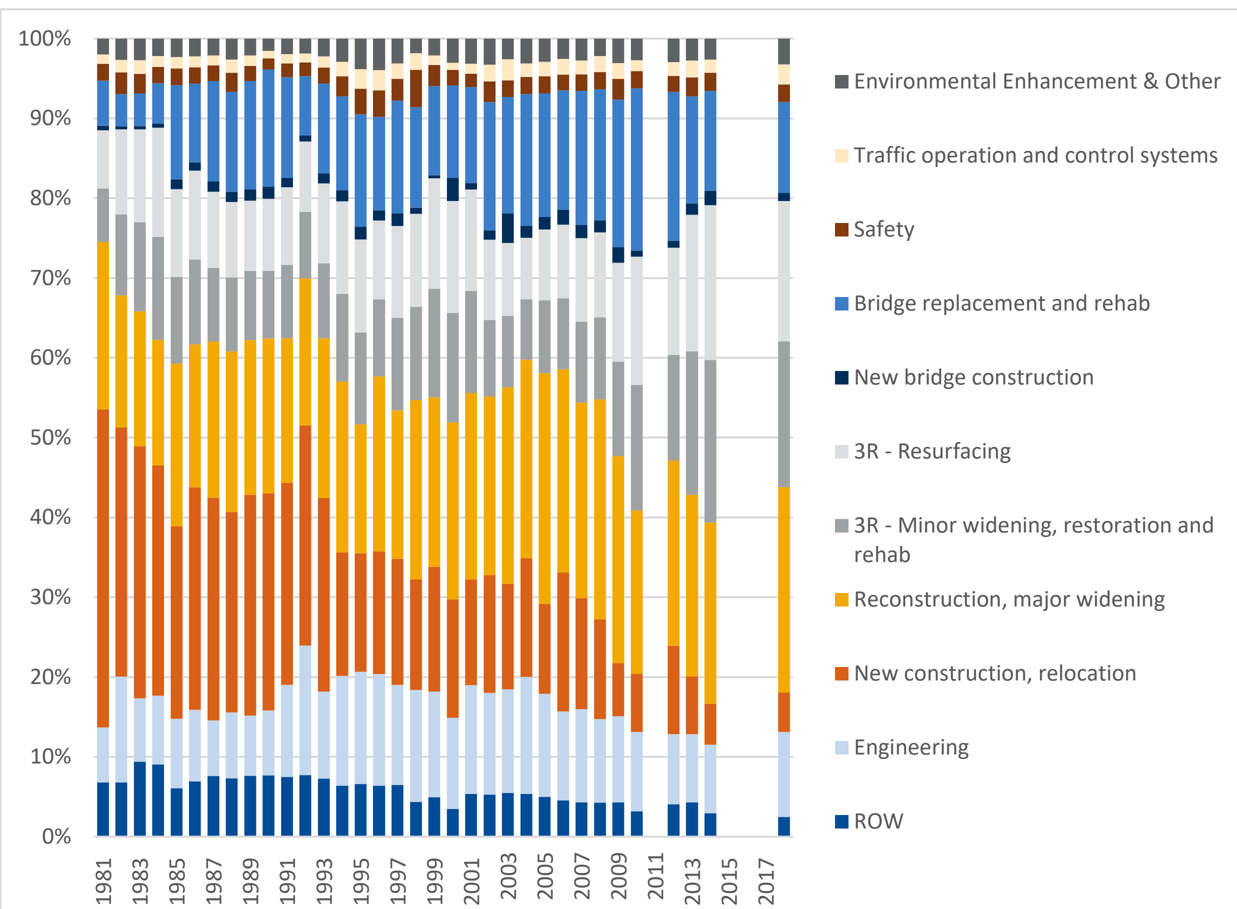


Figure 14: Shares of Capital Outlays: Non-Interstate State Roads

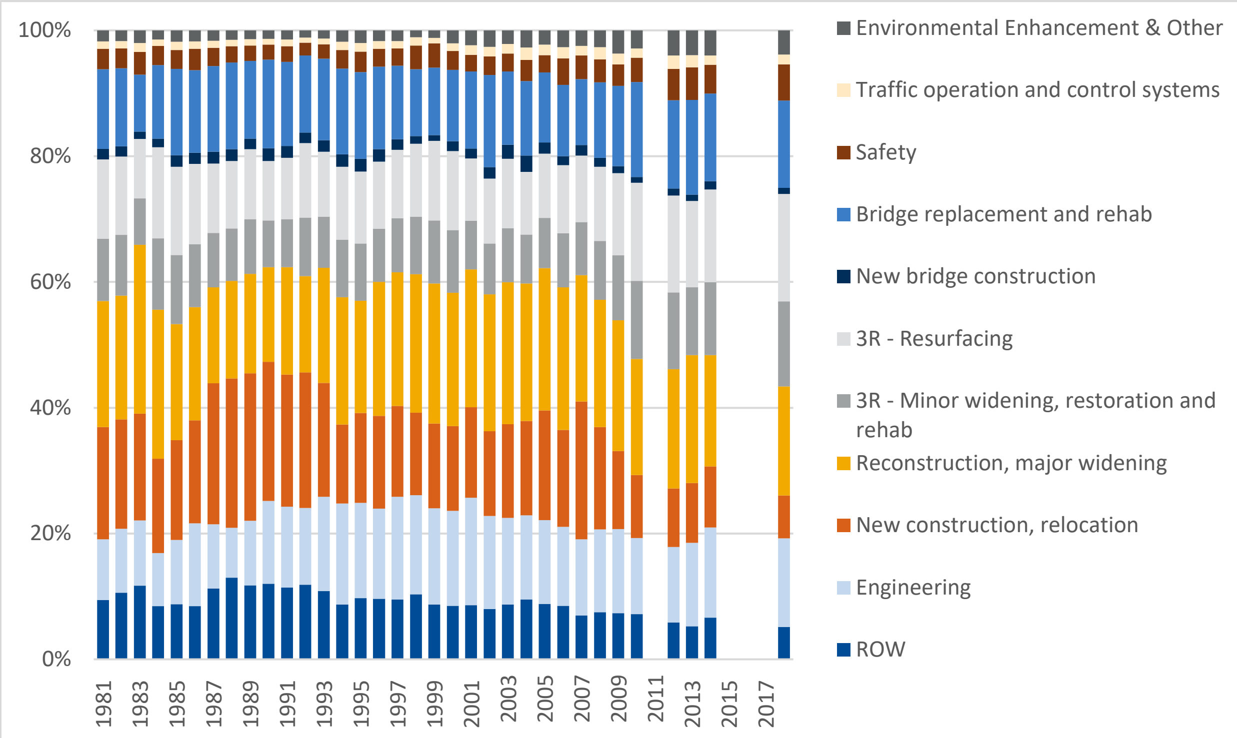


Figure 15: Shares of Capital Outlays: Local Roads

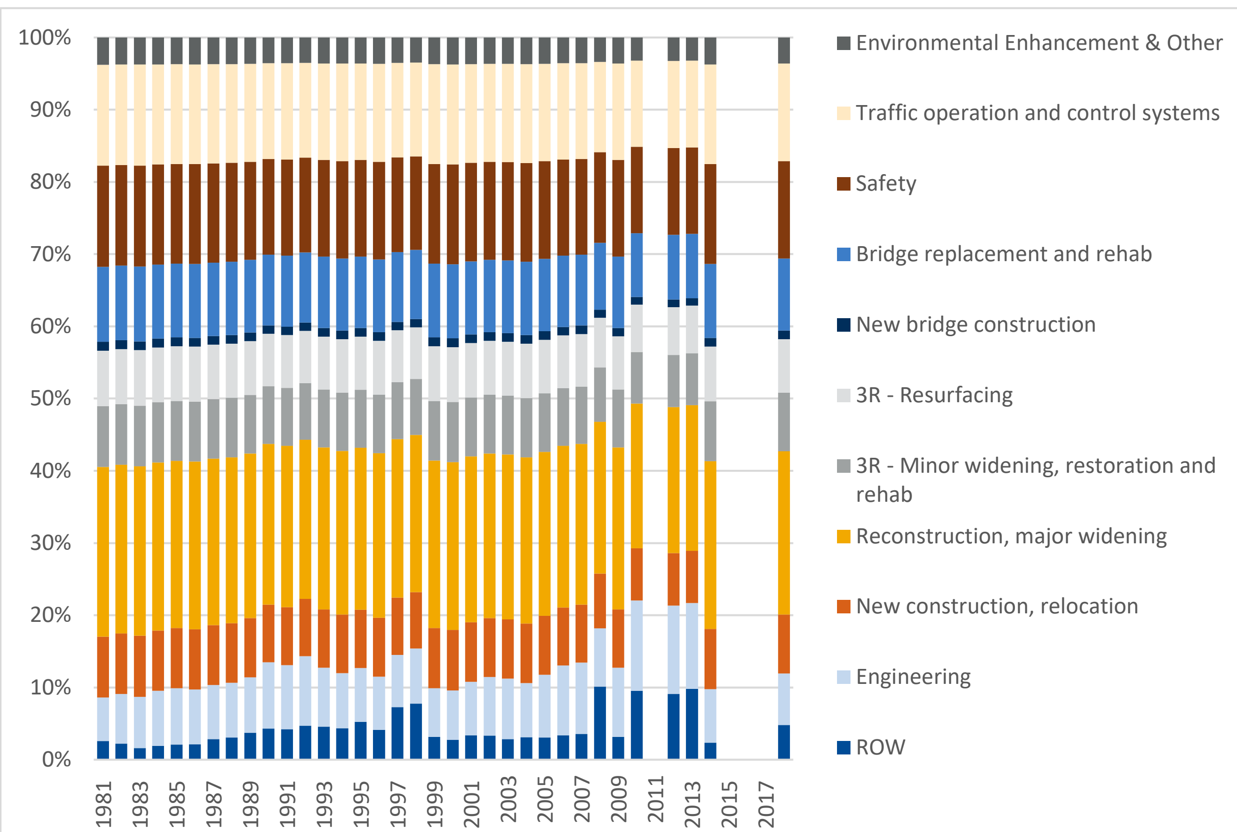


Figure 16: Shares of Capital Outlays, All Roads, 1921–2018

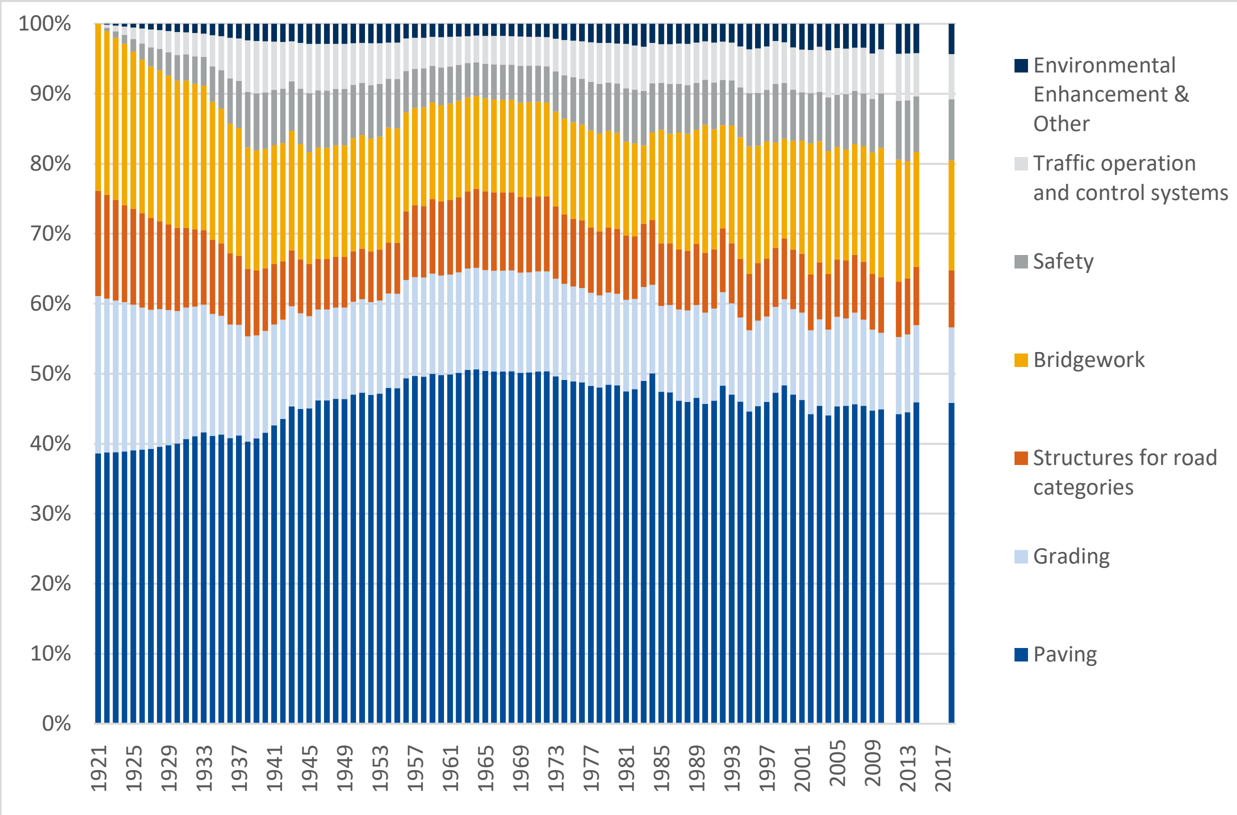


Figure 17: Constant-Price (2012) Net Stocks, Published and Updated Estimates

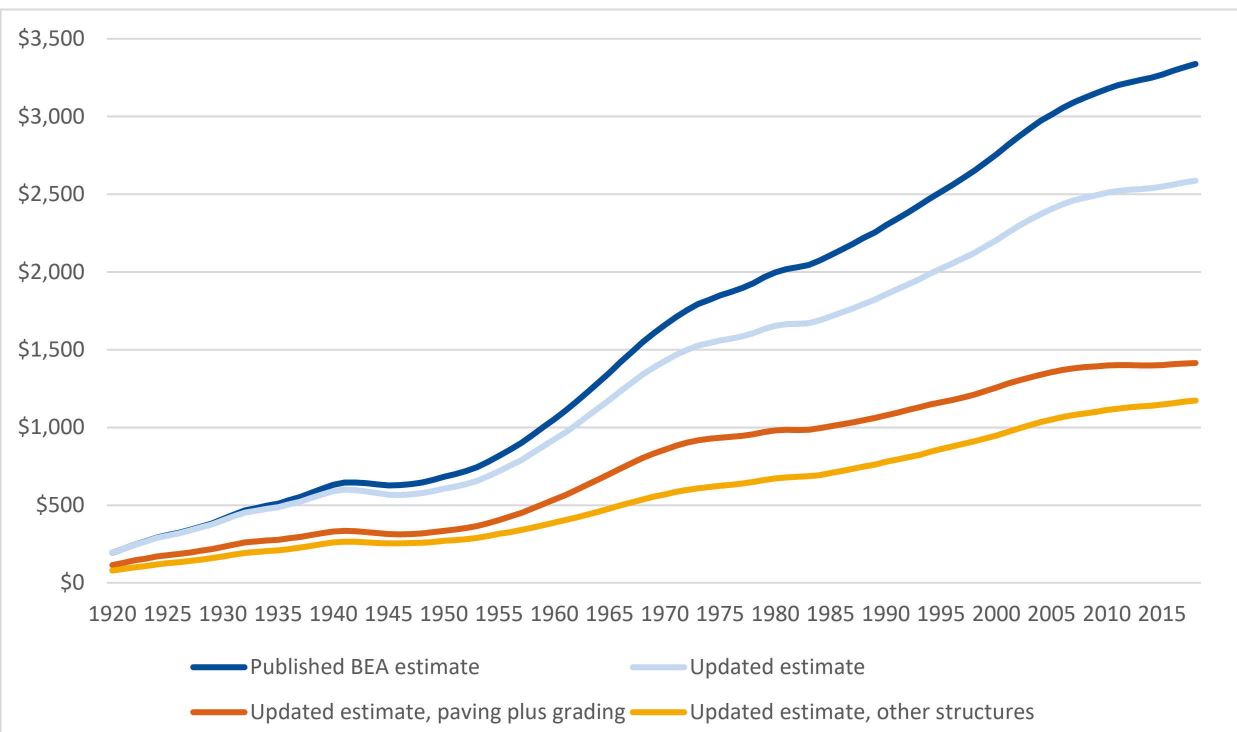


Figure 18: Constant-Price (2012) CFC, Published and Updated Estimates

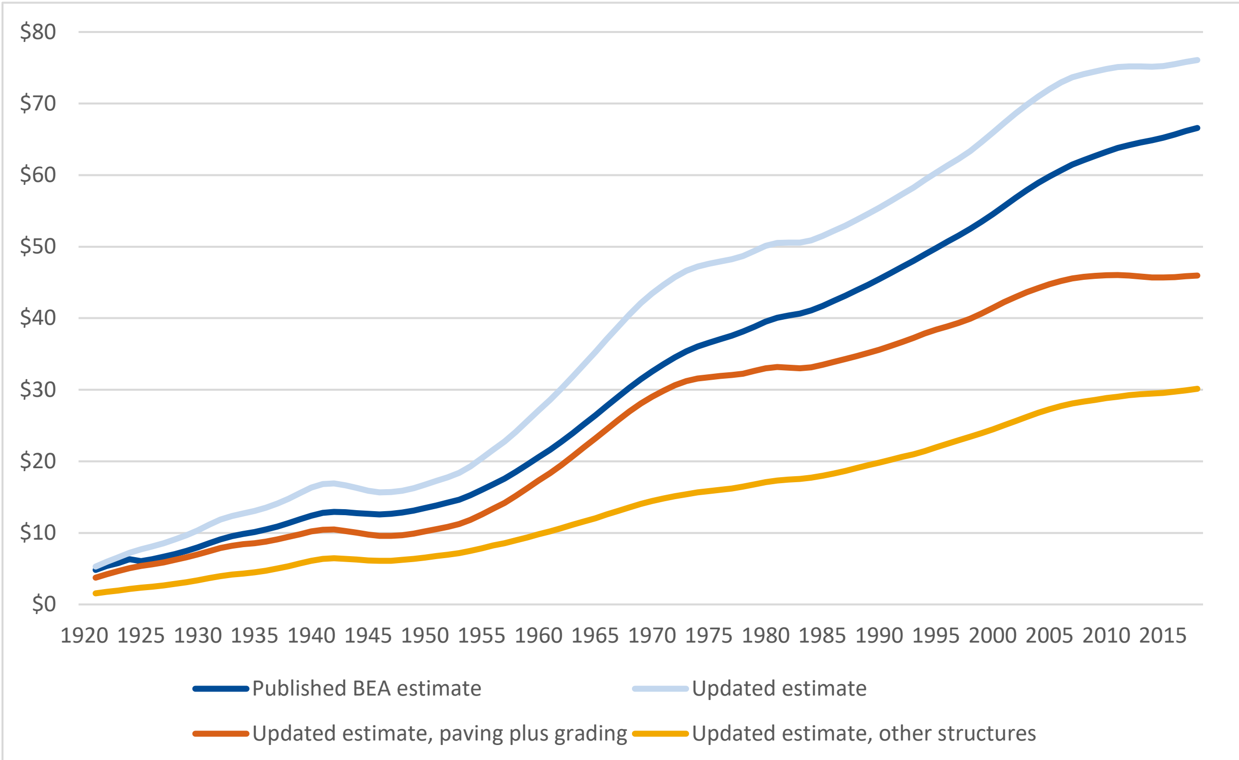


Figure 19: Constant-Price (2012) Net Stocks, Alternative Estimates

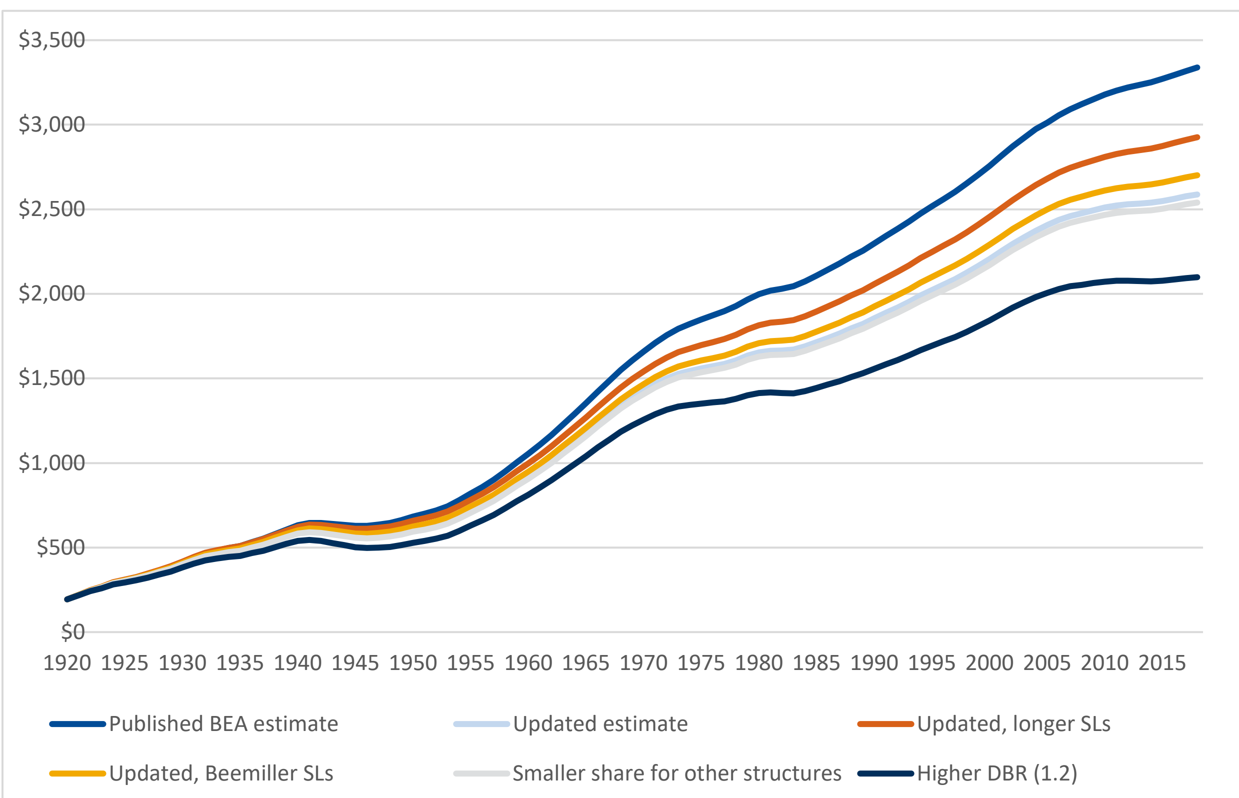


Table 5: Average Annual Growth Rates: Constant-Price (2012) Net Stocks, Alternative Estimates

	Road miles	Paved road miles	Published BEA estimate	Updated estimate	Updated estimate, paving plus grading	Updated estimate, all other structures
1925-1939	0.04%		4.20%	3.83%	3.57%	4.19%
1939-1945	0.23%		0.58%	-0.03%	-0.28%	0.28%
1945-1960	0.44%		3.51%	3.29%	3.63%	2.85%
1960-1968	0.48%	3.04%	4.94%	4.78%	5.21%	4.17%
1968-1982	0.34%	2.10%	1.95%	1.56%	1.45%	1.72%
1982-1997	0.16%	0.93%	1.67%	1.52%	1.29%	1.83%
1997-2007	0.22%	0.89%	1.73%	1.66%	1.48%	1.89%
2007-2018	0.32%	0.76%	0.70%	0.46%	0.22%	0.76%
1945-2018	0.32%		2.32%	2.10%	2.08%	2.12%
1968-2018	0.26%	1.21%	1.55%	1.32%	1.14%	1.57%

	Updated estimates, if we assume...			
	Longer service lives (SLs)	SLs similar to Beemiller (1999)	Smaller share of outlays for other structures	DBR = 1.2
1925-1939	4.03%	3.90%	3.77%	3.51%
1939-1945	0.30%	0.07%	-0.13%	-0.63%
1945-1960	3.31%	3.29%	3.30%	3.26%
1960-1968	4.75%	4.77%	4.82%	4.82%
1968-1982	1.72%	1.62%	1.55%	1.27%
1982-1997	1.58%	1.54%	1.51%	1.42%
1997-2007	1.69%	1.66%	1.65%	1.59%
2007-2018	0.58%	0.50%	0.44%	0.24%
1945-2018	2.17%	2.12%	2.10%	1.98%
1968-2018	1.42%	1.36%	1.31%	1.15%

Table 6: Average Annual Growth Rates: Constant-Price (2012) CFC, Alternative Estimates

	Published BEA estimate	Updated estimate
1925-1939	4.23%	4.37%
1939-1945	1.01%	0.35%
1945-1968	3.87%	4.15%
1945-1960	3.29%	3.61%
1960-1968	4.95%	5.16%
1960-1982	3.11%	2.88%
1968-1982	2.08%	1.59%
1982-1997	1.65%	1.40%
1997-2007	1.77%	1.69%
2007-2018	0.73%	0.29%
1945-2018	2.30%	2.17%
1968-2018	1.59%	1.27%

Table 7: Average Annual Growth Rates: Constant-Price (2012) Net Stocks Per Capita

	Published BEA estimate	Updated estimate
1939-1945	-0.52%	-1.12%
1945-1968	2.39%	2.19%
1945-1960	1.76%	1.54%
1960-1968	3.57%	3.42%
1968-1982	0.89%	0.51%
1982-1997	0.58%	0.43%
1997-2007	0.72%	0.64%
2007-2018	-0.03%	-0.27%
1945-2018	1.13%	0.92%
1968-2018	0.56%	0.34%

Figure 20: Fraumeni Constant-Price Capital Stock Estimates

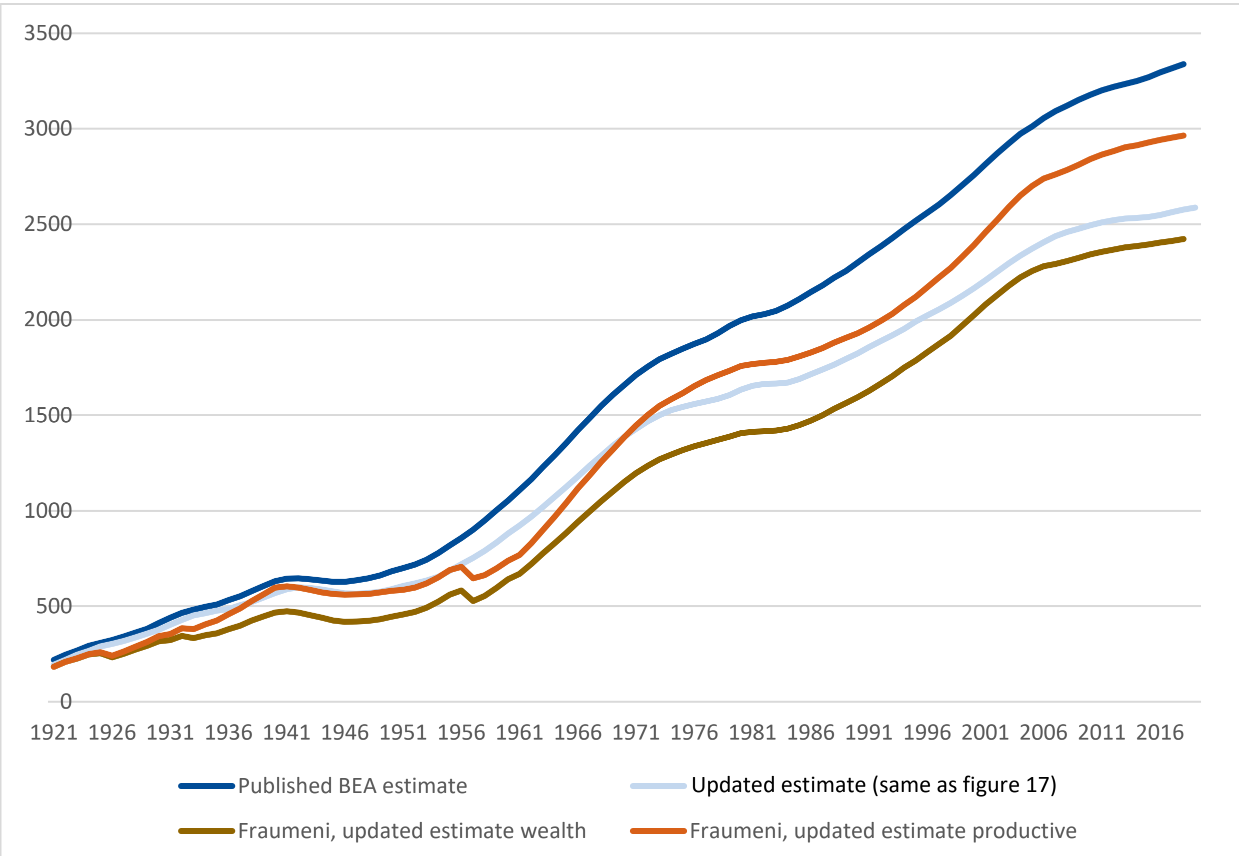


Table 8: Average Annual Growth Rates: Alternate Capital Stocks

	Published BEA estimate	Updated estimate	Fraumeni wealth	Fraumeni productive
1925-1939	4.20%	3.83%	4.82%	5.78%
1939-1945	0.58%	-0.03%	-0.78%	0.06%
1945-1968	4.01%	3.81%	4.08%	3.61%
1945-1960	3.51%	3.29%	2.86%	1.88%
1960-1968	4.94%	4.78%	6.36%	6.87%
1960-1982	3.03%	2.72%	3.70%	4.10%
1968-1982	1.95%	1.56%	2.17%	2.52%
1982-1997	1.67%	1.52%	1.88%	1.51%
1997-2007	1.73%	1.66%	2.04%	2.19%
2007-2018	0.70%	0.46%	0.51%	0.65%
1945-2018	2.32%	2.10%	2.44%	2.33%
1960-2018	2.01%	1.79%	2.34%	2.45%
1968-2018	1.55%	1.32%	1.69%	1.74%

The "updated estimate" is the same as the updated estimate in Table 5.