

The Economic and Social Value of Autonomous Vehicles:
Implications from Past
Network-Scale Investments



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Executive Summary

This report describes the economic and social impacts of three network scale investments—the Interstate Highway System, the Internet, and electricity. These are compared with autonomous vehicles (AVs), the most recent proposed network-scale program.

Each of the three examples show the impact of network-scale investments in stimulating new industries and new markets. These are particularly clear in the case of electricity, with the development of new products ranging from electric light bulbs, to rail transit, to central heating, to elevators and sky scrapers, to refrigerators. The economic and social impacts were profound—in Robert Gordon’s words, they brought the “American home from dark and isolated to bright and networked.”¹

The Internet stimulated new markets (every firm could gain access to international markets) to new products and services, many with corporate names that have become household words—Google, Facebook, Amazon etc. The Interstate Highway System has similar impacts. Who dreamed it was possible to get California oranges in New York City? The Interstate Highway System generated returns of 50-60 percent a year over two decades and accounted for one fourth of the nation’s overall growth in economic productivity—and all from just four cents a gallon tax.

In each example, job losses were created as new industries grew to replace old ones. In each case the net impact on jobs was clearly positive. For the Internet, about 2.6 new jobs were generated for every job that was lost. For electricity the ratio is likely much higher since there were relatively few jobs displaced (gas works used for lighting is one example).

When these new networks are first introduced, it is difficult to forecast what new products, services, or industries might occur. In the 1990s, who would have guessed businesses such as Google or Facebook? The development of AVs is linked with that of shared mobility—10 years ago, who would have imagined the success of shared mobility companies such as Uber and Lyft?

In each case, new businesses and business models emerged. The Internet companies that are household names today are a recent example. For electricity, the model of a capital-intensive business that served all electric customers within a metropolitan area was new. This also generate new regulatory regimes. The Interstate Highway System generated coast-to-coast distribution companies. AVs have already generated new firms with no prior experience in vehicles—it is too early to say which ones will be household words in 10 years, but there is no reason to suspect that past trends will change.

The role of government varied widely. For the Interstate Highway System, the federal government served as banker, while the states implemented the plan and the private sector responded with vehicles and new businesses. Electricity was dominated by private firms, with

¹ Robert Gordon, *The Rise and Fall of American Growth*, (2016).

public sector regulations to control prices and, at a later date, financial support to provide service in rural areas that were not economical. The Internet was largely driven by the private sector, but key early investments came from the federal government. AVs (AVs) are not dependent on direct public funding, in large part since they can take advantage of past investments to build the nation's network of roads and bridges.

Economic analysis was not a key decision factor in any of the three network studies. Rather, decisions passed the "common sense" test. Of course electricity provided safety, economic, and comfort benefits well beyond current practice at the time. Of course we needed a national high-level road network. True, the scale of the Interstate Highway System reflected political issues, but no surprise here given the need to secure Congressional support. In fact, a large network turned out to generate economic value.

The world may differ today, in part given the large private investment in AVs and the need for market studies to support these investments. Also, public agencies and interest groups are more analytically oriented than in the past. At the same time, there is a "common sense" aspect to AVs—why not try to save lives.

The tables below summarize the major findings of this study. Table ES-1 shows the timing for each network investment and the role of public and private entities. Table ES-2 summarizes the direct and indirect economic and social impacts.

The two figures that follow depict the timing for each network, from initial concept to development, to deployment and then maturity. The first figure shows the times on a calendar basis and the second compares the number of years needed for each investment program.

While the specific dates selected for each phase can be debated, they nonetheless demonstrate that investments and events on this scale take time. The dates selected for AVs are definitely open for debate, since most of the events have yet to occur.

The electrical grid moved relatively quickly after development of the generating equipment and the incandescent light bulb. The time to deploy the network took longer than for the others since the industry started from scratch.

The development period for the Interstate Highway System ignores the time in Europe when the Autobahn and other roads were being developed, and is slowed in part due to World War II and the need to develop a political consensus.

The Internet shows that the network is still evolving, with increased connections evolving out of the rapidly growing wireless branch.

The autonomous vehicle chart takes a somewhat optimistic view by assuming deployment begins in 2021 and a mature system is in place by 2040. Disagreement regarding these dates is reasonable, though the broader point remains the same.

TABLE ES-1. NETWORK SCALE PROGRAMS: Overview, Timeline and Sector Roles

Program	Electrical System	Interstate Highways	Internet	AVs
Description	Nationwide electrical grid	National network of Expressways	Global computer and communications network	Driverless vehicles (cars, buses, trucks)
Timeline				
Concept	1876	1938 (US)	1950s	1939
Development	1878-1890	1939-1956	1950s-1970s	1995-2020
Deployment	1890-1940	1956-1970s	1980s-2000	2021-2040
Maturity	1940-1980	1970s -2000	1995-present	2040 — ??
Leadership				
Federal	Funds for rural electrification (late in process)	Planning, Funding, Oversight, Vehicle safety regulations	Technology, Fund early deployment, Regulations	DARPA challenges; R&D – focus on connected vehicles, Regulations
State & Local	Regulation, Some financial aid (at city level), Need for location of generating stations etc. required strong lobbying, etc.	Construction, O and M, Finance (fuel taxes), Toll roads	Access to rights-of-way for fiber and wireless facilities	Regulations, Supporting investment (signs, road markings, infrastructure communications, traffic signals (SPAT), V2I) Need to change planning process, with new assumptions. Regulatory conflicts with shared mobility firms. Future of traditional transit may change.
Private	Commercial deployment, Business models, Finance, Related industries (transit, real estate development)	Vehicles, Warehouses and related distribution systems, Some toll roads and bridges	Commercial deployment, Develop new applications, new markets, Link with wireless technology	Develop technology, Develop business models (shared mobility very important), Corporations and individuals invest in vehicles

TABLE ES-2. NETWORK SCALE PROGRAMS: Direct and Indirect Program Benefits Scorecard

Benefit	Electrical System	Interstate Highways	Internet	Autonomous Vehicles
Economic	Improved manufacturing efficiency; Helped develop new processes and new industries, New jobs in manufacturing; Stimulated rail transit industry	Gains by all industries (reduced costs, larger markets, better access to labor and materials); Services gained more than manufacturing; Created national markets; Access to labor / jobs; New products and services, Shift of housing and business to suburbs harmed inner cities (not permanent?), Encouraged relocation to places with better economic opportunities	Gains by all industries; Encourage national and international markets; New products and services, Access to labor in other locations (local and around the world); Improved access to under used labor (telecommuting)	Improved access to labor / jobs; Access to new markets and larger markets, Job losses in some industries (trucking, taxi, short-haul aviation, maybe vehicle manufacturing...); Public finance – reduced capital required for traditional transportation investments; Stimulated growth in shared mobility markets; Changed land use (parking facilities etc.); Reduced cost for long-haul freight transport
Social	Safety (end of gas lighting and candles), Personal comfort (central heating), Light for reading etc. (education); Access to better housing (transit access to lower density locations)	Safety, Access to social contacts, recreational, health, education; Lower cost suburban housing	Access to information, social contacts (local and around the world), education, telecommuting.	Safety – eliminate most highway accidents; Option to reduce auto ownership; Increase location opportunities – lower cost housing; Access for elderly and handicapped.
Valuation	5 percent of US GDP; \$100 billion a year in new investment; ADD MORE DETAIL	50-60 percent return on public investment over two decades; One fourth of overall economic productivity over 20 years	21 percent of GDP growth in developed countries between 2005 and 2010; Generated 2.4-2.6 times new jobs versus jobs lost; Stimulated international trade.	\$6-8 trillion; Benefit cost ratio of 8:1 – excluding economic productivity gains.

FIGURE ES-1: Network-Scale Program History

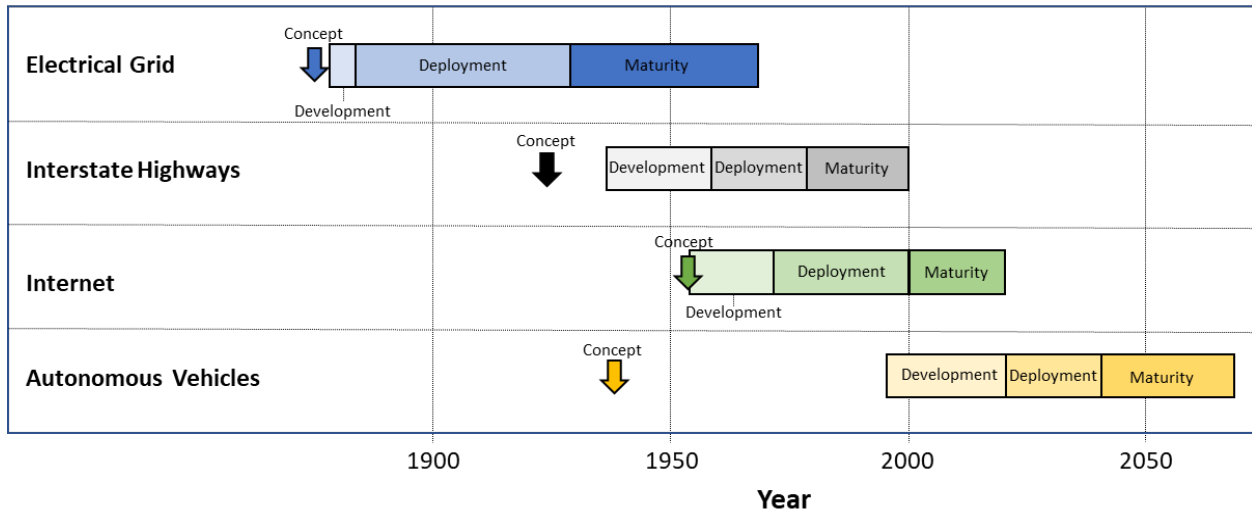
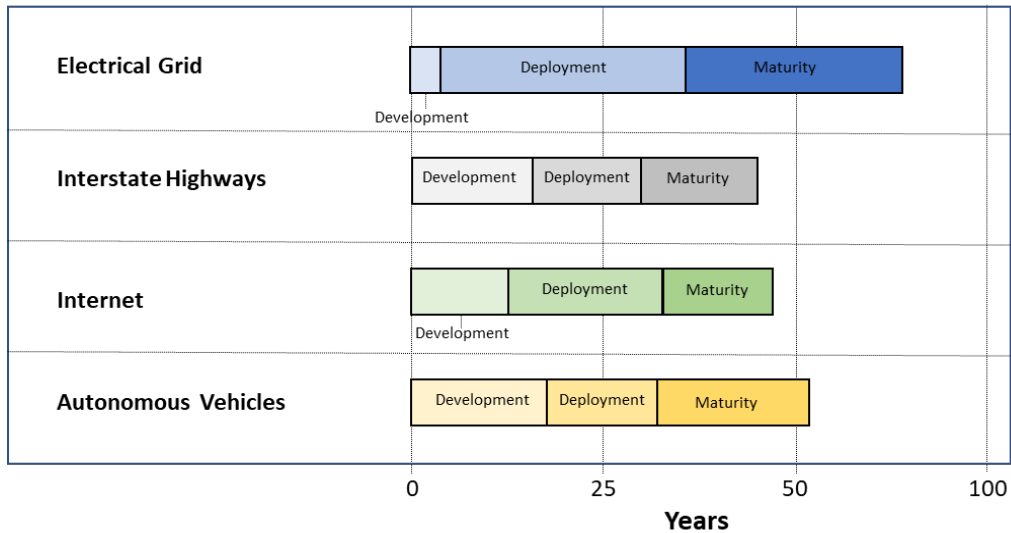


FIGURE ES-2: Network-Scale Programs: Comparative Development Cycles



I. Introduction

The economic history of the United States can be traced through a series of large, network-scale investments. Every generation or so there has been a sea-change in the nature and level of our economic activity that has been stimulated by a new means of transportation or technology. Such structural changes in the U.S. economy are not everyday occurrences, although they do happen on a regular basis.

The most recent of these changes was stimulated by the Internet and related wireless technologies. Our economy is ready for another such burst—this time, from AVs.

The economic and social impacts of AVs go well beyond traditional transportation. Much of the debate over AVs has focused on transportation system impacts and the risk of job losses within

certain groups (truck and taxi drivers are often mentioned). But a review of similar past changes can help shed light on the potential for positive change.

These examples combine a spatial network (say, the Interstate Highway System or the electrical grid) along with a variety of equipment that make the core infrastructure useful to individuals and corporations. These bursts in economic development and economic change involve different mixes of public and private investment. Examples that span the 20th century include:

- The Internet—including its continued rapid expansion via wireless networks (i.e., cellular, Wi-Fi, and satellite systems),
- The Interstate Highway System, and
- Electricity, including the electric generation and transmission networks.

Of course, these changes are not limited to those of these more recent networks. Examples from the 19th century include the transcontinental railroad, the Erie Canal, and the opening of the Ohio and Mississippi Rivers.

Each has significant differences in terms of how they function, what types of direct impacts they have, and how firms and individuals interact with them. But they are similar in terms of the breadth and scale of their impacts.

[Guide to paper](#)

The next chapter summarizes the type of economic and social impacts that these network investments generate, with particular focus on the non-linear nature of many of these impacts. This includes the ability to make new industries and their related businesses possible, and to generate gains in economic productivity. In combination, these changes create economic growth, including new jobs, beyond those linked directly to the original network.

Later chapters will describe:

- The Interstate Highway System
- The Internet
- Electricity, including the electric grid.

Each chapter will summarize the history of each development, including the organizations that supported each, the debate regarding development, and what is known about the economic and social impacts of each network.

The final chapter builds on lessons learned from these past network deployments to suggest implications for the development of AVs. These implications will cover economic and social values, different roles for public and private entities, and suggestions for next steps.

II. What is so special about a network investment?

Economists have long built mathematical models that try to describe the economy and forecast how the size and nature of the economy is likely to respond to either discreet, individual

changes, or broader multi-variate changes. In concept, these take a very simple form. In classic economics, how much we produce and how well we do so depend on a limited number of economic inputs, most importantly:²

- Capital investment by private firms. This includes investment in manufacturing facilities, machinery, and vehicles as well as technology in the form of computers, telecommunications equipment and so forth,
- Labor, reflecting both the amount of labor and its quality, and
- Other resources (raw materials, intermediate goods, and the like).

Since the value of each of these economic components can be measured in dollars, economists build models that provide estimates of the importance or rate of return to the economy of each broad sector. Given the size and structure of today's economy, it is not surprising that the mathematics used to develop these models can be quite complex (the term *econometrics* is used to describe this field).

Economist Ronald Coase found that economic efficiency improved when firms were able to reduce transaction costs. These changes were more important in allocating resources and shaping economic efficiency than were changes in prices.³ Coase focused on transaction costs that affected individual firms, such as the need for negotiations, contracts, inspections, legal and related disputes. The value in these changes has been used to explain the value generated by the Internet.⁴

His principles also apply to the importance of reducing transaction costs in the form of spatial barriers. Most of these barriers relate to transportation and include individual work commutes, access to intermediate goods, to connections to the final customer. Each of the network changes described in this report provide examples of how reducing transaction costs can help stimulate economic growth both within existing industries and in new industries and markets.

Network-scale investments have several characteristics:

- Geographic scale. National scale for the three examples described in this report, but regional or corridor examples can be found, as well.
- Non-linear impacts. Economic and social impacts are more than the sum of individual benefits. As discussed later, this implies changes in what goods and service we produce and how this is done. These changes can improve overall economic productivity—less labor and capital are needed to produce a given level of output.

² Samuelson, P.A. and W.D. Nordhaus; *Economics* is merely one of many standard textbooks that describes this relationship.

³ Coase received the Nobel Prize for Economics in 1991 for this work. His Nobel Prize Lecture (December 9, 1991) provides a good summary of his work and how it changed the thinking among economists.

⁴ John Naughton, "How a 1930s theory explains the economics of the Internet." *The Guardian*, September 7, 2013.

- Breadth of impact. The investment should provide services across multiple products or sectors of the economy and society. A specialized network that serves one product or one type of service might not qualify—a national police radio network, for example, or perhaps a network of natural gas pipelines (although this last example could be debated).
- Speed of deployment. Incremental change over multiple decades risks not being noticed. Certainty of funding is important. For example, while the Interstate Highway System in the United States was not completed until the early 1970s⁵ the existence of a financial mechanism that was independent of political winds, and a clearly defined road map (literally) gave assurance to businesses that the system would be completed in the near future. As a result, the economic impacts appeared well before effective completion of the network.

The economic (and social) impacts of network-scale investments also differ from traditional transportation or technology investments. In sum, they:

- Stimulate positive shifts in the supply and demand curves. These shifts reflect a new economy and are generated by:
 - Economies of scale
 - New markets
 - New products/services
- Improve access to
 - labor/jobs
 - markets
 - intermediate goods
 - raw materials

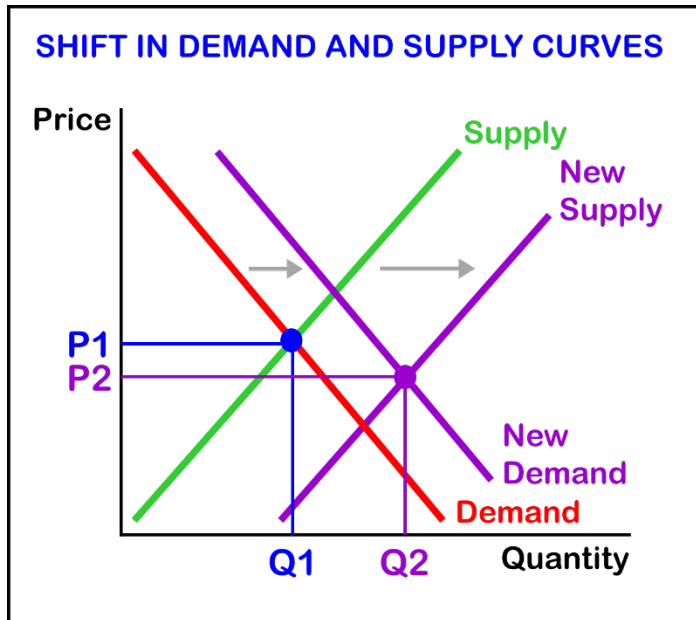
Most analysis of the economic impact of transportation focuses on linear changes – direct benefits to travelers and consumers and indirect benefits from people and industries that depend on these changes. These impacts are important and relatively straightforward to measure. For example, coordinated traffic signals along a given roadway should reduce average travel times, improve safety, and improve overall reliability of travel. The nature and magnitude of these direct personal benefits vary by type of project, but dollar values can be readily estimated.

The conceptual diagram displayed in Figure II-1 shows how shifts in demand (up and to the right) and supply (down and to the right) implies an increase in production and a decrease in costs.⁶ This shift, however, does help to explain why the analytics around network investments is more difficult than those of smaller, more discreet investments, such as adding a new lane to a road.

⁵ Some small segments were not finished until the late 1980s.

⁶ This is a conceptual diagram, not an effort to describe any specific industry or economy.

FIGURE II-1: Implications of Demand and Supply Shifts on Production and Costs



Economic Productivity

More important than linear changes, however, are economic productivity impacts. These involve non-linear changes as individuals and businesses adjust their practices in response to improved infrastructure. These types of changes are not relevant for projects with a local impact (say adding a lane to an existing highway), but there is a long history of change in response to investments with a national- or regional-scale impact.

These changes are more than interesting from an academic perspective.⁷ Improved economic productivity is a key part of international competitiveness—countries that can improve how much they produce from given resources or improve the quality of what their citizens can produce, will gain a competitive advantage relative to other countries. Improved productivity also makes it possible to increase compensation for labor and capital.

Very simply, productivity gains allow the economy to produce more with less. In the modern economy, both capital and labor are scarce resources, so it is important to maximize their value; that is, to maximize their rate of return to the economy. Productivity gains come from a variety of sources, including new technology (such as improved computers and the Internet), improved logistics, better labor skills, and of course, improved access to labor, intermediate goods, and markets.

⁷ Many economists are concerned that the rate of growth in US economic productivity has slowed in recent years relative to what was achieved in previous decades. For example, see *Wall Street Journal*, “Productivity Slump Threatens Economy’s Long-Term Growth,” (August 9, 2016), Ben Leubsdorf.

Productivity is an important part of GDP and changes in productivity indicate the likely direction of future GDP levels. At its simplest level, productivity is usually measured as GDP divided by total hours worked during a given time period. Most countries report these results on a regular basis—for example in the United States this number is reported four times a year by the Bureau of Labor Statistics.

In sum, growth in labor productivity is the key factor behind the ability to generate long-term growth in a country's standard of living. It also plays a key role in competition between nations. Countries with good growth in productivity of labor and capital will have a competitive advantage over countries with lower rates of growth. Innovation is a key factor in stimulating changes in productivity. Most literature focuses on technology improvements as a driving force, but as summarized above, network-scale transportation improvements play an important role here. This role can be enhanced if technology is part of transportation.

A Rule of Thumb to Measure Economic Productivity

Remy Prud'homme and Chang-Woon Lee's "Size, Sprawl, Speed and the Efficiency of Cities" compared productivity of European cities, particularly Paris and London. The researchers concluded that, "The efficiency of a city is a function of the effective size of its labor market."⁸ The research found that a 10 percent improvement in access to labor increases productivity, and therefore regional output, by 2.4 percent.⁹

David Hartgen and Gregory Fields found that for a sample of U.S. cities, a one percent improvement in accessibility to a region's central business district improves regional productivity by 1.1 percent.¹⁰

Prud'homme and Lee's work notes that transportation costs and additional benefits can be evaluated by looking at the effective size of an urban area's labor market—i.e., what fraction of the total job possibilities can a worker access within a reasonable commuting time? For example, a 10 percent increase in average speed, all other things constant, leads to a 15-18 percent increase in the labor market size and a 2.9 percent increase in productivity.¹¹

These rules of thumb have application for efforts that improve effective travel times. As discussed later, AVs improve overall access, including the potential for reduced travel times.

⁸ Size, Sprawl, Speed, and the Efficiency of Cities. Remy Prud'homme and Chang-Woon Lee. <http://www.dublinpact.ie/word/Prud-homme-paper.doc>.

⁹ Ibid.

¹⁰ "Gridlock and Growth: The Effect of Traffic Congestion on Regional Economic Performance" (June 2009), "Reason Foundation Policy Study. http://www.hartgengroup.net/Projects/2009-06-22_Final_PS371.pdf

¹¹ Size, Sprawl, Speed, and the Efficiency of Cities. Remy Prud'homme and Chang-Woon Lee.

How does this work?

Three connected stages show how the impacts progress from linear impacts to broader economic changes including gains in productivity and shifts in the structure of the economy.

1. An improved infrastructure system (either larger in size or higher in the quality of service that it provides) allows industry to produce the same amount of goods and services for less. This can be called a “productivity effect.” But the story does not end here.

Firm-Level Productivity Case Study

Koley’s Medical Supply was (in 1990) a wholesale distributor for a coalition of six hospitals in Omaha Nebraska and parts of Iowa that converted to a stockless purchasing system. In the hospital industry, stockless purchasing goes further than just-in-time by offering pick-and-pack operations in addition to frequent deliveries of medical products to hospitals. Koley’s packs items in their proper units of issue and delivers them in bins several times a day to user departments in the hospitals.

Transportation is critical to meeting frequent order cycles in a stockless purchasing system. Good access makes frequent (several times a day) delivery efficient costs over the whole hospital materials chain from manufacturer to patient.

One hospital reduced its distribution staff by 12 full time employees and eliminated trucks. Another hospital converted its storeroom to more productive uses.

SOURCE: “Transportation: Key To A Better Future;”

- *Example: Investments to reduce travel congestion allow a national retailer’s distribution network to make the same volume of deliveries in less time, saving driver and fleet costs.*

2. An improved system also allows firms and industries to change how much they use of other economic inputs—labor, intermediate goods, and private capital. These changes may result in greater efficiencies as the investment allows firms to substitute for one or more of their traditional economic inputs. Termed “factor demand effects.”

- *Example: Investments to improve connectivity and travel times allow a manufacturer to reduce inventories of production inputs and to consolidate its supply network, reducing production costs overall.*

3. The cost reductions caused by the first two changes will, in turn, stimulate increased overall demand since individuals and firms can now purchase more goods and services than previously. Called an “output expansion effect.”¹² This is similar to the classic multiplier effect based on increases in economic activity.
 - *Example: As production or distribution becomes less costly, firms may pass along some portion of the savings to consumers, who may purchase more as the price falls.*

¹² The National Cooperative Highway Research Program—Rate of Return from Highway Investment. NCHRP Project 20-24(28) (August, 2005).

In effect, in response to transportation investments, industry changes how much it costs to produce goods, then changes how it produces goods (maybe even changing what is produced), and finally changes how much it produces. Of course, this last change may also involve another round of changes in how goods are produced as increased demand encourages larger factories and economies of scale come into play.

In sum, when viewed as a network, infrastructure stimulates shifts in the demand and supply curves for goods and services. This is a fancy way of saying that economic productivity improves. These changes can be seen at the firm level as well, although it is harder to quantify the effect precisely.¹³

Even though examples are easier to cite for manufacturing businesses, these changes cover all parts of the economy, including services and the government. Every industry benefits from improved access to labor and customers. Indeed, in the 21st Century where businesses depend on labor quality more than in the past, service industries are likely to be more sensitive to improvements in access.

The overall effect from this set of changes is clear—an improved infrastructure creates significant overall increases in economic activity both by reducing costs and by stimulating demand. The result can be positive changes in the economic structure. Similar shifts occur due to technology changes, such as occurred following the introduction of the Internet and of wireless telecommunication.

¹³ Both AASHTO (association of state Departments of Transportation in the United States) and the Federal Highway Administration published reports that include case studies of how these changes occur at the individual firm level. For example, see: Apogee Research; “Transportation: Key To A Better Future;” published by the American Association of State Highway and Transportation Officials; (December, 1990).

III. Interstate Highway Network

History

The concept of a national transportation network has been a common topic, with examples from throughout history. The Roman Empire relied on a road network both to move troops and to link commerce. In the United States, the Gallatin Report¹⁴ prepared by President Thomas Jefferson's Secretary of the Treasury, called for a national transportation program as a way to stimulate economic growth. Little was done to implement this, although from time to time starting in 1811 Congress provided funds for "The National Road" that was to connect Washington DC to the Midwest. It eventually reached Indiana, and parts of US 40 follow this route today.

Demand for modern roads in the U.S. was stimulated by the rapid growth of bicycles in the late 19th Century. The League of American Wheelmen stimulated the Good Roads Movement which in turn helped generate interest in improved roads. Both organizations were funded by a manufacturer of bicycles. They did stimulate interest in better roads, an interest taken advantage of by the early manufacturers of automobiles and their customers.

In 1912 interest in national (as opposed to local) roads was stimulated in part by the Lincoln Highway Association, with a focus on a road between Times Square in New York City and Lincoln Park in San Francisco (later U.S. Route 30). Early funds were provided by firms in the automobile industry. This group became a strong advocate for a national network of good roads.

The concept of grade-separated roads with interchanges rather than crossing roads and limits on the type of vehicles that could use them (no horses) began in Europe, with expressways built in Italy in 1924 followed by Germany in the late 1920s and early 1930s. Germany developed this concept into a national network of Autobahns, particularly after Adolf Hitler came into power. This network was motivated largely by economic rather than defense reasons, as the German military relied on rail transport.

The U.S. began to construct parkways in 1906 and 1907 as automobile-only roads (the Long Island Motor Parkway (Vanderbilt Parkway) and the Bronx River Parkway are examples). Grade separated roads were begun in the 1920s and 1930s. Many of these were in the New York metropolitan region and limited to cars. Robert Moses envisioned this as a network to help link state parks.¹⁵ Similar roads were developed in other cities, Kansas City, Missouri, Memphis, Tennessee and Indianapolis. More parkways were built during the 1930s with federal funds, with an emphasis on national parks.

The first "modern" federal highway legislation was the Federal Aid Road Act of 1916.¹⁶ This Act provided funds to state highway departments (with restrictions) and made it clear that the states

¹⁴ Albert Gallatin *Report on Roads, Canals, Harbors, and Rivers* (2008). <http://oll.libertyfund.org/titles/gallatin-report-of-the-secretary-of-the-treasury-on-the-subject-of-public-roads-and-canals>

¹⁵ The Long Island Parkway System New York State Department of Transportation, (1985).

¹⁶ Congressional Budget Office, "Highway Assistance Programs: A Historic Perspective", (February, 1978). <https://www.cbo.gov/sites/default/files/95th-congress-1977-1978/reports/78-cbo-020.pdf>

would own the roads build with federal aid and were responsible for their construction and maintenance. The Revenue Act Of 1932 established the first federal tax on motor fuel (one cent per gallon). Starting with Oregon in 1919, the states established their own motor fuel taxes, usually dedicated to highway investment.

The Federal-Aid Highway Act of 1938 funded a study (Toll Roads and Free Roads) that called for a comprehensive system of free roads with limited access to the right-of-way. A later report published in 1944 proposed a 39,000-mile network of controlled access roads. An interesting side note: In 1938, President Franklin Roosevelt marked on a map the routes on which he wanted the Bureau of Public Roads to construct a network of modern Express Highways. The Interstate Highway System approximates these routes.

The Interstate Highway System was first designated in 1944, but funding was limited a number of states began to build their own limited-access roads as toll roads and as carrying cars and trucks (beginning with the Pennsylvania Turnpike prior to World War II).

In 1955, the President's Committee on a National Highway Program (called the Clay Committee for its chairman) issued a report that called for a national network of limited access roadways with funding provided through a Federal Highway Corporation. They listed four reasons: Traffic growth, civil defense, highway deterioration, and safety. There was no mention of economic benefits. But, in 1956, President Eisenhower's letter to Congress mentioned the future economic importance of avoiding traffic jams and the cost of poor road conditions (a penny a mile). He also listed safety first and urban evacuation needs in case of an atomic attack as the number three reason.

After active debate in Congress and disagreement over specific details proposed by the administration, the Federal-Aid Highway Act of 1956 created the Highway Trust Fund along with a series of dedicated taxes. A three cent-per-gallon motor fuel tax (raised to four cents a couple of years later) was the most important. The administration proposed bonds backed by user fees, but Congress preferred a pay-as-you-go system but based on user fees.

Two key provisions of the 1956 Act called for a 90 percent federal match and funds allocated based on costs to complete the Interstate. Together these ensured rapid completion of the Interstate and a focus on a national network rather than projects of interest to individual states. By the late 1960s (little more than a decade after the start) about half of the miles of the Interstate had been completed. More importantly, every road map showed future routes and construction was underway in every state. Businesses began to plan for future access to new markets long before the system was complete. Atlanta, Georgia built urban Interstate routes before other southern cities, helping to stimulate its growth as the dominant regional economic center.

Economic Value

The economic value unleashed by the Interstate Highway System was a prime mover for the nation's economy for at least two decades. The rate of return varies over time, with the highest

rates during the 1950s and 1960s when the Interstate Highway System was under construction—but annual rates of return on this investment were well over 50 percent a year for almost two decades.¹⁷

This was a clear sign of the economic value of building a nationwide network since it stimulated new markets and provided access to new pools of labor and material inputs. It also probably reflects the accumulated under investment in civilian capital during and immediately following World War II. During this period the Interstate investment accounted for fully one fourth of the nation’s overall gains in productivity.

These Interstate Highway related changes occurred very rapidly—as long as one does not count the two decades or so that it took to develop a practical financial plan and for public leadership to emerge from the early planning stages in the 1930s. The combination of a robust financial institution with a national network helped provide far reaching economic benefits and social change. While the Interstate had been authorized in the late 1940s, little was built until the establishment of the Highway Trust Fund in 1956. This financial mechanism provided an assured source of funds (the federal tax on motor fuel was doubled from two cents per gallon in 1955 to four cents in 1960) combined with a commitment that the federal government would fund at least 90 percent of construction costs.

Professor Ishaq Nadiri of New York University completed the “most notable” empirical analysis to date to assess the relationship between highway investment and economic growth.¹⁸

Professor Nadiri studied the effects of changes in highway assets from the 1950s through the mid-1990s. Dr. Nadiri concluded that highway investment in the 1950s and 1960s (the Interstate Era) provided an average 50-60 percent annual rate of return on public investment. More than one-half of these benefits to private industry were realized in services and non-manufacturing sectors—in contrast to the more traditional view that freight, logistics and vehicle manufacturing benefit the most from highway improvements.

While the absolute rate of return has dropped significantly in more recent years, these studies still find that the rate of return to public investment can equal or exceed the average rate of return from private investment.

When the focus is on a national highway network, however, and on changes over time, firms and industries change how and what they produce and consumers change what they demand and how much they are willing to pay for it. That is, we would expect to see a linked series of changes

¹⁷ Ishaq Nadiri and Theofanis Mamuneas, “Contribution of Highway Capital to Output and Productivity Growth in the United States Economy and Industries,” (August 1998), United States Federal Highway Administration. <https://www.fhwa.dot.gov/policy/otps/060320e/appa.cfm>

¹⁸ The Transportation Challenge—Moving the United States Economy. The National Chamber Foundation. <http://www.uschamber.com/ncf/default>.

that may even generate shifts in what we produce and consume just as it changes the underlying costs.¹⁹

In effect, in response to highway investment, industry changes how much it costs to produce goods, then changes how it produces goods (maybe even changing what is produced), and finally changes how much it produces. Of course, this last change may also involve another round of changes in how goods are produced as increased demand encourages larger factories and economies of scale come into play.

In sum, when viewed as a network, transportation stimulates shifts in the demand and supply curves for goods and services: Economic productivity improves. These changes can be seen at the firm level as well, although it is harder to quantify the effect precisely. Both AASHTO and FHWA published reports that include firm-level case studies of how these changes occur.²⁰

The overall effect from this set of changes is clear—an improved highway network creates significant overall increases in economic activity both by reducing costs and by stimulating demand. Professor Nadiri’s work offers a wealth of important findings.

The rate of return from public investment in highway capital exceeded the rate of return from private capital investment from the 1950s through the early 1990s. This is a dramatic result, since traditional economics teaches that on average public-sector investments are less productive than private investments. Indeed, if they showed a higher return than private business, then one would expect entrepreneurs to enter these businesses. In this case, however, the returns depend on a national scale of investment that has been beyond the capability of private industry in the past and of course strong arguments can be made for public ownership and control of the national highway system (even though segments may be owned or operated by private entities).

- The rate of return averaged more than 30 percent a year from the 1950s into the early 1990s versus 17 percent for the return on private capital,²¹ 12 percent for the return on private equity and 8 percent for the return from corporate bonds. See Table 1 below.
- The rate of return varies over time, with the highest rates during the 1950s and 1960s when the Interstate Highway System was under construction—well over 50 percent a

¹⁹ Ishaq Nadiri and Theofanis Mamuneas, “Contribution of Highway Capital to Output and Productivity Growth in the US Economy and Industries,” (August 1998), p. 24, FHWA.

²⁰ Both were prepared by Apogee Research Inc. and published in the early 1990s.

²¹ The return on private capital comes from the same economic model used by Professor Nadiri to calculate returns from highway capital. This ensures a consistent set of calculations with the public returns. The results are also higher than the more direct measures of private rates of return also included in the table.

year for almost two decades. Private returns of this magnitude are rare for any industry and even less common when they occur over a long period of time.

TABLE III-1: Average Net Rates of Return on Highway Capital, Private Capital, and the Interest Rate

Rates of Return	1960-69	1970-79	1980-91	1960-91
Highway Capital	54 percent	27 percent	16 percent	32 percent
Private Capital	16 percent	18 percent	17 percent	17 percent
Private Equity	11 percent	11 percent	12 percent	12 percent
Interest Rate	5 percent	8 percent	10 percent	8 percent

In recent years the average rate of return on highway investment has dropped considerably, reaching the mid-teens and approximating the return on private capital during the late 1980s — although still well above the rate of returns as measured by private equity or long-term bonds. This is an important change, even though the rate is still attractive.

Almost every economic sector shows significant economic gains from highway investment. That is, gains do not focus on industries with the most obvious ties to highways—trucking, warehousing, and vehicle manufacturing.

The service sector shows the strongest positive gains. This is a bit surprising since we often think of the economic value of highways as being based on trucks and the movement of goods. The individual firm level case studies cited above show the importance of access to labor.

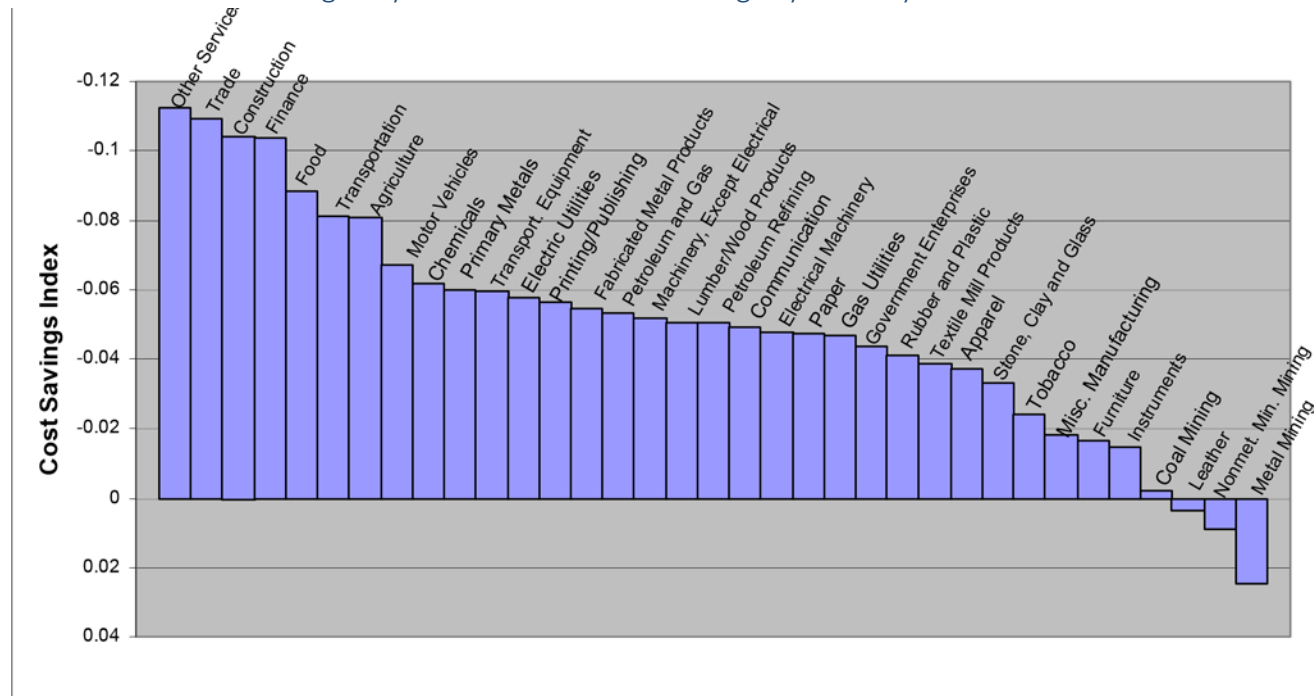
Cost savings provides a tangible measure of the relative value that each industry receives from highway investment. For example, a 10 percent increase in the value of the nations’ highway network would create a 1.1 percent decrease in the overall cost structure for Other Services or for Trade.

Three of the top four industries come from the service sector—Other Services, Trade and Finance Insurance and Real Estate. Obvious transport-oriented industries such as Transportation and Warehousing (which includes trucking) and Motor Vehicle Manufacturing are found near the top of the list, but less prominently. The exceptions are not surprising, with most negative impacts found in mining for example.

Trade, Other Services and Finance, Insurance and Real Estate account for more than half of the overall net benefit. This may reflect the importance of access to labor in the service sector and the role that highway congestion can play in limiting access. Also, many of these industries

depend on transportation for on-time meetings. And, of course, since these sectors support manufacturing they benefit indirectly if their customers also do well. Government and Communications are other service industries with positive signs, but much smaller in magnitude.

FIGURE III-1: Effect of Highway Investment on Cost Savings by Industry



In retrospect, the Interstate Highway System had a clear and dramatic impact on the U.S. economy. But, unlike similar investments today, there was no detailed study of the expected economic impact or benefit-cost ratio. In some ways, the reason for the Interstate was obvious in Post-War America. What forecasts did exist underestimated demand—by 1965 the actual number of vehicles was 11 percent more than forecast (on top of the forecast of 50 percent growth) and VMT was 9 percent higher, with the GDP 40 percent higher than forecast.

Traditional economic studies showed that only about one-third of the mileage could be justified based on traffic in 1956 and only one road over the Rocky Mountains made economic sense (three were built).²² A few lessons:

- It is very hard to forecast the types of non-linear changes that network-scale change can bring about;
- Common sense arguments can be very persuasive (there was little debate over the rationale given for the Interstate—the debate centered on the use of bonds versus “pay as you go” funding);

²² Ann Friedlander, *The Interstate Highway System a Study in Public Investment*, (1965).

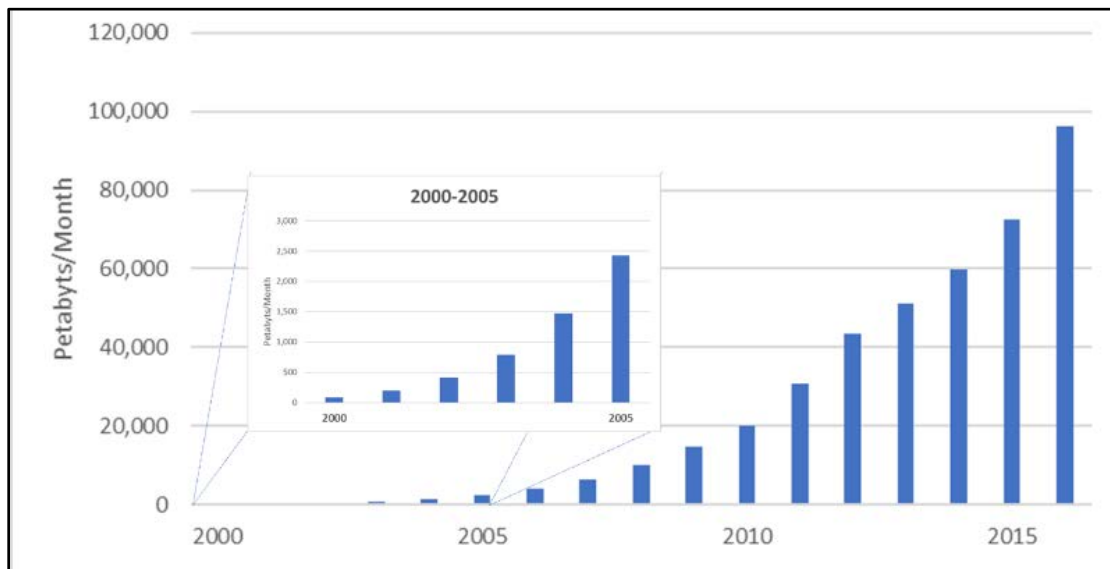
- Economic and social change did not have to wait for official completion of the Interstate once it was clear that it would happen.

IV. Internet

History²³

The Internet has revolutionized computing and communications—and has done so at an unprecedented pace. In 1993, the Internet was responsible for 1 percent of the information flowing through two-way telecommunications networks. That share grew dramatically to 51 percent by 2000, and then on to more than 97 percent by 2007. Cisco Systems estimates global Internet traffic has risen from 84 Petabytes per month in 2000 to nearly 100,000 petabytes per month by 2016 (see chart, shown with two scales to encompass to demonstrate the continued exponential growth). Since its broader access for commercial use starting in 1993, it has grown from a networked platform to support communications and research among a few universities and research centers to become the communications backbone of the global economy.

FIGURE IV-1: Growth in Global Internet Traffic



Source: Cisco Systems *Visual Networking Index*

The concepts behind what we today call the Internet first emerged in the 1950s, concurrent with the development of electronic computers, when notions of wide area networking first surfaced. After many years of research, in the 1960s the U.S. Department of Defense awarded contracts for what would be known as the ARPANET project. The ARPANET project led to the development of protocols for Internetworking, in which multiple separate networks could be joined into a

²³ Based on the Internet Society’s “History of the Internet” (<https://www.Internetsociety.org/Internet/history-Internet/>), History.com’s “The Invention of the Internet” (<http://www.history.com/topics/inventions/invention-of-the-Internet>), and Wikipedia’s “History of the Internet” (https://en.wikipedia.org/wiki/History_of_the_Internet).

network of networks. The first message on the ARPANET was sent in 1969 from the computer science laboratory at the UCLA to the Stanford Research Institute.

The Internet protocol suite (TCP/IP), developed in the 1970s, would soon become the standard networking protocol on the ARPANET.

The ARPANET Transition and Emergence of Commercial Use

ARPA, whose primary mission is research and development, managed the ARPANET from its launch in 1969. In the early 1970s, ARPA began looking for a way to transition operational management to a separate entity or agency. In 1975, the network was turned over to the Defense Communications Agency, part of the Department of Defense.

Importantly, the networks based on the ARPANET were government funded and therefore restricted to noncommercial uses such as research. Commercial use of the networks unrelated to research was strictly forbidden (see text box). This initially limited network connections to military sites and universities. During the 1980s, the connections expanded to more educational institutions, and even to a growing number of companies such as Digital Equipment Corporation and Hewlett-Packard, which were participating in research projects or providing services to those who were.

In 1984, the U.S. military portion of the ARPANET was separated as a distinct network, the MILNET, the first of a series of military networks. Several other U.S. government agencies, including NASA, the National Science Foundation (NSF), and the Department of Energy (DOE) became heavily involved in Internet research and started development of a successor to ARPANET. In the mid-1980s, these developed the first Wide Area Networks based on TCP/IP. NASA developed the NASA Science Network, the National Science Foundation developed CSNET, and DOE evolved the Energy Sciences Network.

In 1986, the NSF created NSFNET, a 56 kilobit-per-second backbone to support the NSF-sponsored supercomputing centers. The NSFNET also provided support for the creation of regional research and education networks in the United States, and for the connection of university and college campus networks to the regional networks. In 1988, NSFNET was upgraded to 1.5 megabits per second, and upgraded again in 1991 to 45 megabits per second.

During this period, research in Switzerland led to creation of the World Wide Web in 1989 and the first browser in 1990. The World Wide Web enabled linking hypertext documents from any node on the network. The first commercially successful browser, and one often credited with

Limitations on ARPANet Use

“It is considered illegal to use the ARPANet for anything which is not in direct support of Government business ...

Sending electronic mail over the ARPANet for commercial profit or political purposes is both anti-social and illegal.”

From MIT AI Lab Handbook, 1982

sparking the Internet boom of the 1990s, was Marc Andreessen's Mosaic (later known as Netscape), introduced in 1993.

In 1992, the U.S. Congress passed the Scientific and Advanced-Technology Act, which allowed the NSF for the first time to support access by the research and education communities to computer networks which were not used exclusively for research and education purposes.

The final restrictions on carrying commercial traffic ended in 1995 when the NSF ended its sponsorship of NSFNET, and it was retired.

Web 1.0

The first decade of the public, commercial Internet has come to be known as Web 1.0. During this period, which lasted until roughly 2004, website design and functionality was limited and comparatively rudimentary. It typically featured static web pages instead of dynamic HTML, and content served from filesystems instead of relational databases. Major applications of the era included email, mailing lists, and e-commerce. Although personal applications were popular, such as online forums and bulletin boards, personal websites and blogs, social media had not yet become one of the prevalent applications.

Web 2.0

Stimulated in part by growing consumer access to computers, high-speed connectivity, and new mobile communications devices capable of accessing the Internet (smartphones), the next generation of the Internet took shape. This “Web 2.0” generation was marked by increasingly interactive web interfaces (allowing connectivity and feedback via social media, for example), as well as location-based services, and mobile platform applications (“apps”) that provided desktop/laptop-like functionality on mobile devices. Today, 43 percent of the world’s population use the Internet regularly.

Economic Value

The economic importance and continued extraordinary growth of the Internet is hard to overstate. According to recent report prepared for the Internet Association,²⁴

- Internet industries were estimated to be responsible for six percent (\$966.2B) of real U.S. GDP in 2014—more than double Internet industries’ real contributions from just seven years earlier.
- The Internet sector increased its total U.S. employment share from 2007 to 2012 by 113.3 percent—over seven times more than the second highest increase in employment share for an industry (healthcare and social assistance).

Beyond size, the Internet also makes a material contribution to the standard of living. In its study of the impact of the Internet on economic growth and prosperity, McKinsey’s Manyika and

²⁴ *Measuring the U.S. Internet Sector*, Stephen E. Siwek Economists, Inc., 2016.

Roxburgh found that the Internet accounted for 21 percent of the growth in GDP for mature economies over the previous five years (roughly 2005 to 2010—up from a “mere” 10 percent of GDP growth over the previous 15 years. The more rapid pace of this change reflects the growing interaction between the Internet and wireless communications—with the smartphone as the example in our daily lives. The growth in real per capita income in 15 years was equivalent to what took 50 years to realize during the Industrial Revolution.²⁵

One lesson from the Internet is that technology changes, with new capabilities generating products and services that were not conceived of in the early years. This growth and the creation of new industries and businesses is enough to offset job losses during this transition. McKinsey mentions a study of the French economy that found that while the Internet “... destroyed 500,000 jobs over the past fifteen years, it created 1.2 million new ones.” This shows 2.4 new jobs for every one lost—McKinsey uses the ratio of 2.6 to one.²⁶ This is not atypical of change on this scale, with examples from the early days of the automobile and the loss of many jobs that supported transportation based on animal power.

One example of how the Internet helped to open new markets and businesses is the link between firms that made heavy use of the web and their growth. These firms grew 2.1 times as rapidly as did firms with low use of the web. This was also true for exports, with high users of the web increasing exports by 2.1 times low users of the web.²⁷ These trends have helped smaller firms compete in international markets than would have been possible prior to the Internet.

Individuals gain from the Internet in part by using the web to find the best price or best price and quality. In the US, the average value per user is \$26 per month, for a total Internet surplus of \$64 billion.

A few lessons:

- The original goal of a network investment can change dramatically over time (and more than once), with profound economic and social consequences.
- Job losses are real, but so are job gains as new industries and new businesses develop.
- Technology deployment is led by the private sector, although early public funds can provide an important stimulus.
- Success requires adequate infrastructure, an emphasis on innovation, encouragement of competition, and human capital.²⁸

²⁵ “The Great Transformer: The impact of the Internet on Economic Growth and Prosperity”, McKinsey Global Institute, J. Manyika and C. Roxburgh, 2011. <https://www.mckinsey.com/industries/high-tech/our-insights/the-great-transformer>

²⁶ Ibid., p.4. No dates are given for the 15 years covered in the French study, but this began prior to 2000 and thus missed the more recent effect of the integration of the Internet and wireless.

²⁷ Ibid, p.4.

²⁸ Ibid, pp 7-8.

V. Electric Generation

History

The first electric motor was invented by Michael Faraday in 1821. This was followed by a steady stream of improvements. In 1844 Samuel Morse invented the electric telegraph, a long-distance communication device that had immediate applications. During the 1860s J.C. Maxwell's work on magnetism, electricity and light provided the theoretical support for electric power, radios, and television (Maxwell's four laws of electrodynamics).

1876 Charles Brush invented the "open coil" dynamo (or generator) that could produce a steady current of electricity. This helped to make it practical to provide electricity to different locations. This was followed in 1879 by Thomas Edison's developed an incandescent light bulb that could be used for about 40 hours, achieving 1200 hours by 1880.

The pace of development and early deployment was rapid. Electric lights (Brush arc lamps) were first used for public street lights in Cleveland, Ohio in 1879. The California Electric Light Company, Inc. in San Francisco was the first electric company to sell electricity to customers.

The electric streetcar was invented by E.W. v. Siemens in 1881, followed by rapid deployment both within urban areas and for intercity trolley lines that connected cities and suburbs (in time it was possible to travel between Chicago and New York City via a series of independent interurban lines).

In 1882 Thomas Edison opened the Pearl Street Power Station in New York City. This was one of the world's first central electric power plants and could power 5,000 lights. It meant that people and businesses no longer needed to rely on an on-site electric generator. This project required considerable lobbying in order to secure approval from the City of New York. Edison received their approval in part through a lavish champagne dinner at Menlo Park catered by Delmonico's, then New York's finest restaurant.²⁹ Of course it did not hurt that Edison was backed by J.P. Morgan. This effort led to the founding of General Electric.

In 1883 Nikola Tesla invented the "Tesla coil", a transformer that changes electricity from low voltage to high voltage making it easier to transport over long distances. The next year, Tesla invented the electric alternator, a way to produce alternating current (AC), making long-distance transmission of electricity practical. Westinghouse Electric Company later bought the patent rights to the AC system.

Relevant technical inventions continued for some time, but the major breakthroughs involved new business models. Samuel Insull led much of this change. After leaving the employ of Edison, in 1892 Insull joined the firm that became Commonwealth Edison and developed a new business

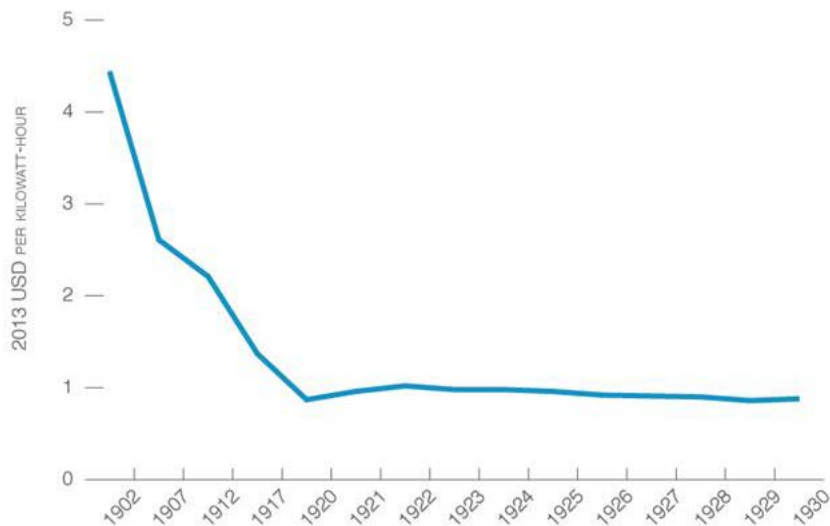
²⁹ Thomas Edison: His Electrifying Life, Time Magazine Special Edition, 2013. Mentioned in the *History of Electricity*, Institute for Energy Research, August 29, 2014.

model that combined the economies of scale needed to produce low-cost energy and the need to develop new markets. The figure below shows the impact on the price of electricity.

The impact on deflation was important, with increases in quality and decreases in price. This, in turn, stimulated rapid growth electric use, particularly in urban areas. The capital-intensive nature of electric generation meant that it has characteristics of a natural monopoly. This stimulated the use of state-level regulations. By 1914, 43 states had such regulations in place. While controlling rates for current customers, this also served to limit future competition.

While electric generation expanded rapidly in urban areas where density encouraged economies of scale, rural areas lagged behind. By the early 1930s, 90 percent of urban dwellers had electricity, but only 10 percent of farmers and rural residents did. In 1935 federal government established the Rural Electrification Administration to provide low cost loans for electric coops. By 1939, 25 percent of rural homes had electric power and by 1945 the total reached 90 percent.

FIGURE V-1: Average Price for Electric Energy, 1902-1930 (In Real 2013 US\$)



Source: Institute for Energy Research

Economic Value

Electricity transformed society and the economy. The impact on the average household was stunning, with a shift from dangerous gas to electric lights that provided significantly more light and at less cost. Electricity also made it possible to have central heating and a host of appliances, ranging from refrigerators rather than ice boxes to vacuum cleaners and washing machines. Robert Gordon describes these changes as going “from dark and isolated to bright and networked.”³⁰

³⁰ Robert Gordon, *The Rise and Fall of American Growth*, (2016).

The impact of business was equally strong: “Electricity is the preferred form of energy because of its high efficiency, instant and effortless access, perfect and easily adjustable flow, cleanliness, and silence at the point of use.”³¹

“Next to the increasing importance of hydrocarbons as sources of energy,” economist Erich Zimmermann wrote in 1951, “the rise of electricity is the most characteristic feature of the so-called second industrial revolution.”³²

Electric power made machines more cost effective and speeded the economic conversion from agricultural to manufacturing that was already underway. Costs dropped and quality improved. New markets were created—witness the new household appliances. Some industries declined (for example the network of gas lines and related equipment used in most urban areas). While jobs were lost, many more jobs were generated.

A host of new industries became possible. Examples range from skyscrapers and their dependence on elevators to rail transit that connected cities and their suburbs. Electricity supported the rapid deployment of telephones.

Possible lessons:

- Technology innovation during the early years was deployed rapidly, creating faster growth as well providing funds for more investment;
- New industries were created, including many that had not been conceived of before;
- New business structures were created – the electric power monopolies with a vested interest in encouraging more use of electricity are one example;
- The public role focused on regulations. Equity concerns motivated the federal government to support rural electrification.
- Demand for electricity was strong once applications such as the incandescent electric light were practical. Investment was almost exclusively from the private sector.

VI. Other Transportation Examples

The Lincoln Highway

The Lincoln Highway was the first U.S. transcontinental highway. The highway ran coast-to-coast from New York City (at Times Square) west to San Francisco (at Lincoln Park). It was formally dedicated October 31, 1913. Construction and improvements to existing road along the alignment were initially projected to cost \$10 million.

³¹ Vaclav Smil, “The Energy Question, Again,” *Current History*, December 2000, p. 409.

³² Erich Zimmermann, *World Resources and Industries* (New York: Harper & Brothers, 1951), p. 596.

The creation and initial construction work for the Lincoln Highway were inspired by Carl G. Fisher, an early automobile entrepreneur and one of the principal investors in the Indianapolis Motor Speedway. He believed that the future popularity of automobiles was dependent on good roads. Yet because the U.S. Congress and federal government were unwilling to fund large scale road construction or improvements at that time, Fisher began soliciting private investments.

In 1913, the Lincoln Highway Association (LHA) was established.³³ The Association was made up of representatives from the automobile, tire, and cement industries, with the primary goal of planning, funding, constructing, and promoting the first transcontinental highway in North America.

The first section of the Lincoln Highway to be completed and dedicated was the Essex and Hudson Lincoln Highway, running along the former Newark Plank Road from Newark, New Jersey, to Jersey City, New Jersey. It was dedicated on December 13, 1913. Construction of the highway would continue for the next 25 years.

Financing

To fund the highway, Fisher in 1912 asked for cash donations from automobile manufacturers and suppliers of 1 percent of their revenues. The public could become members of the highway organization for five dollars.³⁴ Fisher was successful in securing pledge commitments from auto industry executives and others totaling \$1 million in its first year.³⁵ Eventually, the fund would collect an estimated \$5 million of its \$10 million target.

By 1914, with few improvements yet complete, the LHA decided to abandon the fund and instead redirect the association to a new goal: educating the country for the need for good roads made of concrete, with an improved Lincoln Highway as an example. LHA would oversee the construction of concrete "seedling miles" in the countryside to demonstrate the superiority of concrete over unimproved dirt roads. The LHA's hope was that, seeing the value of concrete, citizens would press the government to pay for road improvements.

Thus, although the initial investments to begin design and construction were made by private interests, local, state and federal funding would eventually be required to complete the work. Congress did pass Federal Highway Acts in 1916 and 1921, which provided matching funds to the states for highway construction. The 1921 act limited eligibility of the \$75 million available to "primary" roads, or 7 percent of a given state's total mileage.

³³ Richard F. Weingrof, *The Lincoln Highway*, prepared for the US Department of Transportation Federal Highway Administration's Highway History (<https://www.fhwa.dot.gov/infrastructure/lincoln.cfm>) (2011).

³⁴ James Lin, *Lincoln Highway: A Brief History – Origins 1912-1913* (1998).

³⁵ Henry Ford refused to contribute, believing that the government, not private individuals or companies, should build the Nation's roads, and thus threatening the funding strategy.

No direct accounting of investments and contribution appears to exist today, though it would be safe to estimate that 90 percent or more of the ultimate cost, when including right-of-way and improvements, were made by the public sector.

Long-Term Impacts

The success of the Lincoln Highway and the resulting economic boost to the regions, businesses and citizens along its route inspired the creation of many other named long-distance roads (known as National Auto Trails), including the Yellowstone Trail, National Old Trails Road, Dixie Highway, Jefferson Highway, Bankhead Highway, Jackson Highway, Meridian Highway and Victory Highway.

In 1926, the United States Numbered Highway System converted many named highways to numbered highways. Most of the Lincoln Highway route would become U.S. Route 30, although today's Route 30 aligns with less than 25 percent of the original 1913–28 Lincoln Highway routes.

In 1938, Franklin D. Roosevelt expressed interest in the construction of a network of toll superhighways that would provide more jobs for people in need of work during the Great Depression. The resulting legislation was the Federal Aid Highway Act of 1938, which directed the chief of the Bureau of Public Roads (BPR) to study the feasibility of a six-route toll network. War delayed the program. At the end of the war, the Federal Aid Highway Act of 1944 funded highway improvements and established major new ground by authorizing and designating, in Section 7, the construction of 40,000 miles of a "National System of Interstate Highways." By the time President Dwight D. Eisenhower took office in January 1953, the states had only completed 6,500 miles of the system improvements.

Eisenhower had first realized the value of highways in 1919, when he participated in the U.S. Army's first transcontinental motor convoy from Washington, DC, to San Francisco on the Lincoln Highway. This, together with his experience with the German Autobahn in World War II, is thought to have inspired Eisenhower's support for an interstate highway system and the National Interstate and Defense Highways Act of 1956.

19th Century Examples

Inland Waterways. In the earliest decades of the republic, the Army Corps of Engineers was funded to open up the Ohio and Mississippi Rivers. This played a major role in speeding westward expansion—certainly more important than Daniel Boone's Wilderness Road. This strong direct federal role stands out as unique in a time when state's rights were taken seriously and a restrained domestic federal role was reality. This followed the explicit rejection that the federal government should play a lead role in developing the nation's infrastructure (the famous Gallatin Report). As with much of U.S. transportation, the private sector then invested in barges and provided the direct transportation service.

Land Grants and the Transcontinental Railroads. The transcontinental railroads were a very different story, with the leadership coming from the private sector. The federal and state governments provided funds mostly in the form of land grants along the proposed rights of way. Railroad access would stimulate economic activity, increasing the value of these properties at the same time. The result was a very rapid expansion of the network – along with some shady political and financial dealings. In sum, the federal and state governments gave fully ten percent of the Continental US to spur construction. The federal government continued to reap the rewards of this far-sighted investment through reduced freight rates well into the 20th Century – another example of sharing risks and rewards.

VII. Implications for Economic Value of AVs

History

The General Motors Futurama exhibit at the 1939 World’s Fair is the standard date used for the idea for an autonomous vehicle. The designer of this exhibit, Norman Bel Geddes, followed with a book in 1940, *Magic Motorways*, with more details regarding expressways and AVs.

In later years research was conducted by companies, universities, and research groups. In 1958, the RCA/Nebraska DOT team predicted that vehicles would be commercial by 1975. These efforts took two routes—sensor-equipped roads that would guide vehicles and self-driving vehicles that could operate independently. The focus on highway-based sensors reached a peak in 1997 with a demonstration of a wide range of vehicles and technologies in San Diego. U.S. DOT had provided funds for this effort, but the ability of the public sector to generate funds for the capital costs needed to deploy a national network of sensors seemed unlikely.

DARPA (the Defense Advanced Research Projects Agency) sponsored three “Grand Challenges” in 2004, 2005, and 2007. The first two covered off-road driving and the third was in an urban setting. These generated tremendous interest from universities and corporations. One result was renewed interest by several automobile companies as well as technology firms (such as Google) with no previous interest in vehicles. This has led to some \$80 billion in private investment in AVs (estimate by Brookings Institution) and the development of a new industry.

While field tests continue around the world, deployments that range from specialized locations (mine trucks in Australia and elsewhere) to vehicles with limited capabilities (low-speed shuttle on campuses and restricted locations) to deployments of vehicles with some automated technologies (witness the growing number of vehicles equipped with automatic braking and lane tracking and the Tesla with self-driving ability on certain types of roads). Many more vehicles are on their way:

- Waymo (Google company) has 600 driverless cars in operation in Phoenix Arizona in 2018 and plans to order up to 82,000 vehicles (20,000 Jaguar SUVs and 62,000 Chrysler Pacifica vans) with plans to deploy these in shared ride service starting in 2019.
- Uber just announced that they would purchase 24,000 Volvos (cost about \$1 billion) for deployment as shared use vehicles starting in 2019; this deployment may be delayed following a fatal crash in Tempe Arizona in early 2018.
- A growing number of car companies have begun to sell high-end vehicles with self-driving ability for use on certain roads.

Comparison with Other Networks

The Interstate Highway System was driven by the federal government, but only once a financial plan was put in place. While President Franklin Delano Roosevelt personally sketched out the Interstate network in 1938, nothing happened until the Highway Trust fund with dedicated taxes came along in 1956. In sum, private investment followed the public lead—the reverse of AVs.

Regulations focused on economics of specific modes of transportation (and were a vestige of the late 1890s and the need to control railroad rates). While the economic impact of the Interstate was focused on a couple of decades (with a long tail) one could argue that deregulation of trucking, railroads, and aviation some 25 years later stimulated another burst of economic growth. In the case of AVs, the importance of de facto deregulation of urban transportation brought about by Uber, Lyft and others is a very important positive factor.

In contrast, the private sector led the electric industry from invention (Thomas Edison is most famous) to deployment (General Electric, Westinghouse, Commonwealth Edison in Chicago etc.). This combines a new technology with the need to build a new infrastructure. In that sense, it differs from AV since most of the infrastructure for AVs is already in place. The need to build an infrastructure from scratch meant that electricity had a huge impact on the economy and this impact lasted longer than for the Interstate.

Impacts covered industry and individual lives. As with AVs, safety was an important motivator—gas lights, etc. were dangerous. Safety debates were important as part of the battles between the promoters of AC and DC—politics were at least as important as analytics. Electric regulations focused on economics since electric utilities were viewed as a “natural monopoly.” Public funds focused on loans to help with rural electrification.

The Internet was stimulated by DARPA—a nice parallel with AVs. Even though the Internet was originally conceived as a tool for public universities and government agencies, the private sector stimulated development. This involved the birth of many new firms—another parallel with AVs. As with the Interstate Highway, the Internet stimulated economic growth in large part by its ability to communicate at long distances with an international aspect missing from the Interstate Highway. This improved access to markets and access to both labor and jobs.

Summary of Past Examples

The volume of literature regarding AVs is very large. Many that cover economic issues focus on possible job losses, with an emphasis on truck drivers and taxi cabs. Several studies cover broader sets of impacts, with safety, vehicle operating costs (assuming some—and some believe most—people will no longer own private cars), traffic congestion, and newly found “free” time while traveling. As yet, no one has attempted to estimate the “non-linear” impacts including gains in economic productivity.

Most of these general economic reports of AVs are really market studies. They focus on the likely timing of deployment and on the volume of vehicles (adjusted for different levels of shared mobility). Most of the detail covers different types of direct impacts. When they refer to productivity, all they mean is the ability to work on e-mails while the car drives itself. This really just reduces the cost of travel—a true benefit but quite different than economic productivity that stimulates changes in economic structure. This is where the big gains are, as shown with the Interstate, the Internet, and electricity (among others).

Each of the three examples show the impact of network-scale investments in stimulating new industries and new markets. These are particularly clear in the case of electricity, with the development of new products ranging from electric light bulbs, to rail transit, to central heating, to elevators and sky scrapers, to refrigerators. The economic and social impacts were profound—in Robert Gordon’s words, they brought the “American home from dark and isolated to bright and networked.”³⁶

The Internet stimulated new markets (every firm could gain access to international markets) to new products and services, many with corporate names that have become household names—such as Google, Facebook and Amazon. The Interstate Highway system has similar impacts. Who dreamed it was possible to get California oranges in New York City? The Interstate Highway System generated returns of 50-60 percent a year over two decades and accounted for one fourth of the nation’s overall growth in economic productivity—and all from just four cents a gallon tax.

In each example, job losses were created as new industries grew to replace old ones. In each case the net impact on jobs was clearly positive. For the Internet, about 2.6 new jobs were generated for every job that was lost. For electricity the ratio is likely much higher since there were relatively few jobs displaced (gas works used for lighting is one example).

When these new networks are first introduced, it is difficult to forecast what new products, services, or industries might occur. In the 1990s, who would have guessed businesses such as Google or Facebook? The development of AVs is linked with that of shared mobility – ten years ago who would have imagined the success of shared mobility companies such as Uber and Lyft?

³⁶ Robert Gordon, *The Rise and Fall of American Growth*, (2016).

In each case new businesses and business models were developed. The Internet companies that are household names today are a recent example. For electricity, the model of a capital-intensive business that served all electric customers within a metropolitan area was new. This also generate new regulatory regimes. The Interstate network generated coast-to-coast distribution companies. AVs have already generated new firms with no prior experience in vehicles—it is too early to say which ones will be household words in 10 years, but there is no reason to suspect that past trends will change.

The role of government varied widely. For the Interstate Highway System, the federal government served as banker while the states implemented the plan and the private sector responded with vehicles and new businesses. Electricity was dominated by private firms, with public sector regulations to control prices and, at a later date, financial support to provide service in rural areas that were not economical. The Internet was largely driven by the private sector, but key early investments came from the federal government. AVs are not dependent on direct public funding, in large part since they can take advantage of past investments to build the nation’s network of roads and bridges.

Economic analysis was not a key decision factor in any of the three network studies. Rather, decisions passed the “common sense” test. Of course electricity provided safety, economic, and comfort benefits well beyond current practice at the time. Of course we needed a national high-level road network. True, the scale of the Interstate reflected political issues, but no surprise here given the need to secure Congressional support. In fact, a large network turned out to generate economic value. The world may differ today, in part given the large private investment in AVs and the need for market studies to support these investments. Also, public agencies and interest groups are more analytically oriented than in the past. At the same time, there is a “common sense” aspect to AVs – why not try to save lives.

The attached tables summarize the major findings of this study. Table VII-1 shows the timing for each network investment and the role of public and private entities. Table VII-2 summarizes the direct and indirect economic and social impacts.

Figures VII-1 and VII-2 summarize the timing for each network, from initial concept to development, to deployment and then maturity. The first figure shows the times on a calendar and the second one provides a comparison of the number of years needed for each.

The dates selected for each phase can be debated, but they do show that events on this scale take time. The dates selected for AVs are definitely open for debate, since most of the events have yet to occur.

The electrical grid moved relatively quickly after development of the generating equipment and the incandescent light bulb. The time to deploy the network took longer than for the other since the industry started from scratch.

The development period for the Interstate ignores the time in Europe when the Autobahn and other roads were being developed and takes time in part due to World War II and the need to develop a political consensus.

The Internet shows that the network is still evolving, with increased connections with the wireless and related applications.

The autonomous vehicle chart takes a somewhat optimistic view and assumes deployment begins in 2021 and a mature system is in place by 2040. Disagreement regarding these dates is reasonable.

TABLE VII-1. NETWORK SCALE PROGRAMS: Overview, Timeline and Sector Roles

Program	Electrical System	Interstate Highways	Internet	AVs
Description	Nationwide electrical grid	National network of Expressways	Global computer and communications network	Driverless vehicles (cars, buses, trucks)
Timeline				
Concept	1876	1938 (US)	1950s	1939
Development	1878-1890	1939-1956	1950s-1970s	1995-2020
Deployment	1890-1940	1956-1970s	1980s-2000	2021-2040
Maturity	1940-1980	1970s -2000	1995-present	2040 — ??
Leadership				
Federal	Funds for rural electrification (late in process)	Planning, Funding, Oversight, Vehicle safety regulations	Technology, Fund early deployment, Regulations	DARPA challenges; R&D – focus on connected vehicles, Regulations
State & Local	Regulation, Some financial aid (at city level), Need for location of generating stations etc. required strong lobbying, etc.	Construction, O and M, Finance (fuel taxes), Toll roads	Access to rights-of-way for fiber and wireless facilities	Regulations, Supporting investment (signs, road markings, infrastructure communications, traffic signals (SPAT), V2I) Need to change planning process, with new assumptions. Regulatory conflicts with shared mobility firms. Future of traditional transit may change.
Private	Commercial deployment, Business models, Finance, Related industries (transit, real estate development)	Vehicles, Warehouses and related distribution systems, Some toll roads and bridges	Commercial deployment, Develop new applications, new markets, Link with wireless technology	Develop technology, Develop business models (shared mobility very important), Corporations and individuals invest in vehicles

TABLE VII-2. NETWORK SCALE PROGRAMS: Direct and Indirect Program Benefits Scorecard

Benefit	Electrical System	Interstate Highways	Internet	AVs
Economic	Improved manufacturing efficiency; Helped develop new processes and new industries, New jobs in manufacturing; Stimulated rail transit industry	Gains by all industries (reduced costs, larger markets, better access to labor and materials); Services gained more than manufacturing; Created national markets; Access to labor / jobs; New products and services, Shift of housing and business to suburbs harmed inner cities (not permanent?), Encouraged relocation to places with better economic opportunities	Gains by all industries; Encourage national and international markets; New products and services, Access to labor in other locations (local and around the world); Improved access to under used labor (telecommuting)	Improved access to labor / jobs; Access to new markets and larger markets, Job losses in some industries (trucking, taxi, short-haul aviation, maybe vehicle manufacturing...); Public finance – reduced capital required for traditional transportation investments; Stimulated growth in shared mobility markets; Changed land use (parking facilities etc.); Reduced cost for long-haul freight transport
Social	Safety (end of gas lighting and candles), Personal comfort (central heating), Light for reading etc (education); Access to better housing (transit access to lower density locations)	Safety, Access to social contacts, recreational, health, education; Lower cost suburban housing	Access to information, social contacts (local and around the world), education, telecommuting.	Safety – eliminate most highway accidents; Option to reduce auto ownership; Increase location opportunities – lower cost housing; Access for elderly and handicapped.
Valuation	5 percent of US GDP; \$100 billion a year in new investment; ADD MORE DETAIL	50-60 percent return on public investment over two decades; One fourth of overall economic productivity over 20 years	21 percent of GDP growth in developed countries between 2005 and 2010; Generated 2.4-2.6 times new jobs versus jobs lost; Stimulated international trade.	\$6-8 trillion; Benefit cost ratio of 8:1 – excluding economic productivity gains. ADD MORE DETAIL

FIGURE VII-1: Network-Scale Program History

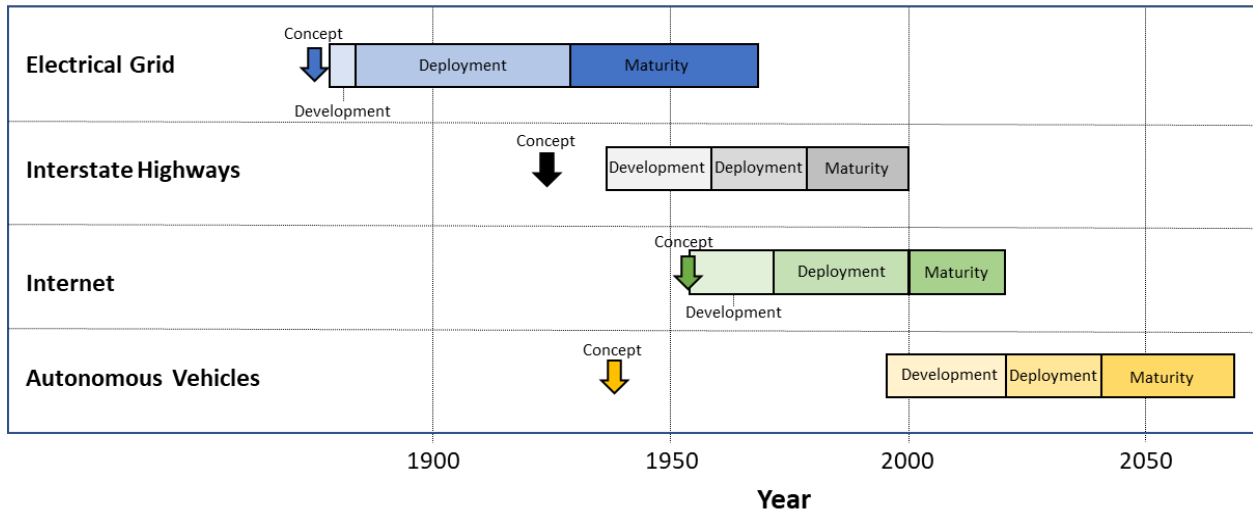
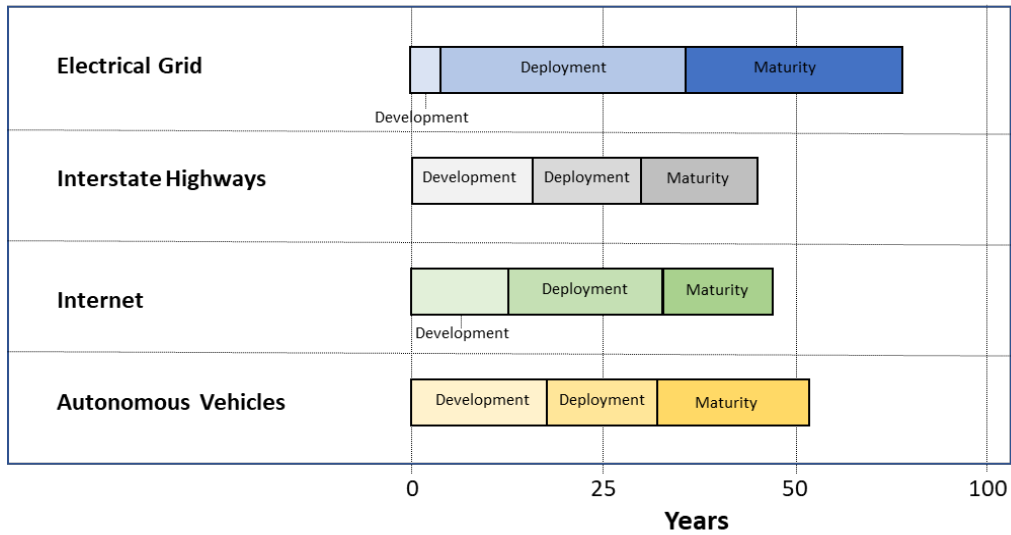


FIGURE VII-2: Network-Scale Programs: Comparative Development Cycles



Overall Economic Impact of Autonomous Vehicles: Implications from a Review of Literature

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Introduction

Transportation is in the midst of a revolution. Part of this revolution is here already, generated by the de facto de-regulation of urban transportation brought on by firms such as Uber and Lyft (and a growing number of competitors, some organized by automobile manufacturers). These firms are called transportation network companies (TNCs) and provide low-cost, convenient transportation, mostly using shared vehicles. They have already taken market share away from the taxi business and changes for public transit are on their way (not all negative).

More profound shifts are expected as various types of autonomous vehicles begin to be deployed. These will affect all aspects of transportation, including enhancing the shared mobility business of many transportation network companies. Examples range from the use of low-speed shuttles to safety technology (automatic braking, lane tracking, etc.) in most new cars, to vehicles capable of self-driving on certain roads (these can be purchased from GM, Audi, Tesla and others today) to driverless vehicles. Google spinoff Waymo will provide driverless vehicles in Phoenix in the spring of 2018 and Uber has purchased 24,000 driverless vehicles from Volvo with deployment planned between 2019 and 2021.

Some characterize these changes as the most important since the Interstate Highway System or since the invention of the automobile. In order to take full advantage of this “sea change” we need to analyze the expected impacts on society and the economy. As with many large-scale investments, it is easier to identify costs than benefits. Thus, it is no surprise that many of the economic studies of autonomous vehicles have focused on likely job losses in specific industries: long haul trucking and taxi and Uber drivers come to mind.

The number of opinions (and studies) regarding the economic and social implications of autonomous vehicles stands in sharp contrast with past analytic efforts regarding major transportation changes, including the Interstate Highway System in 1956 and the introduction of the automobile in the early 20th century. Today, there is more analytic power in public and private agencies as well as a greater interest in understanding the positive and negative impacts of large-scale changes.

Economic analysis is not just about numbers. Indeed, for network-scale changes such as that generated by autonomous vehicles, no standard forecasting model exists. No analytic approach is likely to gain the support of most economists, or most analysts, or most politicians. As a further complication, the analytic models that people select often reflect their inherent degree of optimism about the underlying technology or their views about what makes for good transportation.

For example, the economist Robert Gordon sees little opportunity for growth comparable to what the US has experienced over the past 150 years since all the important inventions that shape our daily lives have been made, with current inventions just fine tuning.³⁷ Other observers

³⁷ Robert Gordon, *The Rise and Fall of American Growth*, 2016.

are naturally optimistic about the future of technology and its ability to stimulate growth and productivity gains. For example, the futurist Ray Kurzweil believes that “...technological change is exponential, contrary to the common-sense ‘intuitive linear’ view. So we won’t experience 100 years of progress in the 21st century—it will be more like 20,000 years of progress.”³⁸

This pessimistic versus optimistic view carries over into the world of autonomous vehicles. Many of the optimists live in Silicon Valley and still believe in Moore’s Law³⁹ (and its reincarnation in artificial intelligence). Pessimists (or are they realists?) view unsolved technical problems for fully driverless cars (what SAE terms Level Five vehicles). They also see believe that success requires a federal safety mandate from NHTSA to require equipping all new cars with DSRC radios, normal delays while the current fleet turns over, and the need for state DOTs to deploy roadside service units to communicate with vehicles. This latter effort will take time, in part given limited funds for state DOTs.

The rest of this report reviews the range of economic impact studies and then focuses on those that attempt to estimate overall economic impacts. The findings of these studies are summarized, along with a discussion of their strengths and weaknesses. This section also covers the important concept of economic productivity and shows the mathematical link between improved transport access and growth in productivity. A final section provides suggestions for how to improve estimated of the likely overall impact of autonomous vehicles on the economy as a whole.

Types of Economic Impact Studies of AVs

Most economic reports are really market studies. They focus on the likely timing of deployment and on the volume of vehicles (sometimes adjusted for different degrees of shared mobility). Most studies cover different types of direct impacts. Many of these studies are useful and they are certainly better than economic studies done at the time of other network impacts—in most cases, no studies were done.

The burst of interest in AVs and shared mobility has stimulated a cascade of studies. These vary widely in level of detail, care in analysis, and in their focus. These studies may be grouped into three broad categories:

- Industry-specific studies. Most of these that contain job impacts, focus on trucking and taxis. They are often heavy on opinion about what is best for transportation and society in general, rather than following analytic results.
- Those with a focus on implications for car ownership, shared mobility, and urban passenger transportation in particular. Many of these use simulation models to show the ability of shared vehicles to substitute for driving in individual vehicles. The results can be

³⁸ Ray Kurzweil, “The Law of Accelerating Returns,” (March, 2001).

³⁹ Moore’s Law was named for Gordon Moore, a co-founder of Intel. He said that the capacity of semi-conductors (and thus the capacity of computers) would double every two years. This proved correct for some 40 years.

striking. In some cases, the authors appear to have a personal interest in the outcome, often believing that private automobiles will encourage increased VMT, negative environmental impacts, and greater suburban development.

- Studies that cover society as a whole and include efforts to quantify economic impacts. These are limited in number. They offer value in that they cover macro or economy-wide impacts, and thus offer an opportunity to identify positive and negative interactions among different parts of the economy within one set of consistent assumptions. These studies are the focus of this literature review.

Given the scale of private sector investment in autonomous vehicles (up to \$80 billion over the past five years,⁴⁰ there are likely a large number of unpublished market studies. These are unlikely, however, to consider broad social and economic impacts.

General Problems with AV Economic Impact Studies

There are a series of key factors that affect the outcome of any study of the economic impact of autonomous vehicles. Some of these assumptions shape the analysis while others are outcomes from the analysis. In many cases, however, these factors are not considered or are implied, but not reported. Without information on these, it makes it difficult to compare results or to assess the overall quality of the analysis. Here are some examples (not listed in order of importance):

- Non-linear change versus linear changes. Autonomous vehicles represent a class of investment called a network. Changes on this scale are rare, but they also stimulate shifts that cannot be identified based on extrapolation of current trends alone. Some studies recognize these types of change implicitly but they are rarely incorporated into the analytic effort.⁴¹
- Change in vehicle ownership. To what extent will people reduce (or eliminate) ownership of private vehicles and rely on access to shared driverless vehicles?
- Growth in shared mobility businesses. This is closely related to shifts in vehicle ownership since improved, low-cost access to a driverless vehicle will help make it practical for individuals (and some firms) to reduce (or perhaps eliminate) ownership of a private vehicle.
- Cost per mile. Most studies assume (often not explicitly) that passenger vehicle costs will decline. McKinsey, for example, forecasts a cost of 43 cents per vehicle mile by 2025 and costs per passenger mile for shared vehicles of 17-29 cents per mile.⁴² Some individuals foresee a cost as low as 25 cents per vehicle mile.⁴³ ReThinkX sees even more dramatic savings possible for shared mobility, providing an estimate of 15.9 cents per vehicle mile by 2021 (and a range of 6.8 cents to 24.5 cents per mile).⁴⁴ A fundamental economic principle is

⁴⁰ This does include investments in shared mobility applications. *need citation for Brookings report.*

⁴¹ The implications of network-scale investments are discussed in “The Economic and Social Value of Autonomous Vehicles: Implications from Past Network-Scale Investments” prepared for SAFE, by Compass Transportation and Technology, (December, 2017).

⁴² P. 45, McKinsey and Bloomberg, “An Integrated Perspective on the Future of Mobility,” (October, 2016)

⁴³ Brad Templeton, comment at TRB’s Automated Vehicle Symposium, July 2017.

⁴⁴ ReThinkX, “Rethinking Transportation 2020-2030,” (May, 2017), P.19.

that lower prices stimulate increased demand. With significant drops in travel cost, an increase in VMT and/or passenger travel is a logical outcome.

- Growth in VMT. This can be a controversial topic, often reflecting the author's attitude. Is VMT a negative given the link with pollution or a positive given the link with improved access? Will changes in VMT increase some places and decline elsewhere?
- Cost of technology. Will high costs delay deployment, force early adoption by high-income individuals, or mean that only fleets (TNCs) will be able to afford fully driverless vehicles?
- Attitudes regarding transportation network companies. Are these harmful since they create losses in traditional taxis and (perhaps) transit or are they a positive by improving access? Many cities in Europe provide examples of efforts to slow down or even eliminate transportation network companies. Most studies do not address this prospect.
- Focus on gross impacts or net? Most studies are a bit vague about this, in part since they focus on a specific industry. Others are not clear about what costs they include or how costs for one industry may be savings for another.
- Urban versus rural. Most studies focus on urban regions, in part since these are logical early adopters given the application of shared mobility (TNCs) to higher density regions. What will happen in rural or low-density suburban regions? Will the positive impacts likely in higher density locations also apply to rural and/or low density?
- Urban versus intercity. Intercity impacts are rarely analyzed. Urban travel accounts for most travel so this is not a surprise.
- Passenger versus freight. Most studies focus on one or the other. Further, many freight studies focus on inter-city movement. Potential interactions can be missed.
- Economic productivity. This is rarely addressed. Some studies discuss the ability to make more productive use of vehicle time. This is an important benefit but is quite different from shifts in overall economic efficiency that make it possible to produce more with fewer inputs. Economic productivity is a vital part of long-term economic growth and plays an important role in international competition. This is discussed in a later section.
- Role of public regulations. This has two aspects: 1) regulations for safety and deployment and 2) requirements for specialized equipment to support communication among vehicles and with the public agencies (DSRC radios are this focus here). Some studies assume that the DSRC technology will take time to deploy in new vehicles and use this as an argument for a slow pace of deployment. Most of the economy-wide studies implicitly assume that federal and/or state regulations will not slow down deployment and that there are multiple ways to provide vehicle connectivity beyond the DSRC technique.
- Change in public policy. The general assumption seems to be that public policy continues as it has in the past. Some studies encourage changes in policy, particularly to encourage technology deployment (for example, the KPMG study of the UK calls for a rapid expansion of the British auto industry into automated vehicles, citing an opportunity to increase market

share and add new income and jobs)⁴⁵. One area of active debate concerns the need for technology to support V2I (vehicle to infrastructure) communication. Can this be done with new forms of wireless telecommunication (5G, for example) or will success require roadside units—or will some combination be necessary?

- New vehicle types are possible given both the expected drop in vehicles crashes and the ability to design driverless vehicles to meet the specific needs of their customers. These “new” vehicles may be smaller, thus reducing vehicle manufacturing costs and requiring narrower traffic lanes.
- Technology solutions. How close is the industry to solving remaining technical problems (snow and fog present issues as do hard-to-see lane markings for some technology)? Despite optimism among private developers, some public-sector observers worry that a significant number of unsolved problems remain.
- Elderly and handicapped. These groups are recognized as important beneficiaries of driverless vehicles, but while the economic and social value of this access may be mentioned, it is rarely quantified. The recent report by SAFE stands out as an exception.⁴⁶
- Expected impact on roadway capacity. AVs will reduce (perhaps come close to eliminating) the number of vehicle crashes. Since crashes account for 25-40 percent of traffic congestion this will reduce congestion. AVs will be able to reduce headways between vehicles. This will increase the de facto capacity of roadways. In time, AV-only lanes may be deployed, permitting more vehicles to travel per lane per hour. The magnitude and timing of this potential gain in roadway capacity is a subject of debate. Some argue for gains of as much as 500 percent, while others say that increased VMT will offset any potential gains. This topic has significant implications for economic gains from reduced traffic congestion and increased access to jobs and labor.

Review of Economy-Wide Studies

Economic productivity has been mentioned above as an important potential benefit of network-scale changes. This section begins with a summary of economic productivity and recent trends in the United States. Following a review of several studies of the overall impact of autonomous vehicles, a section summarizes efforts to quantify the link between improved transportation access and increases in economic productivity.

Importance of Economic Productivity

Productivity measures the efficiency of production. Mathematically, it is the ratio of output to inputs used in production—that is, output per unit of labor or capital. The term total productivity is used when the calculation includes all outputs and inputs for the economy as a whole.

⁴⁵ KPMG, “Connected and Autonomous Vehicles – The UK Economic Opportunity,” (March 2015).

⁴⁶ Ruderman Family Foundation, “Self-Driving Cars: The Impact on People with Disabilities,” prepared by SAFE, (January, 2017).

Productivity gains are vital to the economy, since they mean that more is being accomplished with less. Capital and labor are scarce resources, so the ability to maximize their value is an important goal for business—and for countries as a whole. Productivity gains can be generated by a variety of sources, including technology advances, such as computers and the internet (and soon autonomous vehicles); supply chain and logistics improvements; and increased skill levels within the workforce. These gains generate additional returns for both capital and labor – that is higher wages for labor and higher returns on investment for business.

Many economists use changes in total productivity as a clue regarding future levels of GDP growth. In recent decades, productivity growth in the United States has slowed from historical levels. During the 1950s and 1960s, US productivity growth gained 3-4 percent a year.⁴⁷ Between 1990 and 2010 this rate dropped below two percent a year. Between 2011 and 2016, the rate was less than half a percent per year.⁴⁸ This decline in productivity may be one reason for the recent slow growth in labor wages despite a low unemployment rate.

Historically, network-scale investments have stimulated growth in overall economic productivity, witness the Interstate Highway System, the internet and wireless telecommunication. Autonomous vehicles offer the potential for another burst in productivity growth. But, while some of the economic impact studies use the word productivity, they usually refer only to the ability to do productive work while in a driverless car. Only the work by KPMG for the UK recognizes this concept.⁴⁹

KPMG uses the term agglomeration economies rather than economic productivity. Agglomeration economies represent changes in economic structure (shifts in supply and demand) generated by increased intensity of activity. These increases are generated by improved access among the factors of production (labor, capital, and intermediate goods) and by improved access to markets. Agglomeration economies generate improved efficiencies and thus improve overall economic productivity.⁵⁰

Figures R-1 and R-2 from the KPMG study summarize the links among the different type of impacts generated by autonomous vehicles and growth in GDP. Figure 1 shows the major economic impacts of autonomous vehicles, showing those that are counted within the nation's

⁴⁷ The Interstate Highway System accounted for one fourth of the nation's productivity growth during the 1960s . Ishaq Nadiri and Theofanis Mamuneas, "Contribution of Highway Capital to Output and Productivity Growth in the United States Economy and Industries," (August 1998), United States Federal Highway Administration.

⁴⁸ US News and World Report, Andrew Soergel, "The Productivity Paradox," June 1, 2016.

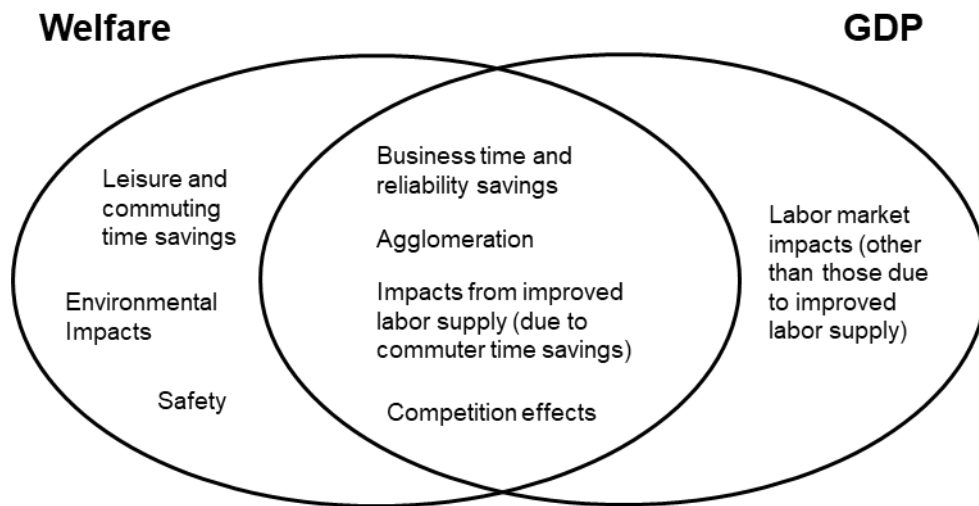
⁴⁹ KPMG, "Connected and Autonomous Vehicles – The UK Economic Opportunity," (March 2015).

⁵⁰ For a discussion of recent changes in the factors behind business location and the importance of access to labor and markets see, "Business Location in Today's Economy," by Richard Mudge and Eric Beshers, presented at TRB's conference on Transportation and Economic Development, (April 2014).

overall gross domestic product (GDP) and those that provide benefits for general welfare.⁵¹ The productivity gains from agglomeration and from improved access to labor count in both categories.

Figure R-2 provides a simple summation of the economic impacts of autonomous vehicles. The first two boxes describe direct impacts to consumers and business. The last box is termed “Wider Impacts” and contains the broader value for the economy as a whole. This category shows how network-scale programs differ from traditional transport investments. The KPMG study stands out for its recognition of these types of non-linear impacts.

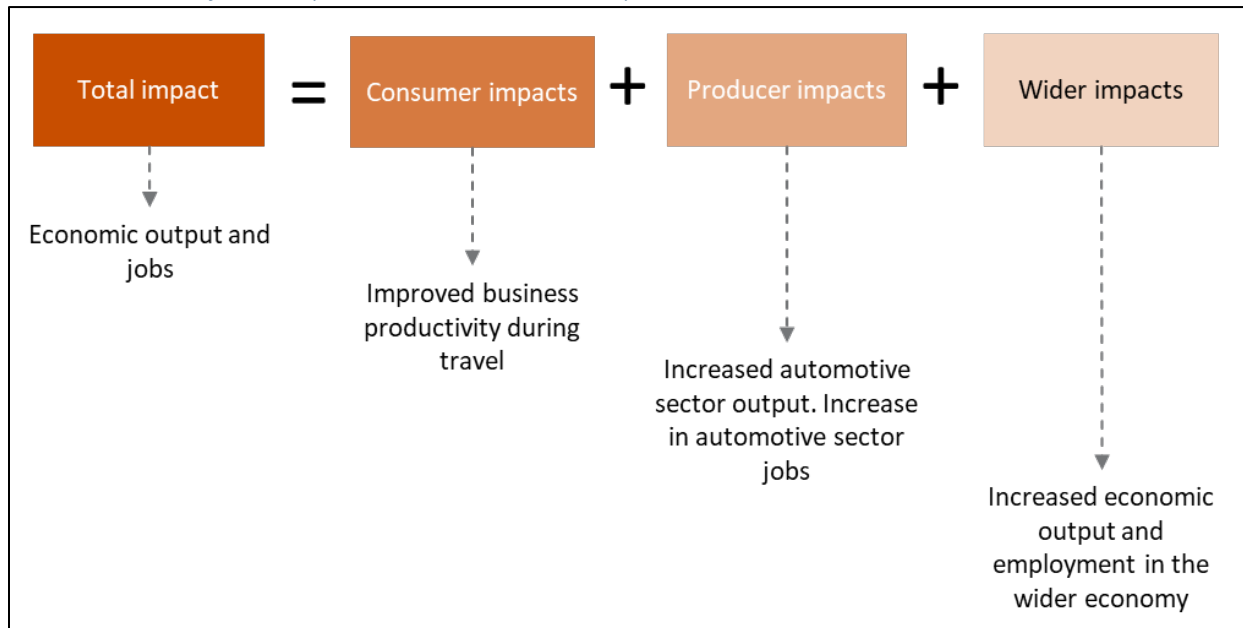
FIGURE R-1: Relationship Between Welfare Gain and GDP



Source: Economic impact of connected and autonomous vehicles: an overview of the estimation methodology, KPMG, (March, 2015)

⁵¹ KPMG adapted this figure from work by the UK Department of Transport. The terminology in the KPMG version has been adapted for US audiences.

FIGURE R-2: Major Components of Economic Impact of Autonomous Vehicles



Source: Economic impact of connected and autonomous vehicles: an overview of the estimation methodology, KPMG, (March, 2015)

Summary of Major Economic Impact Studies

There are a limited number of studies that have attempted to estimate economy-wide impacts of autonomous vehicles. No standard model exists for such efforts, so the results and assumptions vary. Key differences include:

- Specific countries (US, UK, Canada. etc.) versus global estimates. Global impacts (such as prepared by Morgan Stanley) results in huge numbers, but also requires even more heroic assumptions about the pace of change around the world and how to value gains in safety and congestion across disparate economies.
- Single year forecast versus multi-year. The latter require use of a discount rate and assumptions about the pace of deployment of autonomous vehicles. Single year forecasts sound simpler, but they also relate to likely deployment levels in that year. Some studies pick an unnamed year when there will be full deployment. Others, such as KPMG, pick a specific future year (2030 and 2040) and then estimate expected levels of deployment for that year.
- Constant dollars versus current dollars. Most have used some version of constant dollars, although there are always differences in how this is calculated. Studies of individual countries use local currencies. This makes it difficult to compare findings on a consistent basis. We have converted Canadian dollars and UK pounds to US dollars. A more difficult

problem concerns how to scale findings for a smaller country to the US. We have used relative GDP numbers for this.

- Gross benefits or impacts net of costs. There is no consistency here, with most ignoring costs directly or only including some costs. In some cases, lost revenue for one group, may be a benefit for another (one example: reduced revenues for the insurance industry translates into lower premiums paid by vehicle owners). The US Treasury report did offset benefits based on expected higher costs for vehicles and some modest increases in public sector costs.
- Most focus on overall economic impacts, without trying to estimate the potential gain in jobs. KPMG's study of the possible impacts of autonomous vehicles on the UK economy stands out in this regard. They estimate an increase in 345,000 jobs – 25,000 in the auto industry and the balance in the general economy.

While few studies make an attempt to estimate the potential productivity related gains from shifts in the overall economy, many of them do recognize the potential for these changes. A few examples:

- Although there will be significant employment displacement, there is a massive opportunity for all manner of new business models to emerge with AVs, which will create new employment.⁵²

This section summarizes five studies that estimate the overall economic impact of autonomous vehicles. Three cover the United states, while one covers Canada and one the UK. Where noted, the results for the study of Canada and the UK have been scaled to US impacts in order to facilitate consistent comparisons. Table 2 provides a summary of the findings for the four reports that provided detail across impact categories (all but US Treasury and Strategy Analytics).

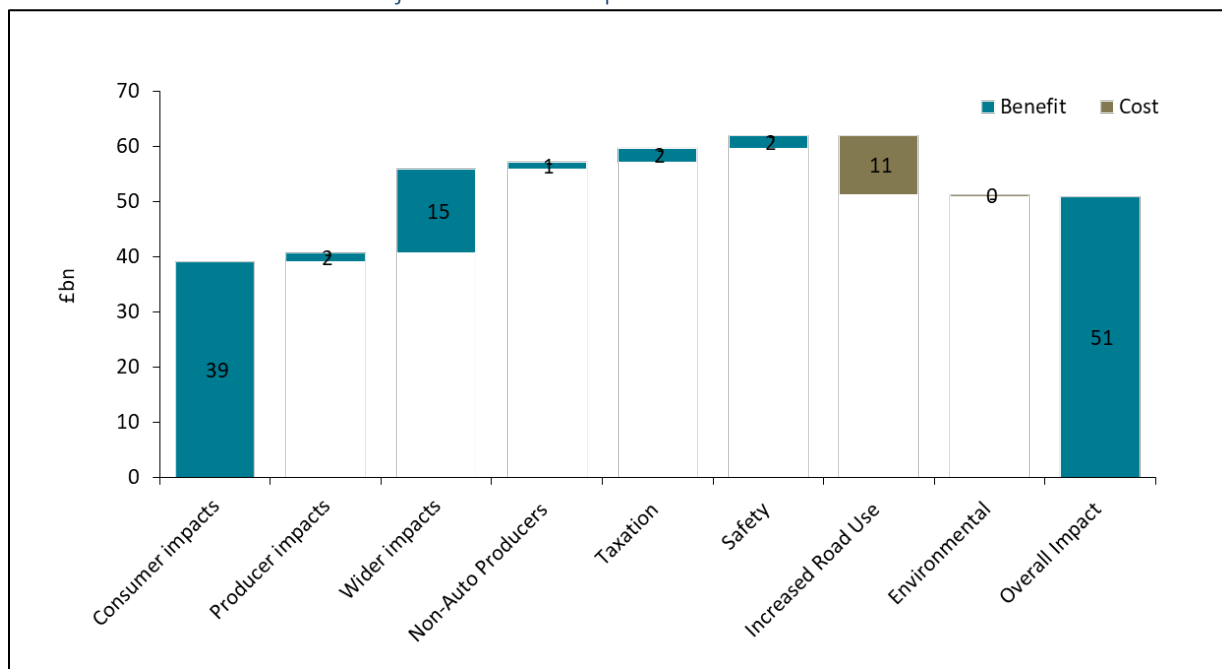
- Morgan Stanley⁵³ has prepared a series of studies about how the revolution in vehicle technology might affect the auto industry. Adam Jonas, who leads their auto practice has made several dramatic presentations about valuing the auto industry not in terms of number of vehicles sold each year but on how they are used. Morgan Stanley estimates the annual economic impact in the US as \$1.3 trillion (with a range of between \$700 billion and \$2.3 trillion). This includes safety benefits of \$488 billion, \$507 billion from use of time in the car (they call this productivity benefits), \$149 billion from the elimination of congestion, and \$158 billion from fuel savings, largely due to smoother traffic flow. They estimate an annual global impact of \$5.6 trillion. No estimate is made of offsetting costs, but the focus is on net gains from safety and congestion. This was the first consistent national impact and the basic methodology was copied by the Conference Board of Canada and the US Treasury.

⁵² P. 34, Conference Board of Canada, "Automated Vehicles," (January 2015).

⁵³ Morgan Stanley, "Tesla's new Path of Disruption", (2014). Also see Morgan Stanley, "Autonomous Cars: Self-Driving the New Auto Industry Paradigm," (2013)

- KPMG⁵⁴ picked two specific years for analysis and then backed into deployment levels for those years rather than picking an undefined future year with full deployment might occur. Their total estimate of \$68 billion (51 billion pounds) includes productivity gains from improved access to labor as well as new technology and better use of urban space. The study stands out as the only one to include estimates for these “non-linear” gains. The estimate of safety benefits (\$2.7 billion) seems quite small even though they assume only a 50 percent drop in crashes. They also reduce benefits by \$14.8 billion for increased infrastructure costs due to increased VMT. Unlike the other studies, they include an estimate of new jobs from autonomous vehicles – 345,000 in 2030 including 25,000 new jobs in the auto industry. If their results are scaled for the US, based on the relative size of each country’s GDP, their study implies a \$1.25 trillion net impact for 2040 (very close to the Morgan Stanley number) and a job impact of about 6 million. Figure 3 provides a summary of the major impacts identified by KPMG, including increased infrastructure costs.

FIGURE R-3: Breakdown of Major Economic Impacts of Autonomous Vehicles for the UK



Source: Connected and Autonomous Vehicles – The UK Economic Opportunity, KPMG, (March, 2015)

- Conference Board of Canada:⁵⁵ This report tracked the Morgan Stanley methodology, but with different parameters. The safety benefits are quite close to that of Morgan Stanley, but their other estimates are much lower for congestion gains, fuel savings, and productivity while driving. When converted to US dollars and scaled for the

⁵⁴ KPMG, “Connected and Autonomous Vehicles – The UK Economic Opportunity,” (March 2015).

⁵⁵ Conference Board of Canada, “Automated Vehicles: The Coming of the next Disruptive Technology,” (January, 2015). Prepared by CAVCOE and the Van Horne Institute.

difference in GDP for the two countries, their overall estimate is about \$750 billion a year. This is about the low estimate for Morgan Stanley.

- Clements and Kockelman⁵⁶ provide detail impacts for 13 industries, including losses for seven of them (largest loss is for insurance industry and largest gain is for freight transportation). The net effect across these 13 industries is positive (\$63 billion). Most of their estimated benefits comes from safety and reduced traffic congestion. The total annual impact of \$1.1 trillion is not far off from that found by Morgan Stanley and KPMG. Table 1 shows the detail of estimates by industry from this report.

TABLE R-1: Summary of Economic Effects (Industry and Economy-Wide)

<i>Industry-Specific Effects</i>				
Industry	Size of Industry (\$billions)	Dollar Change in Industry (\$billions)	Percent Change in Industry	\$/Capita
Insurance	\$180	(\$108)	-60%	\$339
Freight Transportation	\$604	\$100	17%	\$313
Land Development	\$931	\$45	5%	\$142
Automotive	\$570	\$42	7%	\$132
Personal Transportation	\$86	(\$27)	-31%	\$83
Electronics & Software Technology	\$203	\$26	13%	\$83
Auto Repair	\$58	(\$15)	-26%	\$47
Digital Media	\$42	\$14	33%	\$44
Oil and Gas	\$284	\$14	5%	\$44
Medical	\$1,067	(\$12)	-1%	\$36
Construction/Infrastructure	\$169	(\$8)	-5%	\$24
Traffic Police	\$10	(\$5)	-50%	\$16
Legal Profession	\$277	(\$3)	-1%	\$10
Industry-Specific Total	\$4,480	\$63	1%	\$203
<i>Economy-Wide Effects</i>				
Type of Savings		Dollar Change in Industry (\$billions)		\$/Capita
Productivity		\$448		\$1,404
Collisions		\$488		\$1,530
Economy-Wide Total		\$936		\$2,934

⁵⁶ Lewis Clements and Kara Kockelman, "Economic Effects of Automated Vehicles," Transportation research record 2602, (2017).

Collision Value Overlap	\$138	\$432
Overall Total	\$1,137	\$3,569

Source: Economic Effects of Automated Vehicles, TRB, K. Kockelman and K. Clements (2017)

Note: addition errors in the original have been corrected.

- The U.S. Treasury⁵⁷ based its numbers on the Morgan Stanley base, but they provided multi-year forecasts and reduced gross benefits by the increased cost for the vehicles and a small sum for state DOT spending. The multi-year extrapolation was based on a conservative assumption regarding deployment. Over thirty years they estimated total net economic benefits of between \$5 trillion and \$7.5 trillion dollars with a benefit cost ratio of between 7 and 10 to 1. Including a benefit-cost ratio and the focus on a net number is useful. But, the report provides very few details regarding specific assumptions behind the calculation.
- Strategy Analytics⁵⁸ focused on the market for mobility as a service (MaaS) and estimated a worldwide passenger market of \$7 trillion annually by 2050. They did not provide an estimate for specific countries. They include a small (three percent) estimate for new and emerging pilotless vehicle services. The number is large, but so far in the future and for the world as a whole that it has limited value relative to the other estimates here.
- RethinkX⁵⁹ has focused on the opportunity for transportation as a service (TaaS – similar to mobility as a service) to “collapse the internal-combustion vehicle and oil industries.” The cost advantages (4-10 times cheaper per mile than buying a new car by the year 2021) will stimulate a profound change in how people move. TaaS will provide 95 percent of passenger miles within ten years of regulatory approval of autonomous vehicles, even though private cars still account for 40 percent of the overall fleet. This shift would provide annual consumer benefits of \$1 trillion a year and an additional increase in the US GDP of \$1 trillion. These numbers are larger than reported by the other studies.

These studies used a variety of different models, although most included the “Big Three”—safety, Congestion (including fuel savings), and more productive time while traveling. KPMG included detail on “wider economic impacts” and included some impacts that could be characterized as economic productivity gains. KPMG, Clements and Kockelman, and the Treasury study included

⁵⁷ US Treasury Build America Initiative, “40 Proposed US Transportation and Water Infrastructure Projects of Major National Significance,” (January 2017), prepared by consulting team led by AECOM. Pages A-96 and A-97 describe autonomous vehicles.

⁵⁸ Strategy Analytics, “Accelerating the Future: The Economic Impact of the Emerging Passenger Economy.” (June 2017).

⁵⁹ ReThinkX, “Rethinking Transportation 2020-2030,” (May, 2017)

specific cost items, although there was no consistency here. The last two studies focused on gains from shared mobility (transportation as a service).

Only KPMG estimated job impacts, although estimates could be made based on the total economic gains estimates by the other studies. The four detailed studies generated similar numbers (although the Canadian study is on the low end). The RethinkX study is the largest numbers -- \$2 trillion annually in about ten years after the industry starts.

TABLE R-2: Summary of Studies on Overall Economic Impact of Autonomous Vehicles

Impact measure	Morgan Stanley	Conference Board (Canada) in \$US	KPMG (UK) In \$US	Clements and Kockelman
Time frame	Full deployment	Full deployment	2030 (and 2040)	90 % deployment
Safety	\$488 Billion 90 % of crashes eliminated. \$7.9 million value of life	\$48 billion 80 % of crashes eliminated.	\$2.7 Billion 50 percent drop in crashes	\$488 Billion plus \$138 billion in “collision value overlap”
Productivity (while working in car etc.)	\$507 Billion \$22.5/hour for 25 percent of time	\$25.5 Billion Uses value of time of \$7.6 per hour	\$26.8 billion	\$448 billion
Congestion	\$ 149 Billion from elimination of congestion \$138 = time saved \$11 = fuel saved	\$6.4 billion	\$20 Billion including improved access to labor market Consumer benefits only	
Fuel savings	\$ 158 Billion 30 percent gain from smoother traffic flow	\$3.3 Uses 10 percent gain from smoother flow		
Industry				\$63 Billion (net) \$241 Bill in gains \$178 Bill in losses
Other consumer savings			\$6.7 Billion Insurance, parking etc.	
Producer gains			\$2.7 Billion; mostly in auto industry	
Wider econ impacts			\$21 Billion Large list including trade; many types of technology; better use of urban space	
Tax receipts			\$2.7 Billion	
Infrastructure Cost			Minus 14.8 Billion Due to more VMT	
Total	\$1.3 trillion annual	\$83.2 Billion annual	\$68 Billion for 2030 \$162 billion in 2040 345,000 new jobs	\$1.1 trillion annual

			1 percent increase in GDP (2030)	
Other comments	Range: \$0.7 to \$2.3 trillion Global = \$5.6 trillion	\$750 Billion scaled to US economy	If scaled to US economy \$490 Billion in 2030 2.4 million new jobs \$1.25 trillion in 2040 6 million new jobs	

[Link Between Access and Economic Productivity⁶⁰](#)

Several studies have attempted to estimate the link between improvements in transportation access and the growth in regional or national economic productivity. Despite differences in their methodologies and underlying data sets, with one exception they generate similar results: a ten percent improvement is linked with a two percent (or a bit more) improvement in overall economic productivity or improvement in GDP.

The Eddington Transport Study, “Transport’s role in sustaining the UK’s productivity and competitiveness,” provides an international context for transportation’s role in productivity and economic competitiveness. The study noted that, on average, a 10 percent increase in transportation infrastructure investment increases GDP by approximately 2 percent. The challenges of properly addressing the economic benefits of transportation investment were also addressed, stating that up to 50 percent of all potential economic benefits of transportation investment go unreported.⁶¹

Remy Prud’homme and Chang-Woon Lee’s “Size, Sprawl, Speed and the Efficiency of Cities” compared productivity of European cities, particularly Paris and London. The researchers concluded that, “The efficiency of a city is a function of the effective size of its labor market.”⁶² The research found that a 10 percent improvement in access to labor increases productivity, and therefore regional output, by 2.4 percent.⁶³

Prud’homme and Lee’s work notes that transportation costs and additional benefits can be evaluated by looking at the effective size of an urban area’s labor market—i.e., what fraction of the total job possibilities can a worker access within a reasonable commuting time? For example, a 10 percent increase in average speed, all other things constant, leads to a 15-18 percent increase in the labor market size and a 2.9 percent increase in productivity.⁶⁴

⁶⁰ This section draws on Bipartisan Policy Center, National Transportation Policy Project, “Performance Metrics for the Evaluation of Transportation Programs,” prepared by Delcan Corporation, (November, 2009).

⁶¹ The Eddington Transport Study: The case for action: Sir Rod Eddington’s advice to Government. Volume 3: Meeting the challenge. <http://www.dft.gov.uk/about/strategy/transportstrategy/eddingtontstudy/>.

⁶² Size, Sprawl, Speed, and the Efficiency of Cities. Remy Prud’homme and Chang-Woon Lee. <http://www.dublinpact.ie/word/Prud-homme-paper.doc>.

⁶³ Size, Sprawl, Speed, and the Efficiency of Cities. Remy Prud’homme and Chang-Woon Lee.

⁶⁴ Size, Sprawl, Speed, and the Efficiency of Cities. Remy Prud’homme and Chang-Woon Lee.

David Hartgen and Gregory Fields found that for a sample of U.S. cities, a one percent improvement in accessibility to a region's central business district improves regional productivity by 1.1 percent (in "Gridlock and Growth: The Effect of Traffic Congestion on Regional Economic Performance").⁶⁵ These results are significantly larger than those from the other studies mentioned here.

So can we use these results? The terms are not completely consistent. Much of the debate regarding autonomous vehicles and congestion begins with estimates of possible increases in roadway capacity. These numbers vary widely, even reaching 500 percent in some cases. A 50 to 100 percent increase in roadway capacity is used by a number of state and local planning efforts. A doubling of roadway capacity would be enough to eliminate most urban congestion. Even a 50 percent change could come close. Some rough numbers:

- if the average commute time is 25 minutes
- and the average speed is 35mph,
- a change to 50mph is about a 40 percent improvement.
- Using a 2.5 percent gain in productivity for every ten percent improvement in speed or access, this implies a 10 percent gain in overall economic productivity. This is a huge number.

Even a twenty percent improvement due to the near elimination of urban traffic congestion would generate a five percent gain in economic productivity. This would not happen immediately of course, but would be phased in over 10-20 years. One of the lessons learned from the Interstate Highway System and other network scale changes is that business and individuals react to change once they believe the change is on its way. The Interstate generated significant economic gains decades before it was completed.

More work is needed to convert the general findings regarding congestion and economic productivity, but the overall numbers are large enough to shift the rate of growth in the economy as a whole. These numbers do not include the likely impacts of gross dollar benefits.

Lessons Learned: Next Steps

Table 3 provides an overview of major findings, the general approach used by each study and possible implications for interpreting their results and possible future studies.

General conclusions for future research:

- There is value in a consistent, broad-based study. Many assumptions are called for about the pace of deployment and the specific values (travel time, improvement in traffic congestion etc.). to the extent possible, they should reflect a similar approach.

⁶⁵ "Gridlock and Growth" (June 2009), Reason Foundation, Policy Study 371.
http://www.hartgengroup.net/Projects/2009-06-22_Final_PS371.pdf

- An update makes sense. Much has happened in the past year or two that implies a more rapid deployment is possible than when the earlier studies were done. Morgan Stanley dates to 2013 and O214 and KPMG to 2015.
- Costs should be included. Coverage of specific industries is useful, in part to recognize that not everyone will be a winner. These industries should include the public sector, in part since there is an active debate regarding the scale of public investment.
- A multi-year focus would help, given the uncertainty over the pace of deployment that makes any specific year uncertain.
- Employment should be estimated. These studies imply that net employment should grow (the KPMG study says this explicitly).
- Some sensitivity analysis would help, given uncertainty over the pace of deployment, possible shifts in vehicle operating costs etc.
- Recognition of variance across different geographic areas would help. The unstated assumption in most cases is that the focus is on large metro area. Rural and low-density suburban impacts may be quite different—and there is a political sensitivity that these regions are often over looked.
- Specific recognition of freight would add value. Most studies focus on passenger travel (Clements and Kockelman included freight and KPMG mentioned this).
- A specific recognition of non-linear changes and potential gains in economic productivity would help.

TABLE R-3: Findings, Techniques, and Implications from Economy-Wide Studies

Study	Major Findings	Approach	Implications
Morgan Stanley	<ul style="list-style-type: none"> - \$1.3 trillion annual impact when fully deployed - Range = \$0.7 trillion to \$2.3 trillion - \$5.6 trillion impact worldwide 	Analyze major categories of impacts	<ul style="list-style-type: none"> - Did not include economic productivity - Did not consider costs - Assumptions: reasonable to optimistic
KPMG for UK	<ul style="list-style-type: none"> - 51 billion pounds annual impact by 2030 (\$490 billion when scaled to US) - 345,000 jobs by 2030 (2.4 million jobs when scaled to US economy) - 121 billion pounds impact by 2040 (\$1.25 trillion when scaled to US) - Highlighted national gains from becoming a center for AV auto industry 	<ul style="list-style-type: none"> - Analyze major categories of impacts - Focus on auto industry: found it would do well - Analyzed gains from increased share of AV market 	<ul style="list-style-type: none"> - Considered some economic productivity gains - Major cost = infrastructure due to growth in VMT - Did not emphasize shared mobility / reduced car ownership. - Safety gains seem quite small - Focus on specific years: 2030 and 2040
Conference Board of Canada	<ul style="list-style-type: none"> - \$750 billion impact if scaled from \$83 billion in Canadian dollars 	<ul style="list-style-type: none"> - Tracked Morgan Stanley model but with assumptions relevant to Canada – generally more conservative 	<ul style="list-style-type: none"> - Conservative assumptions regarding value of time, smoother flow of traffic etc.
Clements and Kockelman	<ul style="list-style-type: none"> - \$1.1 trillion annual impact based on 90 percent deployment 	<ul style="list-style-type: none"> - Focus on individual industries, using findings from other studies 	<ul style="list-style-type: none"> - Analysis of individual industries shows net positive impact despite large number of industries with losses.
US Treasury	<ul style="list-style-type: none"> - \$5-7.5 Trillion net economic benefits over 30 years - Benefit cost ratio between 7 and 10 	<ul style="list-style-type: none"> - Modified Morgan Stanley numbers based on assumed deployment rate 	<ul style="list-style-type: none"> - Few details on assumptions - Multi-year impact - Emphasis on net impact (mostly private sector costs of vehicles)

		<ul style="list-style-type: none"> - Costs based on higher cost of cars and small public spending - Three percent discount rate 	<ul style="list-style-type: none"> - Did not emphasize shared mobility / reduced car ownership. - Not aggressive deployment assumptions
Strategy Analytics	<ul style="list-style-type: none"> - \$7 trillion new global market for mobility as a service by 2050 - Limited number of “new” businesses beyond mobility as a service. 	<ul style="list-style-type: none"> - Analysis of markets in individual countries. 	<ul style="list-style-type: none"> - 2050 pretty far off - Global market hard to assess
ReThinkX	<ul style="list-style-type: none"> - \$1 trillion a year in consumer benefits within ten years of regulatory approval - Plus \$1 trillion gain for GDP 	<ul style="list-style-type: none"> - Estimated cost changes and used this to forecast switch from private cars. 	<ul style="list-style-type: none"> - Based on dramatic cost reductions from new technology and shared mobility